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Sustainable Development and Food Insecurity

Edited by
Hanna Dudek, Joanna Myszkowska-Ryciak,
Ariun Ishdorj and Marzena Jeżewska-Zychowicz

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About the Editors

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Preface

This Sustainable Development and Food Insecurity topic collection, published by MDPI, offers a comprehensive and multidisciplinary examination of the complex issues related to food insecurity at different levels of society. This collection explores the challenges faced by individuals and households in accessing adequate, safe, and nutritious foods, as well as the broader implications of food insecurity at the community, regional, national, and global levels. This topic collection aims to improve understanding of the multifaceted nature of the problem and the interconnected nature of challenges that need to be addressed to achieve sustainable food security for all.

Central to the topic collection is the recognition that addressing food insecurity requires more than simply alleviating hunger; it necessitates ensuring universal access to safe, nutritious, and sufficient food for years to come while simultaneously working to eliminate all forms of malnutrition. The United Nation's Sustainable Development Goals, established in 2015, set a bold target of eradicating hunger, ensuring food security, improving nutrition, and promoting sustainable agriculture by 2030. However, the scale and severity of these problems cannot be overstated. Currently, one in nine people globally suffer from malnutrition, and a staggering one in four children experience stunted growth. These challenges are further compounded by the looming threats posed by climate change and the ongoing degradation of vital natural resources such as soil, freshwater, and biodiversity. As these environmental pressures intensify, they pose significant risks to food production and threaten to exacerbate the already dire situation of food insecurity. The primary purpose of this topic collection is to shed light on the persistent issue of food insecurity and its intricate relationship with sustainable development. By bringing together a diverse range of research articles, this collection seeks to deepen our understanding of the root causes, far-reaching consequences, and potential solutions to food insecurity. The articles in this collection cover a wide range of subjects related to sustainable development and food insecurity, including:

- Macro-level drivers of food insecurity;
- Socio-demographic correlates of food insecurity;
- Statistical modeling and projections;
- Sustainable development goals and social policy ;
- Consumer behavior and preferences;
- Agrobiodiversity and sustainable food production.

The motivation behind this topic collection stems from the urgent need to address the global challenges of food insecurity, which continues to affect millions of people worldwide, despite significant strides made in development worldwide. This collection is aimed at a broader audience, including researchers, policymakers, practitioners, and all those interested in understanding and addressing the complex challenges of food insecurity and sustainable development. The articles within this collection provide valuable insights and innovative views and strategies that can inform future research, policy decisions, and effective interventions to create a more resilient and equitable food system.

As Editors of this Topic, we would like to express our gratitude to the authors who contributed their research, sharing their expertise and insights on various aspects of food insecurity and sustainable development. We would also like to thank MDPI and the editorial teams of all five journals for providing this extraordinary learning and development opportunity. We particularly appreciate the constant support and attention provided by editorial team members, especially Julyn Li. Thanks to their joint efforts, we were able to put together a collection of 35 articles, including systematic literature reviews and original research. By bringing together a diverse range

of perspectives and insights, this topic collection contributes to the growing body of knowledge on sustainable development and food security. It serves as a valuable resource for researchers, practitioners, and policymakers addressing one of the pressing challenges of our time, and we hope this collection will inspire further research in this crucial area.

Hanna Dudek, Joanna Myszkowska-Ryciak, Ariun Ishdorj, and Marzena Jeżewska-Zychowicz
Editors

foods

Article

Integrated Approach to Achieve a Sustainable Organic Waste Management System in Saudi Arabia

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Abstract: Organic waste management (OWM) has always been a fundamental aspect of human populations. Approaches to OWM must be matched to the characteristics of a certain population. In this consideration, the Kingdom of Saudi Arabia (KSA) is no exception. Organizations are being aligned to focus on sustainability matters sharing significant features with universal trends, especially the integration of 3Rs (reducing waste, reusing, and recycling resources). However, the degree and nature of advancement in the direction of sustainability vary depending on the economic level of a state. High-income economies can afford to pay a higher price to integrate 3Rs technologies. Most recent endeavors have focused on achieving 'Zero Waste', which is costly for low-income developing countries. The expectations of OWM systems in KSA must be estimated. In this work, the situations in KSA and other countries are analyzed, and pertinent aspects are explored. Matters relating to the sustainability of OWM are conceptually assessed. This study proposes an integrated method for an organic waste management system to achieve sustainable OWM in the context of state policy and appropriate frameworks, suitable technology, institutional order, operational and monetary administration, and people consciousness and involvement. A genetic-based waste collection transportation algorithm that enhances the efficiency of waste collection truck management is presented in line with this technology. The selected routes based on the R_{fs} and IPv are the most efficient among those available for the examined smart bin destinations. The minimum R_{fs} of selected routes is less than the maximum R_{fs} of available routes by 2.63%. Also, the minimum IPv of selected routes is less than the maximum IPv of available routes by 27.08%. The proposed integrated approach, including the waste collection transportation algorithm, would be beneficial across a variety of country-specific layouts.

Keywords: genetic-based waste collection; IoT; truck waste collection management; Zero Waste

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1. Introduction

Millions of Muslims visit the Kingdom of Saudi Arabia (KSA) every year to do Pilgrimage (Hajj) and Umrah. Muslims visit holy areas of worship, such as the holy mosques al Haremeyn (Makkah and Medina) and Al-Masha'ir (Arafat, Mina and Muzdalifah) [1]. The number of pilgrims arriving in KSA for Hajj (the 12th month of the Islamic lunar calendar) and Umrah has significantly increased in recent decades due to the ongoing expansion of the holy mosques, enhanced transportation services and safety, and decreased aggregate cost and time, with an annual increase of 1.15% from 1993 to 2014 [1–3]. The KSA produces approximately fifteen million tons of municipal solid waste (MSW) per year, with a daily average of 1.4 kg per person. The average rate of waste generation is projected to increase to 30 million tons by 2033 due to continued population growth and civic expansion. Medina city generates approximately 887 thousand tons of MSW on an annual basis. This rate will increase due to the growing number of pilgrims every year. The highest rate of waste generation occurs during the last 10 days of Ramadan (the 9th month of the Islamic lunar calendar) due to large numbers of local and foreign pilgrims in Makkah and Medina cities [1]. The new Vision 2030 strategy in KSA aims to minimize all types of waste and to generate renewable energy from natural origins, including generated waste. The strategy has produced a roadmap for the implementation of a solid waste management system to enhance the economic and environmental importance of waste beyond recycling and reuse [4].

The increase in food waste is placing robust strain on the environment and increasing worldwide the economic value of proper management. Among the conventional technology for processing organic waste (incineration, waste processing, anaerobic digestion, etc.), composting is an economically feasible and dependable PT, regardless of technical shortcomings and social problems, and recycling technology.

Recent research describes diverse techniques to enhance PB composting, as well as co-composting, the addition of organic/inorganic collectives, the reduction of fuel line emission, and microbiological diversities.PT composting carried out using current technology quickens the deterioration of natural waste, produces value introduced mature compost, saves costs, and is technically possible for PT composting [5].

Many researchers, such as Nizami et al., Rehan et al., Miandad et al., Khan et al. and Ouda et al. have presented various solutions to the waste elimination problems of KSA, in line with the country's vision for 2030. These solutions have included producing energy and value-added outputs, such as chemicals, organic fertiliser and nutrition, from different domestic waste origins through waste recycling [1,6–9]. In recent years, waste recycling has gained widespread recognition for its ability to keep products and materials in use, which can then be utilized in extraction, natural systems regeneration, transportation, and production of new raw substances, thereby enabling the circular economy in countries like KSA [1].

Composting natural waste merchandise on agricultural land is considered one of the maximum economical, practical, and environmentally useful control options. As a rule, the system includes the herbal organic decomposition of natural waste additives and various species of microorganisms [10]. The generation of food as a type of organic waste is a natural result of human behavior. The elimination of such waste is necessary to improve the quality of life. Organic waste management (OWM) mechanisms were firstly designed to remove waste from close proximity to living areas to maintain public health. After understanding the risks of uncontrolled disposal, procedures to remove waste were designed and fundamentally implemented. Diverse substances and energy recovery mechanisms have been designed and recently included in modernistic systems. Waste management systems must now be redirected towards sustainability in international undertakings.

Furthermore, adhering to the United Nations' Sustainable Development Goals to minimize malnutrition and extirpate starvation necessitates effective management and proactive efforts to ensure sustainable food security. The Group of Twenty (G20) is an intergovernmental forum of large and advanced economies (19 countries and the European Union) that plays a pivotal role. G20 members comprise 60% of citizens, 80% of economic production and 75% of greenhouse gas (GHG) emissions [11]. This commercial success has a negative effect on the environment. While the G20 nations are preparing for the coming decades, this is an opportunity to use their experience to set an example for other nations around the world.

Japan, Germany, Canada, France and Australia are amongst the G20 members who performed best in the Food Sustainability Index (FSI) in 2021. Although these nations still have room for improvement, they combine great production with a strong strategy. Techniques for dealing with food scarcity and waste are well understood amongst the group. However, more procedures can be carried out to execute the mandated law that holds all stakeholder economies accountable. Figure 1 presents the FSI score results of the G20 countries, according to the Economist Intelligence Unit and the FSI 2021.

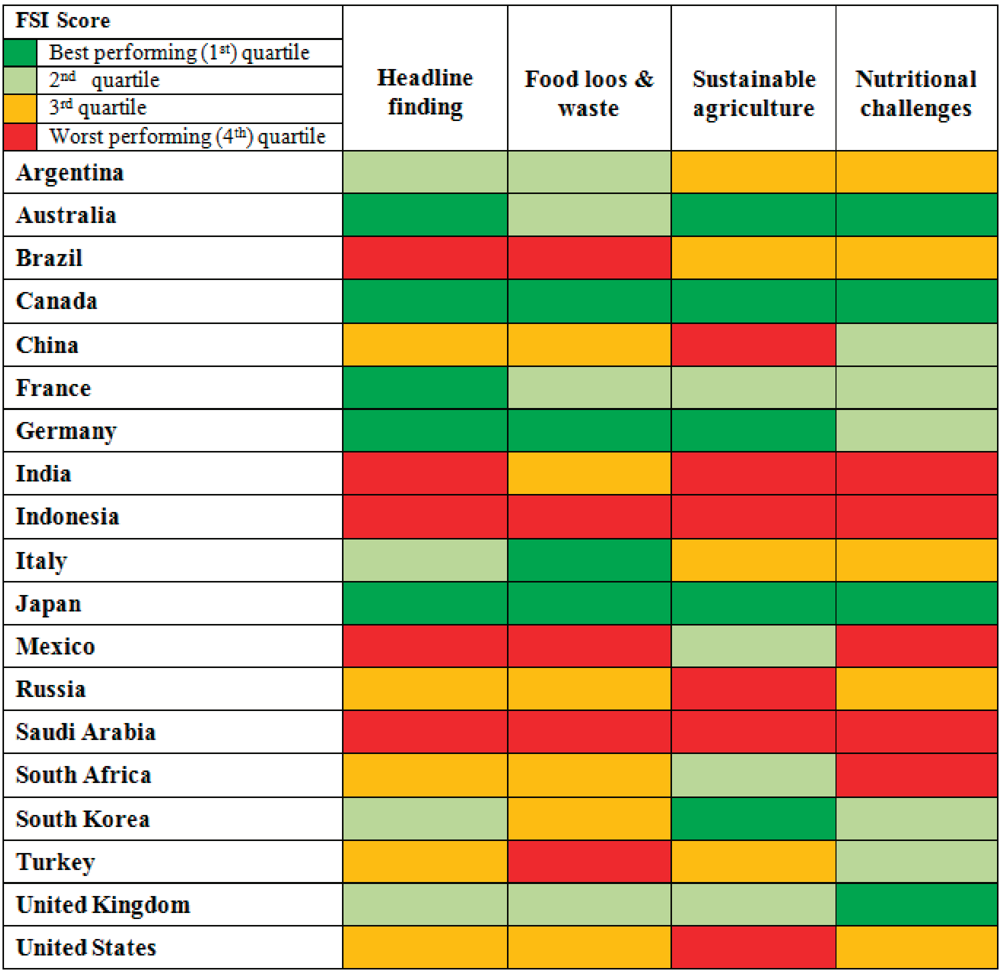

Figure 1. FSI results—G20 countries.

The significance of this study is in finding solutions to reduce pollution and maximize resource use, especially organic waste management systems, and utilizing this technology to achieve the highest levels of waste management. The research's significance extends to the development of a methodology for implementing these solutions. This research proposes an integrated organic waste management approach for KSA, to enhance waste management performance.

Related studies in waste management mainly focus on solid waste management, which encompasses different waste types in addition to food waste. Some researchers have used IoT architecture to enhance waste management performance. However, this study addresses a variety of issues.

The issues are as follows:

- The sources of organic waste are not specified and clearly classified.
- The management of organic waste using IoT is not properly addressed.
- Transport lacks the use of intelligent algorithms.
- Public awareness of the law.

This research aims to address the above-mentioned pressing issues of source waste generation, collection and transportation in Saudi Arabia, by using the proposed integrated organic waste management system.

2. Food Waste Is a Problem

According to the World Bank report in 2020, more than two billion tons of MSW were produced annually, with at least 33% of this being ecologically harmful. On a global scale, the average amount of waste produced per individual each day is 0.74 kg. These values range from 0.11 kg to 4.54 kg. Despite accounting for just 16% of the world's population, high-income exports account for approximately 34% or 683 million tons of global waste [12,13].

Waste generation has enormously increased across the world in the last decades, and there is no indication of it decelerating down. Global MSW generation is expected to have increased by 70% to 3.4 billion metric tons by 2050. This situation is a result of a number of factors, such as world population growth, urban expansion, economic evolution and consumer shopping behavior. People generate millions of tons of waste each year, and this is rapidly becoming a worldwide problem. The necessity for authorities to provide appropriate waste remediation and disposal facilities has become ever more significant with the massive quantities of waste accumulating. However, less than 20% of waste is recycled each year, with massive aggregates still transmitted to landfills. Waste is frequently disposed of in hazardous open tips, particularly in developing countries. High-income countries produce more waste than low-income poorer countries, but they often have better waste management systems to help address these issues [14].

Waste generation statistics by billions of metric tons are presented in Figure 2. These statistics clarify the amount of MSW produced globally in 2016, with projections for 2030 and 2050. According to estimates, approximately 3.4 billion metric tons of MSW will be produced globally.

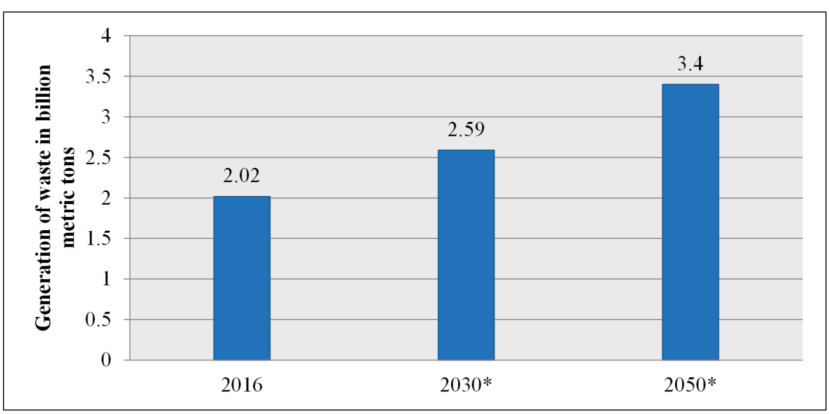

Figure 2. Worldwide municipal solid waste generation planning (2016–2050) [15]. *: Prediction values.

The East Asian region, the Middle East, North Africa and the Pacific region produce the greatest volume of waste, but produce the least in absolute terms. The whole waste area of the fast-developing areas of Sub Saharan Africa, the Middle East, North Africa and South Asia are predicted to more than triple, double, and double by 2050, respectively.

More than 50% of waste in these areas is currently overtly thrown, and the trend of waste accumulation will have huge ramifications for the environment, health and economic growth, necessitating immediate action [2,3].

Organic waste accounts for more than 50% of global MSW, and is a serious problem in many regions. The East Asia–Pacific (EAP) region produces the most organic waste, accounting for approximately 62%, followed by the Middle East and North Africa (61%) [12].

Organic waste recycling is one of the strategies for solving this problem. Moreover, different methods are available for utilizing organic wastes, such as composting for fertilizer production, and anaerobic digestion (AD) for energy production [16,17].

Vlachokostas et al. proposed a scheme that included a Region for Biodegradable Waste Treatment Installation. The distance to the municipality is two km, and it is seven km to the slaughterhouse [18]. This public place is effortlessly approachable and also is even in near proximity to a municipal vegetable garden. The chosen place was agriculturally intense, with focused production of biodegradable waste. The study examined different types of organic wastes, including manures, hygienized slaughterhouse waste, cheese whey, rotten potato pulp, and olive mill residues. These could be gathered from their disposal places and transported using boxes and heavy obligation vans to the Biodegradable Waste Treatment Installation center. Hygienization is a crucial factor in the remedy of such waste, specifically stomachs, animal fat, and blood [18].

Moreover, modern linear agricultural manufacturing structures make it feasible to supply meals in large portions for a developing population. However, this leaves a quantity of agricultural waste to be discarded or recycled for reintroduction into the manufacturing chain for new uses. To obtain this goal, numerous processes for handling meals waste were explored [19].

The gathering and transportation of waste are primarily based on predetermined paths, ensuing in needless costs and wasted equipment. Empty packing containers are often gathered first, even as waste-stuffed packing containers spill onto the road. This spillage might additionally bring about elevated cleaning costs, health and safety dangers, and court cases from residents.

Figure 3 presents the classification of MSW produced globally according to substance class, with food and green waste accounting for 44%.

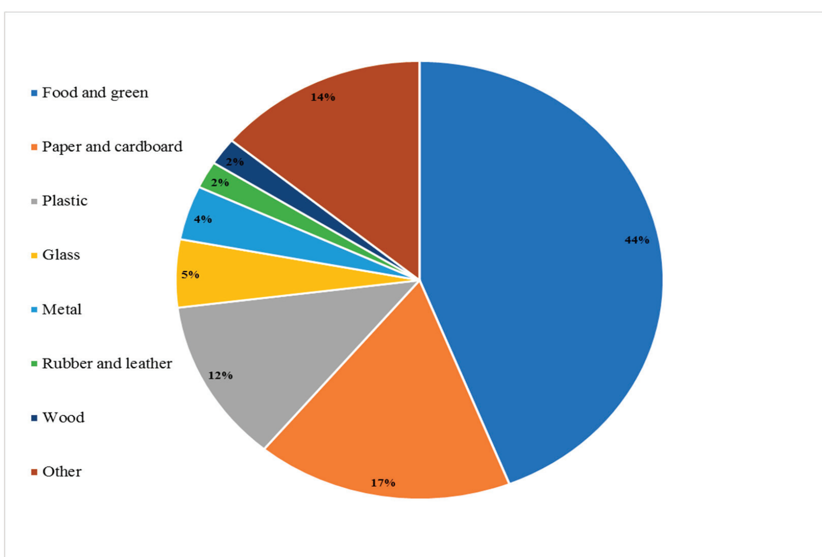

Figure 3. Classification of municipal solid waste produced globally in 2016 by the substance class [12].

According to UNEP, statistics are distributed in an inequitable manner amongst nation income classes and regions. Based on a regional level, developed economies in Australasia, North America and Northern and Western Europe have made the most progress in data collection in the sectors of household, food service, and retail. Meanwhile, numerous developing economies in the Caribbean, Latin America and Africa remain data-deficient [20].

However, the UNEP data challenged the conventional view that food waste is a problem that only affects advanced and high-income nations, and instead emphasized it as a global concern. Accordingly, the most important obligation in minimizing food shortage and waste is to recognize the problem. Hence, people should be more aware of the scope of the problem, the amount of food wasted, and the manner food is utilized. The first step, and a form of protection, is to estimate the costs [20].

Although UNEP admits that their data are weak in terms of numbers, information is more abundant in advanced economies, implying that it still provides relevant information for the FSI. Household waste is frequently greater than the aggregate of other food waste categories (retail and food service waste). The US is an exception due to the preferences of the American people and a and culture of dining outside the house. The G20 nations that perform well in all three categories are Japan, which ranks in the top six for all three categories, Italy, the UK and Germany, in spite of the latter two each having a task to work on reducing household waste, as shown in Figure 4. However, Saudi Arabia and France are particularly short on household and retail waste. Mexico and Turkey also rank poorly, as presented in Figure 4.

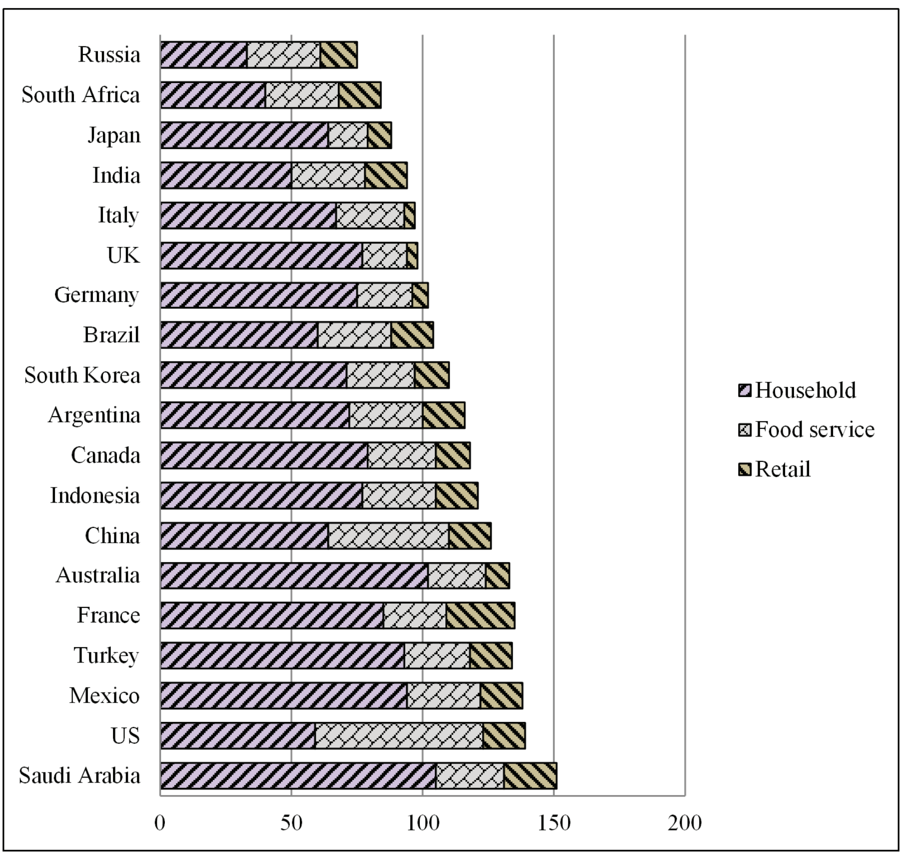

Figure 4. Food waste index flowchart (kg/head/year) 2021 [20].

According to the retail waste index, France came in last place, noteworthy because the French government has been paying greater attention to this issue since 2016. Legislation was passed that required retailers with a certain inventory size to partner with a company to distribute unsold food for free or face a penalty. However, France's legislation may have resulted in a more careful assessment of food waste from retail establishments. A possible situation is that food waste is under-reported. Legislation like this may be a more appropriate model that some other nations lack. Japan imposed penalties for food organizations that violated recycling and reuse legislations in 2020. Such laws are not imposed in the UK.

Certain religious and cultural elements can play a critical role in reducing food waste. In many cultures, serving a large amount of food during hospitality is essential to be a gracious host. Accordingly, changing this mindset and consciousness to minimize food waste can be difficult. However, governments should raise awareness and take steps to align with current trends to ensure that the lawful system is a viable choice [21].

As previously mentioned, the oldest and largest religious gatherings in the world happen every year in KSA. Millions of Muslims from all over the world do Pilgrimage to worship at Al-Haram (Holy Mosques in Makkah and Medina) and Al-Masha'ir (Mina, Arafat and Muzdalifah) [1]. The Al-Haram mosque in Makkah has a total size of approximately 356,800 km^2, which includes indoor and exterior prayer areas. More than two million Muslims gather to worship during Ramadan and Hajj [22]. Garbage collection and disposal are major tasks for the authorities during the Ramadan and Hajj seasons, which result in a significant increase in waste production in a short amount of time. Moreover, this situation becomes more challenging due to the combination of rising food waste and plastic waste [23]. Most waste is disposed of in landfills that lack leachate and landfill gas collecting methods [24,25]. This activity results in water and soil pollution and emission of huge quantities of GHGs [9]. Hence, the demand for an appropriate waste management system in Makkah city has intensified to deal with the enormous quantities of waste produced by the local population and the pilgrims [1].

In KSA, garbage is collected using private or social funds and disposed of in landfills. The waste management system in Saudi Arabia lacks waste disposal services and transfer charges. In the next 10 years, most landfills are expected to be full and unable to be used. Although recycling, energy recovery and reuse are often considered, they are still at an early phase. Waste recycling and sorting are powered by an effective unofficial sector. The recycling average ranges from 10% to 15%, mainly due to the existence of the unofficial sector that reuses paper, plastics and minerals from domestic waste [26].

The existing collection system in populated urban zones increases the expense of installing air systems in residential areas. Moreover, restricted placement of trucks and waste bins causes issues in the operation of the collection system, especially in historical areas.

The collection of organic waste is based on pre-determined paths, resulting in unnecessary expenses and a lack of equipment. Empty containers are frequently collected first, whilst waste-filled containers leak onto the street or onto a lot, which may result in increased cleaning costs, health risks and complaints from residents.

This research focuses on IoT technologies in the OWMS and proposes an effective waste management based system based on the IoT to improve waste collection activities in the waste source area, an important stage, especially for recycling waste in KSA's urban areas.

The increased functionality of cloud services, applications and databases will make communication easier amongst different IoT gadgets, forcing new communications between the existing system and the new system. The ensuing data networks will minimize expenses and dangers and enhance waste management operations. The IoT architecture is predicted to reduce waste collection operating expenses in Saudi Arabia, through the use of collected data shared between bins, smart containers and vehicles, to allow automation and coordination of the identification of waste for recycling and waste processing. The implementation of future Internet technology enhanced by the utilization of the Internet Protocol on many wireless sensors permits the IoT paradigm.

Many sensor units can be considered to be a component of Wireless Sensor Networks (WSNs) when utilized in a city. These sensors collect and process ambient information to improve legacy city infrastructure, which is referred to as smart cities [27].

3. IoT-Based Waste Management Systems

A variety of waste management models have been produced using specific IoT devices. This part of the study presents the most common IoT-based waste management techniques.

Various models employ IoT gadgets, including capacity, weight, temperature, humidity, and chemical sensors, depending on the need for these devices.

Mustapha et al. presented a MSW stage using recycling collection data based on IoT Innovation. The study involved a demonstration of waste collection, transportation, reuse and processing [28]. Chaudhari et al. presented an option for strong waste recycling, which involved reusing materials and energetic optimization. An choice of factors was created and thereafter the quality of waste in each container was compared on a daily basis [29].

Chaudhari et al. presented a monitoring system to monitor bins and trucks via RFID and ICT, utilizing cameras and GPS. The bin used for variant waste types is located outside the doors. Homogenous and heterogeneous trucks are used for waste collection [28,29]. The absence of a DSS for determining choices in actual time, IoT equipment, such as RFIDs and actuators, or the association of a single sort of sensor are among the fundamental aspects [29]. Gupta et al. recorded the collection of bins, for studying and enhancing waste collection. The article explains the design and implementation of the waste disposal system needed to demonstrate the significance and diversity of the facility's value [30]. The system assigns zones to increase the efficiency of nutrients, and reflect people's lifestyles at different times of the year. The system has a smart structure and framework for the use of data in statistical communication processes.

Anagnostopoulos et al. have proposed a system in which WSN is used to inform the driver training process. The study displays the WSN model as a technology that allows for the active implementation waste collection in towns. This system is designed to improve performance and supervise waste transportation to the site through the collection process [31].

Vitorino de Souza Melaré, et al. presented a collection-monitoring model for early detection and evaluation of waste by sensory bins. Their research described a new application using distributed sensor technology and GIS to observe and track MSW. They also presented an energy use model for improving solid waste collection that can be used in big cities [32]. It provides three models for the optimization of dynamic scheduling routing. Di Maria and Micale proposed a model for analyzing the effect of intensity of solid waste source isolation on collection costs and fuel consumption [33].

Mak et al. examined the economic performance of pneumatic and door-to-door waste collection systems in real city settings, presenting hypothetical analysis of how the pneumatic waste collection system compares with the door-to-door truck collection system. Intensive pneumatic systems and door-to-door collection have different disadvantages in urban areas. The cost of using pneumatic systems in existing residential zones is increased by urban infrastructure and buildings [34].

Adeyemo et al. offered an automated waste collection system according to a Ubiquitous Sensor Network, presenting a new model for collecting MSW in residential and business buildings using IoT technologies. The capacity sensors are the most IoT-enabled technologies, followed by RFIDs and weight sensors [35].

Agricultural food waste is generally available and inexpensive. In addition, its intake is predicted to have remarkable long-term effects on network and financial improvements, through means of reducing environmental pollution, reducing immobile lipase charges, and in the long run achieving downside potential. Expenditure on final goods is reduced in a healthy and safe manner through the process of bio catalysis. Also, recycling the waste of agro-food enterprises is one of the foundations of the sustainable financial system [36]. According to the above review, the majority of proposed models failed to consider the kind of waste and the effect on public health of different types of waste. Moreover, the authors believed that waste cannot be re-used. Although not all waste kinds can be re-used, some types of waste can be utilized to their full potential as raw material. Organic waste can be used for renewable energy systems.

Private waste or household rubbish, such as leftover foods, vegetables peels and natural products, polythene and paper, can be reused. Organic waste can be used for renewable energy systems. Furthermore, surplus peels and vegetables can be utilized as fertilizers, whilst polythene can be sold to major purchasers in advertisements. This situation is only possible if we take responsibility for separating our waste. Separation at home is also simple for housekeepers and laborers. Employees who handle waste work in severe and exhausting conditions to physically segregate the waste, which may result in health issues. Thus, the waste must be isolated at the source.

Waste types can be specified based on their source. For instance, organic waste can be located in markets, restaurants, houses, agricultural areas, etc., whist solid waste can be located in construction places [5]. Moreover, smart algorithms for routing and gathering are not used in the transportation of waste [37,38].

Smart cities are densely inhabited and urbanized, so waste is difficult to collect using standard trucks, especially during peak hours. However, the type of waste determines the size of the trucks. Thus, small trucks will reduce traffic and make it easier to move around the city.

4. Materials and Methods

This research proposes the construction of a waste management system integrated with four main factors as follows: Education: Educated Community; Community: Public Participation; Government: Law and Policy; and Appropriate Technology.

The proposed integrated system includes waste generation to resolve and treat numerous waste issues by identifying organic waste resources. The waste collection uses IoT technology by providing smart bins that are utilized to enhance waste collection and supply information for statistical analysis. Waste collection smart trucks are utilized to enhance the transportation of collected waste. Waste processing and waste administration centers are used for data analysis. The final waste disposal stage is decision-making. Figure 5 shows the integrated approach for organic waste management.

4.1. The Architecture of the Waste Management System

The architecture of the waste management system is shown in Figure 6, which includes waste resource building, a waste management center (MC) for handling diverse waste issues, smart bins with IoT technology to enhance waste collection and provide information for collection decision-making, and waste collection trucks.

4.1.1. Waste Generation

Waste source locations, such as homes, shops, restaurants and supermarkets, have unique IDs and priority averages, depending on the situation of the waste and the significance of the site, such as hospitals and schools. Priority is based on different factors, including place category (medical center, school, accommodation, or market), type of waste (e.g., mixed food, vegetables, meat, and medication) and the level of danger of the waste type. Organic waste resources are categorized as follows:

- **Residential areas:** Blocks, compounds and hostels;
- **Commercial establishments:** Hotels, supermarkets and restaurants;
- **Medical organizations:** hospitals and medical centers;
- **Educational buildings:** Schools and universities;

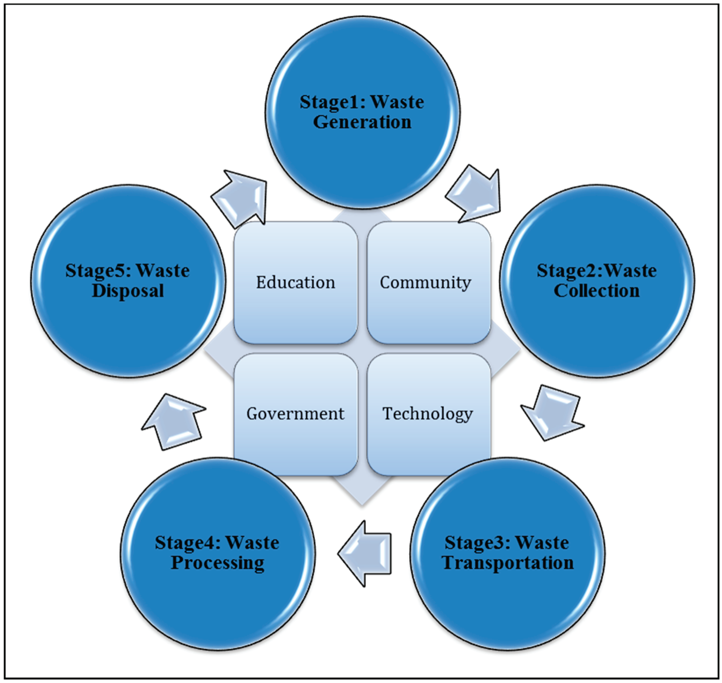

Figure 5. Integrated approach for organic waste management.

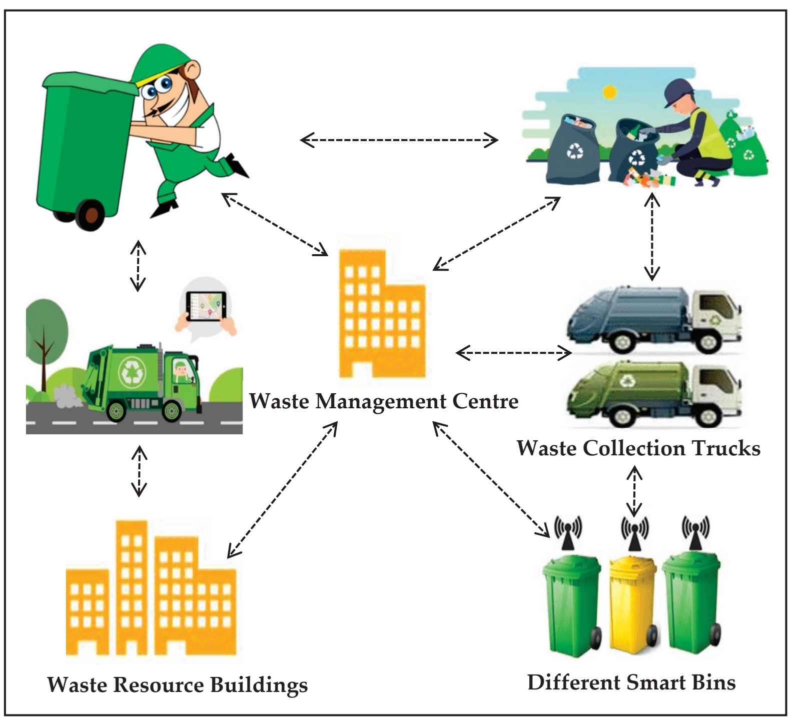

Figure 6. Waste management system architecture.

As shown previously in Figure 4, households in KSA produce more waste food compared with food services and retail than in other countries, indicating that we should pay more attention to the household and educate residents about the importance of waste management systems.

4.1.2. Waste Collection

At this stage, smart bins send the information about the waste to the waste MC via the cloud system by using GSM or GPRS according to the area infrastructure.

The bin will call the waste MC to send a truck to collect the waste only if the bin attains its threshold weight, or if the bin is full. The bin is considered full when its level exceeds or is equal to 90%.

The system dispatches the information from the bin to the waste collection transport. The system then supplies a weighted priority in status, which overrides the threshold value. Subsequently, the system locates the most suitable truck with an optimal route to gather the waste by utilizing a smart routing algorithm. Figure 7 presents the intelligent bin handling information according to the following equations:

$$\text{If } R_{fs} \leq R_{fs}\ max \rightarrow \text{then send the information to perform an action; else, read the residual free space}$$

or

$$\text{if } V_{ip} \leq V_{ip}\ max \rightarrow \text{then send the information to perform an action; else, read weight;}$$

where R_{fs} is the residual free space, $R_{fs}\ max$ is the threshold residual free space, V_{ip} is the weight measure, and $V_{ip}\ max$ is the threshold importance priority value.

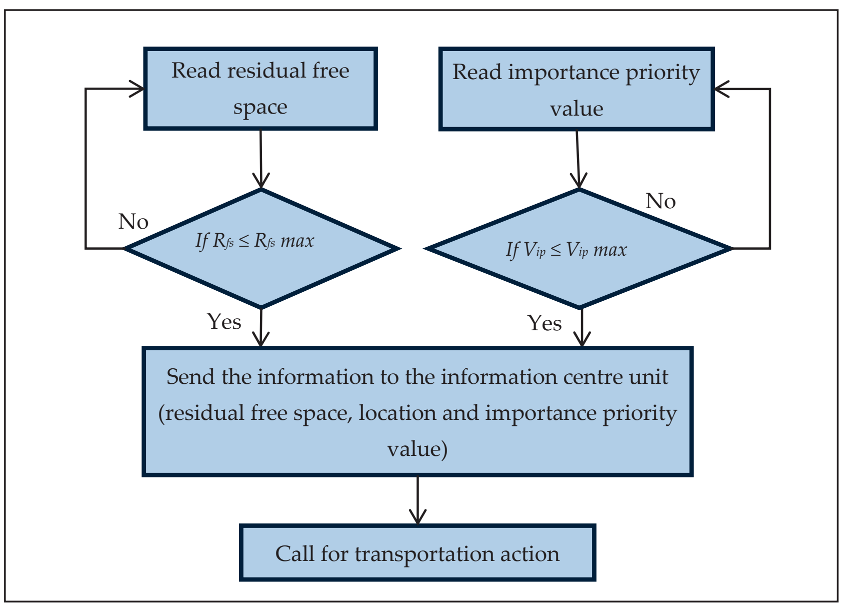

Figure 7. Intelligent bin handling information.

4.1.3. Waste Transportation

This work proposes a transport algorithm as part of an integrated approach for organic waste management. Collecting waste utilizing normal trucks through peak hours is difficult during peak hours because smart cities are densely inhabited and urbanized. The volume of collection trucks is determined based on the type of waste. Small trucks are proposed for waste collection because they can help in minimizing traffic and can more simply move around an urban area. Trucks are utilized to collect wastes from their source and transport them to a disposal area where they can be used for renewable energy systems, to a recycling center, or to a landfill site. Every truck is linked to a GPS/GPRS. This technique suggests various truck sizes depending on the zone and expected waste-producing volume. Thus, the location of the truck and bins are determined.

The transportation system proposes an efficient algorithm for collecting organic waste from the specific destination bins. In the same time, it will collect other bins with a status close to full. Figure 8 presents the transportation system process as follows:

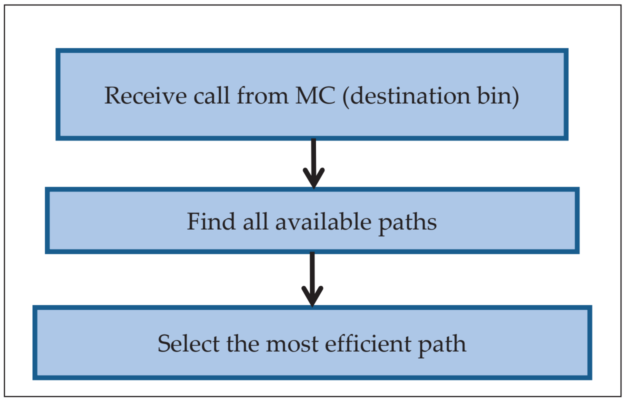

Figure 8. Process of the transportation system.

The destination bin ID and location are received from the waste MC. The system calculates all the available paths from the truck origin location to the destination bin location by using a genetic algorithm (GA) based on the transportation network and bin distributions. Then, the efficient path is selected according to the full status for each bin amongst every available path. The collection decision-making for each bin is calculated by the MC according to the available information received from the bins.

A proposed transport algorithm for collecting full waste bins is based on the residual bin space for waste as the first constraint parameter, and the consuming time of collecting waste for the same waste bin as the second constraint parameter.

The transportation network map information is formulated as follows:

Rout (edge) $e(u, v)$: $u \in V$, $v \in V$, and all link $e(u, v) \in E$.

The constraints parameters are as follows:

Residual free space (bin_id) = R_{fs}(bin_id) < R_{fs} *max*: R_{fs} *max* is the maximum residual free space in the bin that is considered to be ready to collect.

Importance priority value (bin_id) = V_{ip}(bin_id) < V_{ip} *max*: V_{ip} *max* is the maximum importance priority. Low value is important to clean the bin.

The route from the truck position (S) to the target bin (T) is defined as a sequence of other bins that are considered ready to collect.

R_{st} (S,T) = bin_1, bin_2, bin_3, . . . , bin_*t*, when all bins are on the same route.

RR_{fs} (S,T) is the route residual free space for all bins from the truck position to the target bin.

RV_{ip} (S,T) is the route importance priority value for all bins from the truck position to the target bin.

$$Rfs(R(vs, vt)) = \sum_{\mathrm{i=s}}^{\mathrm{i=t}} Rfs(\mathrm{bin\_i}) : \ \mathrm{bin\_i} \in R_{st} \text{ and } 1 \ \leq \ \mathrm{i} \ < \ \mathrm{n} \tag{1}$$

The cost for each path is computed as follows:

$$RVip(R(vs, vt)) = \sum_{\mathrm{i=s}}^{\mathrm{i=t}} Vip(\mathrm{bin\_i}) : \ \mathrm{bin\_i} \in R_{st} \text{ and } 1 \leq \mathrm{i} < \mathrm{n} \tag{2}$$

On the basis of Equations (1) and (2), we calculate the fitness function as follows:

$$F(R) = Max(RVip(R(vs, vt)),\ Rfs(R(vs, vt))) \tag{3}$$

The waste MC provides this information based on data received from smart bins around the city. The proposed algorithm in this experiment responds to the call from the specific target bin that needs a waste collection truck. The algorithm considers all the bins that have less residual free space on the way to the target bin, by using GA. According to the available information on the road map, the sequence procedural steps of the GA are as follows:

Step1—The population is randomly assigned to one of the available transportation paths, based on the bin's residual statuses. Each path has information on how to deal with the case.

Step2—Assessments: The available transportation paths in a population are assessed by utilising the fitness function to locate the most efficient route that includes most full waste bins needed to collect.

Step3—Selection: Individuals are chosen based on the classified fitness value.

Step4—GA process: The route is converted to enhance the solution.

Step5—The process is terminated if the transportation path includes all the bins that are ready to collect on the way to the target bin.

Step6—The population is changed: After route alteration, the worst route is avoided and changed with a new route.

Steps 2, 3, 4, 5, and 6 are iterated until termination.

In the experimental study, the area size was assumed to be 1000 m^2, and the smart bins were randomly distributed. Each bin had a location, status (full/not-full/can collect) and the expected time it takes to collect the waste from this bin. The experimental evaluation is presented in the experimental results section.

4.1.4. Waste Processing

The waste management station sends commands to the smart trucks according to truck location and the information available from the smart bins. Figure 9 presents the proceedings of calling trucks for waste gathering.

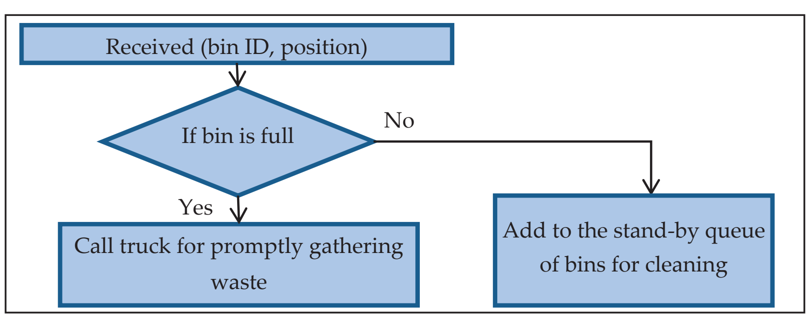

Figure 9. Proceedings for the decision-making process.

The database of smart bins is hosted on a cloud computing infrastructure to supply high data availability. The composite equipment in the bins allows real-time data collection. The waste management station analyses the assembled data from the IoT equipment and provides helpful information for decision-making inside the intelligent waste management system.

4.1.5. Waste Disposal

Waste disposal differs from natural methods because the organic waste is a source of renewable energy.

The proposed architecture of the waste management system is integrated with four factors: education, community, government and technology.

4.2. Education

Consciousness-raising and information distribution are offered to enhance recycling presentation, and are crucial for recycling platform success [39,40]. The researchers conducted seminars and brainstorming meetings for the sessions to provide information on waste administration platforms, such as the advantages of waste sorting, sorting procedures and how to gather the sorted waste, especially for separated organic waste. The meetings also concentrated on the issues and hurdles, giving advice on waste sorting to optimize its benefits.

It is necessary to pay more attention to operating educational campaigns to notify the public about the quantity of wasted food in the nation in household, food services and retail contexts. These campaigns should inform the public about the choices available to them to participate in improving the situation (e.g., how to obtain domestic food donation NGOs, how to avoid excess food offering and how to minimize wasted food at home). Moreover, these campaigns should provide solutions to guarantee that food waste goals and planning are incorporated into outlines of responsibility, and should state methods of food waste conversion. An educated community is more aware. Institutions should focus on enhancing the effectiveness of the food management system, in which private sector involvement should be incorporated when possible. Therefore, the suitable institutions must be organized by firstly determining the functions of each organization inside the system.

4.3. Community

The committee must conduct studies to measure people's willingness to help in reducing wasted food and choose regions with the least attention or compliance. Gathering a sympathetic audience to the cause to encourage good behavior is also necessary. Furthermore, popular knowledge campaigns and supporting government activities must be launched to raise awareness about the extent of the problem of wasted and lost food, and to authorize and guide urbanized society to take the required actions. Moreover, the community should identify charities that are working in areas of wasted and lost food and consider whether they can be provided with public and private funding to expand their actions.

4.4. Government: Law and Policy

Each nation should have an incorporated sustainable organic waste administration, that involves aspects such as cleaning, maintaining public health standards, conserving environmental conditions and sustainable financing. A legal structure in line with the domestic plan must also be established. Legislation is commonly formulated only as a manner of attributing liability. The legal structure should guarantee that the goals determined in the strategic documents are achieved in specific time frames. The structure must also make easier the design and implementation of the method; for example, the simplification of the idiom 'solid waste' should not be used to define responsibilities.

In addition, the framework should also supply information that can be helpful in addressing technical problems related to the selection of some waste administration systems. The legal structure must involve provisions that permit efficient application of the regulations.

Policy estimation includes the production of qualitative and quantitative evaluations of formal policy costs, through strategies to review the consequences of implementation and determine whether to update or discontinue them [41,42].

The latest insurance valuation literature, coupled with software programs from exceptional insurance valuation models, suggests real international interest in recognizing the practical outcomes and societal impact of waste control policies in anomalous countries [42]. Moreover, partnerships with major food service corporations or restaurants should be considered to develop innovative initiatives that go beyond simple acquiescence with the purpose. It should be determined whether the body responsible for insurance is the local authority, business, faculty, or nearby city and residents. In addition, it should decide whether the scope covers the environmental, financial, or social sectors. Also, it needs to determine whether the guarantee consists of policies for family waste types, recycling activities, transportation, waste reduction, infrastructure construction, waste types, use of beneficial waste, remedial standards, remedial methods, decomposition standards, etc., or pioneering standards. Moreover, methods in which households can be encouraged to recycle their wasted food must also be considered, and surveys must be conducted of behavior in nations where governments supply free bins for waste gathering.

4.5. Appropriate Technology

Variable objects, cloud services, applications and databases have been able to connect with the current system of other IoT devices, due to the growing interest in IoT. The IoT will result in a large number of new interfaces between new and existing systems, to provide solutions. The resulting information network will reduce costs and hazards, and improve business operations.

IoT architecture has been proven to reduce operational costs of waste collection and to allow automation and the simplification of waste identification to enable recycling and waste treatment. Figure 10 shows an example of small devices/gadgets with a web-based system that allows the integration of the IoT as a new generation technology.

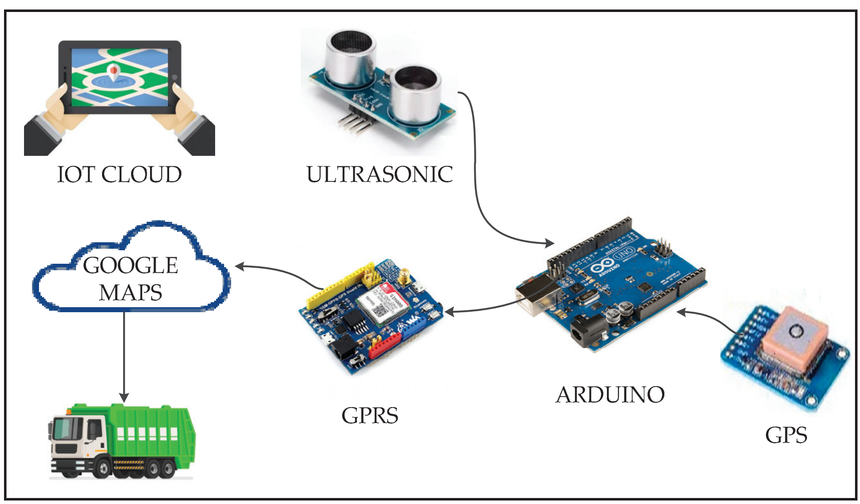

Figure 10. Integrated technology devices/applications.

5. Experimental Results

These experiments were conducted for evaluating the proposed transportation algorithm. The experiment was performed using C++ by creating a random transportation map with a specified number of smart bins and relevant information, including bin status. The status values were randomly assigned for every smart bin, to maintain conformance. The most efficient routes for different transportation road maps were chosen on the basis of the GA. Different routes were evaluated to find the most efficient route from the truck source station to the selected smart bins, which are the smart bins that most urgently need to be cleaned. In this work, the evaluation experiments were executed for one collect truck station with id: 0 and all smart bins on the map as destinations. This experiment was performed with two constraints: R_{fs} (residual free space) and V_{ip} (importance priority value). In this simulation, R_{fs} was fixed as the maximum (50%), and V_{ip} was fixed as the maximum (50).

Priority was given based on the waste source locations, such as homes, hospitals, retail, restaurants, and supermarkets, in addition to the danger of the waste and the significance of the site. Table 1 shows the available routes to selected smart bin nodes, where the residual free space for each route varies.

Table 1. Experiment scenarios.

Call from Smart Bin ID	List of Smart Bins in the Route	Residual Free Space %	Importance Priority
11	0 15 11	2	12
	0 31 11	2	33
	0 23 11	11	20
	0 26 11	18	4
	0 27 11	28	16
	0 21 47 22 11	29	16
	0 36 40 11	29	30
	0 6 10 11	30	33
	0 27 16 11	31	21
	0 23 38 18 16 26 11	49	32
37	0 15 37	11	20
	0 14 37	16	26
	0 23 37	22	25
	0 45 37	23	24
	0 19 37	23	25
	0 36 9 37	29	22
	0 35 37	31	21
	0 38 45 37	35	33
	0 48 34 3 37	44	42
41	0 15 41	1	13
	0 31 11 41	13	39
	0 14 41	17	10
	0 27 41	26	11
	0 6 24 41	28	48
	0 26 11 41	29	10
	0 11 41	30	18
	0 26 5 41	30	28
	0 6 41	33	17
	0 15 36 48 41	35	37
	0 32 14 41	38	21

Path Selection with Priority

In this experiment, organic waste that was collected along a predetermined route was avoided. A predetermined route leads to unnecessary costs and a waste of equipment. Full containers are often collected first. The priority of the waste type is the constraint that reduces leakage of waste containers into the street or in large quantities. This spilled waste can lead to increased cleaning costs, health risks, and resident complaints.

Figures 11–13 present the calculated constraints for all routes to the smart bins with 11, 37 and 41, respectively, among the 50 smart bins randomly distributed in this experiment.

We can see different available routes to each destination smart bin. The residual free space is the main factor when selecting an efficient route. The most efficient route is determined based on the minimum free space in addition to the importance priority value.

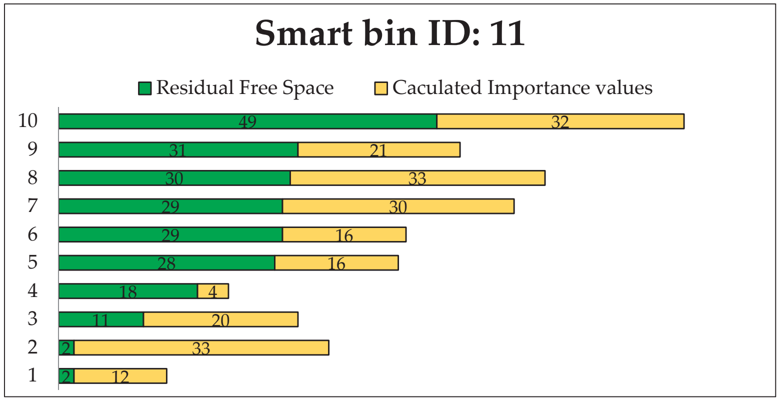

Figure 11. Evaluation routes to smart bin id: 11.

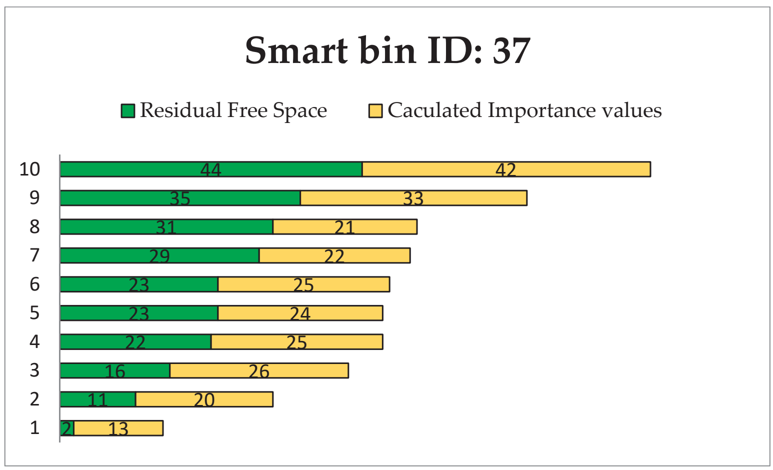

Figure 12. Evaluation routes to smart bin id: 37.

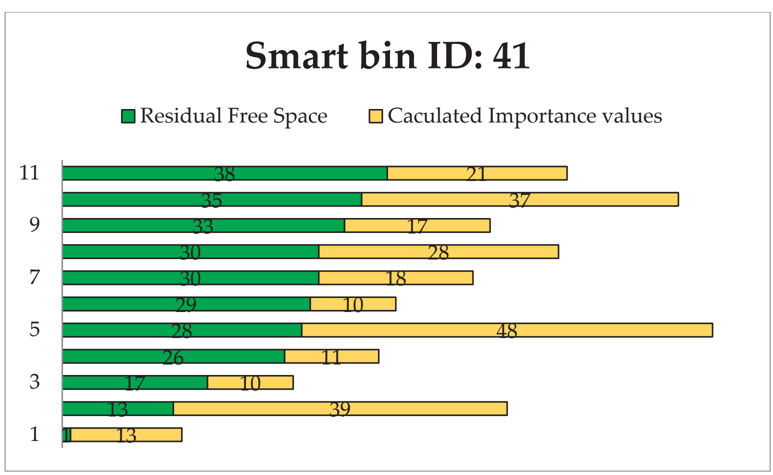

Figure 13. Evaluation routes to smart bin id: 41.

Table 2 shows the result of the simulation of finding an efficient route from the truck station to other selected smart bins with equal priority of residual free space and importance for cleaning the bins, randomly distributed on the transportation map.

Table 2. Efficient route selected.

Smart Bin Target	List of Smart Bins in the Selected Route (R_{fs} Priority)	List of Smart Bins in the Selected Route (Equal Priority)
11	0 15 11	0 15 11
37	0 15 37	0 14 37
41	0 15 41	0 15 41

Figures 14–16 show the minimum and maximum cumulative residual free space R_{fs}, and importance priority values *IPv* for each route directed to the urgent smart bins that send a call to clean the bin. The selected values for R_{fs} and *IPv* are the efficient values.

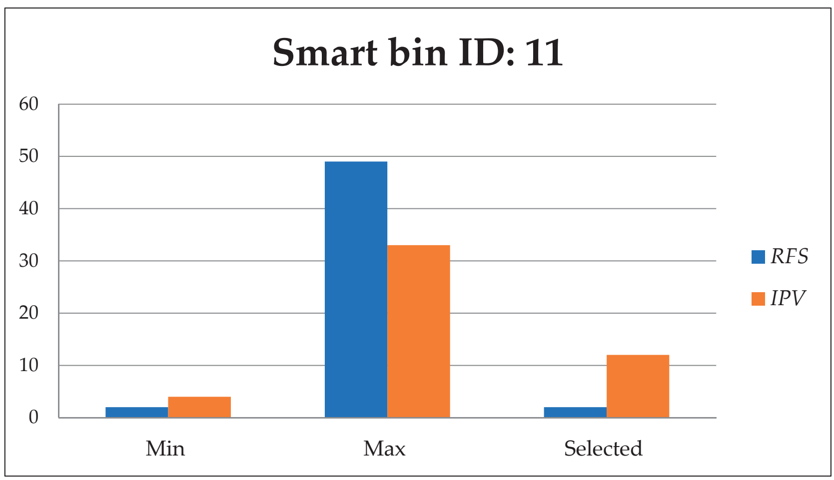

Figure 14. Residual free space R_{fs}, and importance priority value *IPv* to smart bin id: 11.

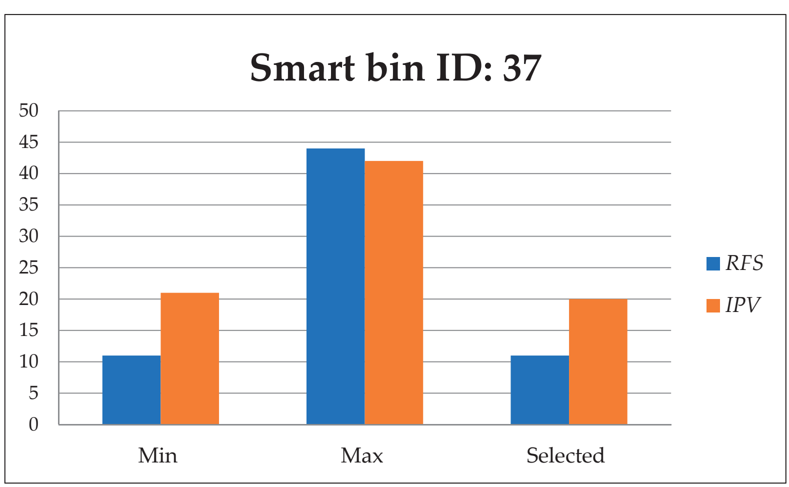

Figure 15. Residual free space R_{fs}, and importance priority value *IPv* to smart bin id: 37.

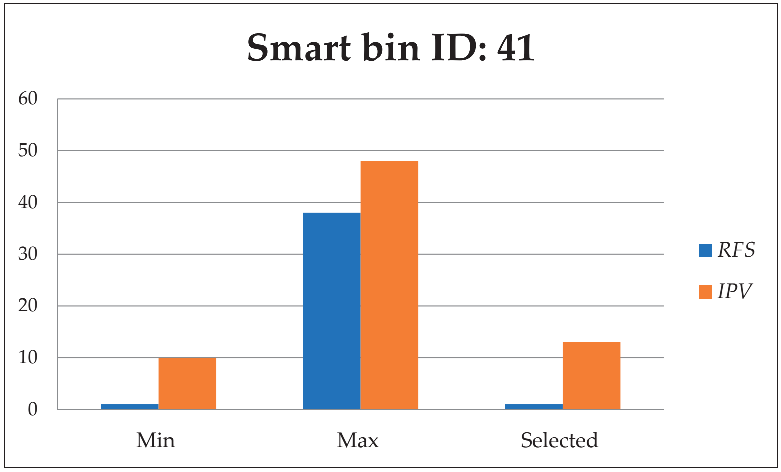

Figure 16. Residual free space R_{fs}, and importance priority value IPv to smart bin id: 41.

Figure 14 presents the minimum and maximum values of residual free space R_{fs}, and importance priority value IPv among 10 available routes including the selected route to smart bin 11.

In Figure 15, the minimum and maximum values of residual free space R_{fs}, and importance priority value IPv are presented over 9 available routes including the selected route to smart bin 37.

Figure 16 presents the minimum and maximum values of residual free space R_{fs}, and importance priority value IPv among 11 available routes including the selected route to smart bin 41.

The most efficient route was selected based on the R_{fs} and IPv to find the most efficient path to reach the target smart bin. Based on the same priority, Table 3 presents the efficient of the selected R_{fs} and IPv values. The selected route to the target smart bin that sends a clean bin request includes each individual smart bin that needs to be cleaned. It is clear that the selected route includes the smart bins that most urgently need to be cleaned on the way to the target smart bin. Thus, the advantage of using the same priority for R_{fs} and IPv is shown in the selected route that has efficient values compared to the other available routes.

Table 3. Residual free space R_{fs}, and importance priority value IPv.

Call from Smart Bin ID	Residual Free Space %			Importance Priority		
	Min	Max	Selected	Min	Max	Selected
11	2	49	2	4	33	12
37	11	44	11	21	42	20
41	1	38	1	10	48	13

In all three selected smart bins, when a call for waste truck collection is considered, the proposed algorithm assumes that all constraints have the same priority in the absence of a priority case. Thus, the experiment demonstrates that the proposed algorithm is sufficient to find the most efficient route and collect the most urgent smart bins required for waste collection, by using GA based on the residual free space and importance priority.

6. Conclusions

'Sustainability' is a buzzword these days. This word is used in many contexts by everyone from goods manufacturers and service providers to international politicians. However, it remains unclear whether all these stakeholders understand the term 'sustainable development' in the same sense. The current rate of resource extraction is predicted to be 10,000 times higher than the rate of natural resource production. This ratio may significantly change in the near future. Moreover, it is not clear whether the WMS system can make a meaningful contribution. Accordingly, a more sustainable OWM than a WMS must be developed for a sustainable society. Organic waste accounts for more than 50% of global MSW. The EAP region produces the most organic waste, accounting for approximately 62%, followed by the Middle East and North Africa (61%). Global waste reduction is a main goal of scientists through various research methods. Several recommendations have been made to control organic waste, including composting and making biochar and bioenergy for cosmetic, pharmaceutical, and food supplements. The proposed integrated system is compatible with government, public organizations, and the environment. The country of Saudi Arabia is a complex cultural mix, a combination that is truly reflected in the OWM system. Countries like Japan demonstrate a sustainable approach to MSW management. Meanwhile, countries like China are struggling to meet new needs due to aggressive development. In every country, organic waste management is an important, ongoing, and meaningful public service system that must be effectively provided to the community to maintain aesthetic and public health standards. Municipal agencies need to plan and manage these systems during increasing urbanization and population growth.

Today, KSA can demonstrate a sustainable OWM system through the proposed integrated approach. Systematic efforts are needed to improve various factors, including governance by using law and policy, education by institutional arrangements, appropriate technologies, and public community participation in system proposals. Various waste control models have been produced for the use of particular IoT devices. Various models use IoT devices, which include capacity, weight, temperature, cup cheer, and chemical sensors, relying on the popularity of those devices. A genetic-based waste collection transportation algorithm is proposed, using IoT technology and a computational algorithm to speed up waste collection and select the most efficient transportation path that improves the efficiency of waste collection truck management. The paths selected based on the residual free space R_{fs}, and importance priority value *IPv* were the most efficient routes among those available to each selected smart bin destination. The R_{fs} of selected routes were less than the maximum R_{fs} of available routes by 4.08%, 25%, and 2.63% for smart bins 11, 37, and 41 respectively. The *IPv* of selected routes was less than the maximum *IPv* of available routes by 36.36%, 47.61%, and 27.08% for smart bins 11, 37, and 41 respectively. However, the proposed integrated approach, including the waste collection transportation algorithm, would be helpful over a variety of country-specific layouts. In future work, smart containers will be implemented and integrated with the proposed garbage transport algorithm. It should consider more criteria for path selection, such as distance, safety, accident-free status, and any other useful criteria.

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Assessing Future Climate Change Impacts on Potato Yields — A Case Study for Prince Edward Island, Canada

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Abstract: Crop yields are adversely affected by climate change; therefore, it is crucial to develop climate adaptation strategies to mitigate the impacts of increasing climate variability on the agriculture system to ensure food security. As one of the largest potato-producing provinces in Canada, Prince Edward Island (PEI) has recently experienced significant instability in potato production. PEI's local farmers and stakeholders are extremely concerned about the prospects for the future of potato farming industries in the context of climate change. This study aims to use the Decision Support System for Agrotechnology Transfer (DSSAT) potato model to simulate future potato yields under the Coupled Model Intercomparison Project Phase 6 (CMIP6) climate scenarios (including SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5). The study evaluates the combined effects of changing climatic conditions at local scales (i.e., warming temperature and changing precipitation patterns) and increasing carbon dioxide (CO_2) concentration in the atmosphere. The results indicate future significant declines in potato yield in PEI under the current farming practices. In particular, under the high-emission scenarios (e.g., SSP3–7.0 and SSP5–8.5), the potato yield in PEI would decline by 48% and 60% in the 2070s and by 63% and 80% by 2090s; even under the low-emission scenarios (i.e., SSP1–1.9 and SSP1–2.6), the potato yield in PEI would still decline by 6–10%. This implies that it is important to develop effective climate adaptation measures (e.g., adjusting farming practices and introducing supplemental irrigation plans) to ensure the long-term sustainability of potato production in PEI.

Keywords: potato (*Solanum tuberusom*); climate change; drought; food security; heat; phenology; tuber

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1. Introduction

Potato is the most common non-grain crop, belonging to the family *Solanaceae* [1,2]. Globally, potato is the fourth most recognized tuber food crop consumed, after maize, rice, and wheat, and is vital for food security because of its excellent potential for high yields and nutritional value [2,3]. Globally, potato is produced in over 155 countries, contributing nutritional value for more than a billion people [4,5]. Even though the global production is one-half that of wheat, rice, and maize, its production has increased by one-fifth since 1990, while its consumption has increased by more than double in developing countries [5,6]. In 2021, the Food and Agriculture Organization (FAO) estimated global potato yield to be 20.7 tonnes/hectare (t/ha), cultivated on about 18.2 million hectares (Mha) of land. The increase in potato production has significantly overtaken many other crops accounting for more than 50% of potato production globally [7]. Specifically, in 2021, Canada was ranked as one of the top twelve countries producing the highest potato yields of about 41.3 t/ha harvested from over 150,000 ha of land [8–11] and was ranked as the fifth and sixth largest exporter of fresh and seed potatoes, respectively, with 25% of the yields from Prince Edward Island (PEI) [9,12,13]. Potato is a major agricultural crop after canola, corn, wheat, and soybean, and a high-producing vegetable crop cultivated in Canada. In PEI, potato contributes majorly to the economy. It is cultivated on an average land size of 35,378 hectares (ha), producing about 36.8 t/ha yields annually [9]. Potato grows well in PEI because of its particular soil characteristics, i.e., red and rich in iron, and retains the required water during growth and development. Potato is grown during spring–summer (May to October) under rainfed conditions. Adequate rainfall with cold winters and warm summers with proper light, heat, and water balance contribute to the optimal quality potato yields in PEI. PEI is a major producer of potatoes exported from Canada [14].

Potato is a staple food consumed daily around the world and is categorized as a dietary vegetable containing many minerals and vitamins [15–17]. Potato contributes to the four pillars of food security, "access, availability, stability, and utilization," for Sustainable Developmental Goal 2 (SDG 2-Zero Hunger). Approximately three-quarters of their total dry weight is in the form of starch, with amounts that depend on the variety [16]. Potatoes have a small protein content, but essential amino acids such as lysine and metabolites increase their biological value and utilization [16]. They are good sources of vitamins such as B6 and C and trace amounts of folate, thiamin, niacin, and riboflavin; 0.5–2% of dietary fiber is contained in potatoes with other minerals, such as magnesium, iron, potassium, and phosphorus [15,16]. Potatoes ensure food security and provide income and employment [18]. Potatoes from Canada, especially from PEI, are globally recognized and exported because of their safety and quality [19]. Assessing the impact of climate change (SDG 13-Climate Action) on potato yields is crucial to enhancing food security.

Potato is one of the most vulnerable crops in changing climates, with events such as long-lasting droughts, extreme heat, and unanticipated frosts [5,20]. The temperature is expected to increase as the climate changes, with inconsistent precipitation patterns. Climate change is impacting the frequency and intensity of extreme climate events, and SDG 2 (Zero Hunger) can be achieved by addressing SDG 13 (Climate Action) [13,21,22]. Although crop management practices cause about 67% of the variations in potato yields, climate change is a significant challenge faced by the agricultural sector [13]. Potato yields likewise depend on factors such as water and soil management practices, seed quality, chemical and bio-fertilization, soil moisture contents, elevation, slope, and supplement irrigation [13]. Potato development stages, such as sprouting, emergence, and leaf area development, are temperature sensitive. Temperature thresholds and photoperiod sensitivity are vital in determining the development of potatoes and initiating potato tuber induction vary with potato varieties [23]. Potato is a temperate crop that thrives between 16 °C and 19 °C if 20 to 24 inches of water requirement are fulfilled; however, when the temperature exceeds 30 °C, it can cause slow tuber initiation and development and physical damage to the tubers [24–28]. Surface temperatures below 0 °C during potato development causes frost, which burns stems, leaves, and potato cell organelles to form soft and blackened parts [29,30]. Considering the potato phenology, climate change can cause an advancement or delays in the emergence, tuber initiation, bulking, and maturity of potatoes, determined by regional location. Likewise, the emergence and drops of leaves could be early or delayed [31,32]. Potato requires 400 to 800 mm of rain/water, which invariably depends on meteorological variables and other factors [26,33]. Water shortage beyond 60% to 65% causes drought that reduces the growth rate, while excessive water causes leaching and tissue decay inside potato tuber called blackheart [26,34]. Considering previous literature, carbon dioxide (CO_2) is reported to be beneficial to potatoes, causing increased photosynthesis rates that make potatoes bulk faster [35–37].

Meanwhile, the elevation of CO_2 increases the rate of potato susceptibility to pests and diseases and yields phenology, causing interferences between implemented and natural biological processes [20,38]. In addition to abiotic factors, biotic factors such as pests, nematodes, and pathogens can affect potato yields [26,39]. Water stress conditions can likewise affect optimal potato yields [26,38,40]. Due to the effect of the changing climate conditions on crops in PEI, there is a dire need to assess the impacts of climate variables, such as temperature, precipitation, and CO_2, on potato yields [41–43]. The development of adaptation strategies relies on understanding the effect of farming practices, genetics, and thermal trends on potato cultivation [5,20,44,45]. Hence, the need to assess the climate change impacts to strategize a coping mechanism for the cultivation of potatoes in PEI.

Recently, there has been high interest in using various crop–weather models to estimate the impacts of climatic changes on potatoes. Crop simulation models (CSMs) are an essential tool that uses input datasets with future emission scenarios to evaluate the potential effects of climate change on crops, e.g., the Decision Support System for Agrotechnology Transfer (DSSAT) model. Many studies use the DSSAT model to assess the effects of climate change on potatoes [31,44,46]. Only a few studies use the model to assess variations in the Canadian province's potato yields [47]. In addition, Coupled Model Intercomparison Project Phase 6 (CMIP6) data have been used to assess the impacts of climate change on crops [48,49]. Many other studies use different methods and tools to assess potato yield response to climatic variables; for instance, Maqsood et al. (2020) [13] used ClimPACT2, and Jiang et al. 2021 [50] used analysis of variance (ANOVA) and second-order polynomial regressions to assess potato yield response to climate change and water. Overall, a study has yet to be conducted in PEI to assess climate change impacts on potato yields using physically based crop models such as the DSSAT model. In addition, the climate change scenarios used in previous studies are from the CMIP3 or CMIP5 datasets rather than the latest CMIP6 dataset [51,52]. CMIP6 is the latest scenario, published in the AR6 of the IPCC in 2021. The pattern of evolution and characteristics adaptation of the previous CMIP, such as CMIP5, continues in CMIP6; nevertheless, CMIP6 evolves from centralized activity to a federated activity with many individual Model Intercomparison Projects (MIPs). CMIP6 has more components and higher spatial resolution [53]. Previous studies using the DSSAT model have yet to investigate the combined effects of multiple climate variables, such as temperature, CO_2, and precipitation, on potato yields.

Therefore, the objectives of this research are:

- To collect potato management, soil, weather, and future climate scenario data;
- To calibrate and validate the DSSAT model for a better performance;
- To assess the impacts of climate change on potato yields in PEI.

Specifically, we will collect the required data to set up the DSSAT model, calibrate, and validate the model. Further, we will use the CMIP6 data from seven global climate models (GCMs), including CanESM5, FGOAL-G3, GFDL-ESM4, MIROC6, MRI-ESM2, IPSL-CM6A-LR, and EC-Earth3-Veg, under five shared socioeconomic pathways (SSPs), including SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5. We will use the CMIP6 data to drive the DSSAT model to evaluate the combined effects of changing climatic conditions, including maximum temperature (T_{max}), minimum temperature (T_{min}), precipitation, and CO_2 concentration in the atmosphere on potato yields in PEI. The results from this research can help potato farmers and stakeholders in PEI understand the ongoing and future challenges that the changing climate will bring to the local potato industries. Furthermore, this study can provide a scientific base for policymakers to develop climate change mitigation and adaptation measures to support sustainable production in the PEI potato sector.

2. Data and Methods

This study uses methods and procedures according to DSSAT (2022) [54–58]. Specifically, we first collect the required input data, referred to as minimum dataset (MDS), for model calibration and validation. The calibration and validation process follow subsequent stages as data collection (observation or measurement) of the experimental data (planting, maturity dates, and tuber yields), calibration of the model using experimental data; sensitivity analysis; validation of the model; assessment of the possibilities and limitations (simulation of potential yields); and the climate change impacts on the yields.

2.1. Study Area

This study focuses on the smallest province in Canada, PEI (Figure 1), popularly called the Island, located off the eastern coast of Canada. PEI is less populated and considered part of Atlantic Canada [10,59].

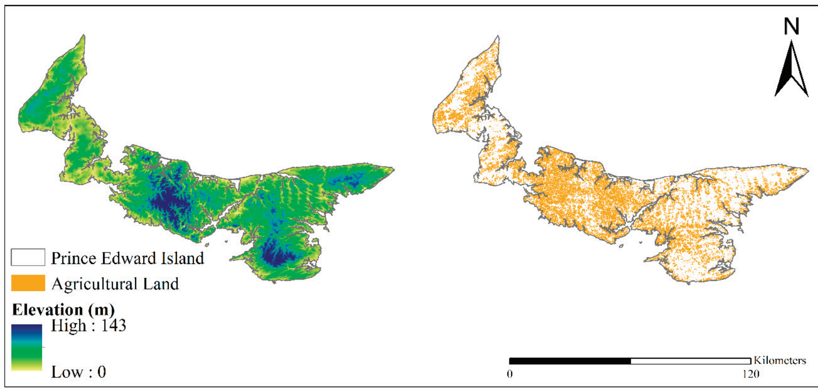

Figure 1. Elevation and agricultural lands in PEI.

PEI is a province that produces and exports a significant quantity of potatoes among other Canadian provinces. As of 1 October 2022, the population of PEI was estimated to be 172,707. The province lies between 46 °N to 47 °N latitude and 62 °W to 64 °W longitude with a total land area of 566,560 ha. Farming occurs on about 42.5% of the total land area (240,514 ha) and ultimately supports the Island's economy, with about 35,378 ha used to cultivate potatoes. The Island produces one-fourth of the potatoes produced in Canada [9,13,60,61]. PEI potatoes are dominant in Canada and contribute significantly to the agricultural economy of PEI. Although potatoes cultivated in PEI have a high nutritional value and quality, according to FAO comparison of potato production, there has been a decline in Canadian potato production since 2017 [8]; specifically, the annual potato yields in PEI [9,62] have fluctuated over the years (Figure 2). Climate change is suggested to be responsible for the instability of PEI potato yields; in essence, there is a need to study the impacts of climate change on potato yields scientifically [13,42,50,63].

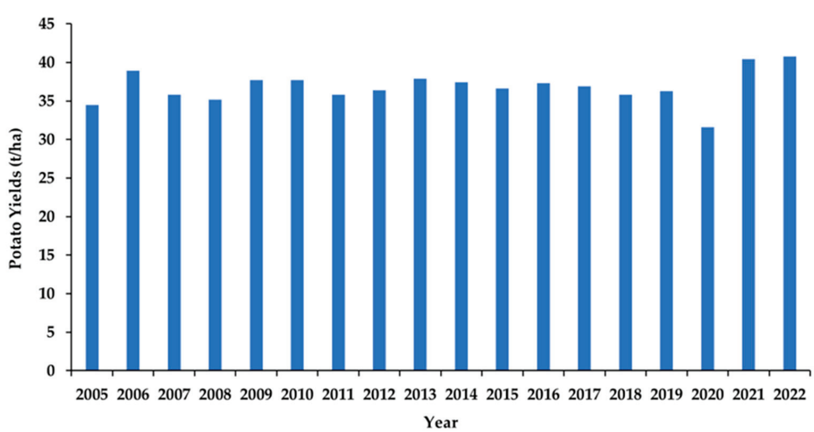

Figure 2. Annual average potato yields in PEI from 2005 to 2022.

2.2. Data Collection

2.2.1. Weather Data

The experiment involves daily measurements of precipitation, solar radiation, T_{max}, and T_{min}. Daily weather data were downloaded from the "Environment and Climate Change Canada" website, while solar radiation is from the National Aeronautics and Space Administration's "NASA-Prediction of Worldwide Energy Resource" website [64,65]. The DSSAT Weatherman module is set up and run with the weather files.

2.2.2. Soil Data

Quantitative information on soil (Orthic Humo-Ferric Podzol class) texture and organic carbon are computed with other parameters such as the drained upper limit, saturated water content, saturated hydraulic conductivity, root growth factor, and lower limit using the Sbuild module, a soil parameter estimation tool in the DSSAT suite (Table 1), and used to set up the DSSAT soil module. Customized soil files by depth, between 10–90 cm, are from the literature of a PEI study [63].

Table 1. Soil properties for PEI.

Depth (cm)	Clay (%)	Silt (%)	Org. C. (%)	BD ($Mg \cdot m^{-3}$)	pH	DUL	SWC	SHC (cm·h)	RGF	LL
0–10	8	36	1.9	1.33	6.1	0.272	0.459	2.59	1	0.118
10–20	9	38	1.9	1.39	6.1	0.282	0.437	2.59	1	0.123
20–30	9	35	1.6	1.39	6.2	2.260	0.439	2.59	0.607	0.115
30–40	9	37	1.2	1.54	6.2	0.244	0.388	2.59	0.497	0.104
40–50	11	36	0.5	1.60	6.2	0.217	0.372	2.59	0.407	0.095
50–60	13	34	0.2	1.60	6.3	0.209	0.375	2.59	0.333	0.096
60–70	14	34	0.2	1.79	6.3	0.214	0.306	2.59	0.273	0.101
70–80	13	35	0.1	1.79	6.3	0.206	0.307	2.59	0.223	0.094
80–90	14	35	0.1	1.79	6.4	0.211	0.307	1.32	0.183	0.099

Note: Org. C—Organic Carbon, BD—Bulk Density, DUL—Drained Upper Limit, SWC—Saturated Water Content, SHC—Saturated Hydraulic Conduct, RGF—Root Growth Factor, and LL—Lower Limit.

2.2.3. Crop Management and Experimental Data

The study follows standard agronomic and management practices to set up the Xbuild and ATCreate modules. Crop management and experimental data are collected through a survey with assistance from the PEI Potato Board and local farmers (see the survey form in Supplementary Information S1). Other required crop management and experimental data are collected from the PEI Potato Board [14]. The collected data are used to simulate PEI's potato yields under rainfed conditions. The primary management practices are shown in Table 2.

2.2.4. Future Climate Scenarios

In our impacts assessment study, we use one historical period (1995 to 2014) as the baseline and three future periods, the 2050s (2045–2055), 2070s (2065–2075), 2090s (2085–2095) under five SSPs (including SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5). We use GCMs data, including CanESM5, FGOAL-G3, GFDL-ESM4, MIROC6, MRI-ESM2, IPSL-CM6A-LR, and EC-Earth3-Veg (Table 3), from CMIP6 developed by IPCC, considering the resolutions for each GCMs accordingly in the study. The data are from the World Bank Climate Knowledge portal and IPCC Our World in Data sites [51,52].

Table 2. Key information about the potato management practices in PEI.

Crop	Potato
Cultivar	Russet Burbank *
Planting month	May
Planting method	Dry Seed
Planting depth	6.5 inches
Planting distribution	Rows
Row spacing	14 inches
Fertilizer	Ammonium Nitrate
Tillage	Mouldboard Plough
Irrigation	Not Irrigated
Harvest month	October
Length of the growing season	130 days
Other practices (e.g., tillage type, depth, and date, initial condition, fertilizer depth, and application date)	Observed according to the recommended practices by the PEI potato board and farmers

* In this study, we use the potato variety Russet Burbank (RB) because it is the most common (about 90%) among the potato varieties in PEI [66]. Additionally, the survey results we received in this study are mostly about RB, and no sufficient data are collected for other varieties in PEI. Note that no supplemental irrigation plan was implemented in PEI for the study period of 1995–2014.

Table 3. List of global climate models used in this study.

Full Name of GCM	Abbreviation	Institute
The Canadian Earth System Model version 5	CanESM5	Canadian Centre for Climate Modelling and Analysis, Canada https://www.canada.ca/en/environment-climate-change/services/science-technology/centres/british-columbia.html#cccma (accessed on 12 November 2022)
Geophysical Fluid Dynamics Laboratory Earth System Model version 4	GFDL-ESM4	Geophysical Fluid Dynamics Laboratory, United States of America https://www.gfdl.noaa.gov/ (accessed on 12 November 2022)
The Meteorological Research Institute Earth System Model version 2	MRI-ESM2	The Meteorological Research Institute, Japan https://www.mri-jma.go.jp/index_en.html (accessed on 12 November 2022)
Model for Interdisciplinary Research on Climate version 6	MIROC6	Division of Climate System Research, Japan https://ccsr.aori.u-tokyo.ac.jp/index-e.html (accessed on 12 November 2022)
Flexible Global Ocean-Atmosphere-Land System Model: Grid-Point version 3	FGOAL-G3	The State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics-Institute of Atmospheric Physics, China http://english.iap.cas.cn/rh/rd/200906/t20090626_9069.html (accessed on 12 November 2022)
The Institute Pierre-Simon Laplace Climate Model	IPSL-CM6A-LR	The Institute Pierre-Simon Laplace Climate Modelling Center, France https://cmc.ipsl.fr/ (accessed on 12 November 2022)
European Community Earth 3 with interactive vegetation module at low resolution	EC-Earth3-Veg	12 European Countries https://ec-earth.org (accessed on 12 November 2022)

SSPs describe the possible range of future climates based on human development, economy, environmental action, atmospheric CO_2 concentration, and sustainability as essential features. Each scenario depicts climate information with specified conditions, and SSP5 represents the worst-case scenario. SSP1 reflects a steadily shifting world, sustainable with regular challenges to mitigation and adaptation. SSP2 is with medium challenges to mitigation and adaptation, representing the middle of the road. SSP3 has mitigation and adaptation with high challenges, leading to a rivalry condition in regions. SSP5 exhibits frequent challenges to adaptation but high challenges to mitigation in a fossil-fueled development era [67–69]. This study considered five greenhouse gas (GHG) emission scenarios, including SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 (Figure 3).

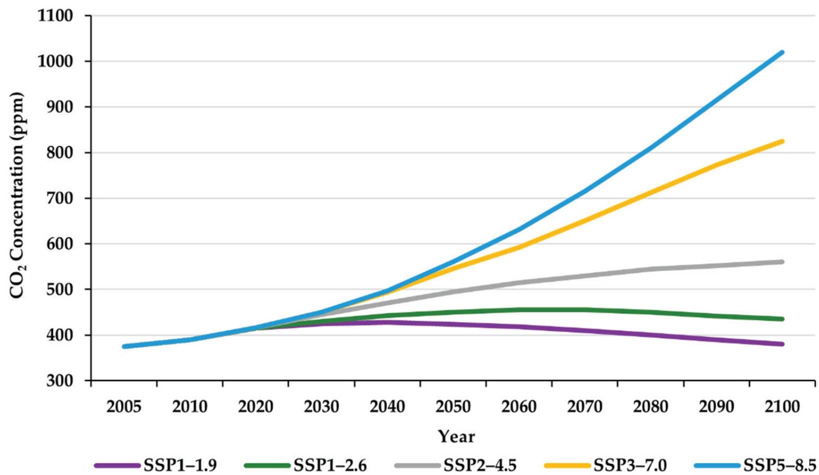

Figure 3. CO_2 concentrations under CMIP6 SSP emission scenarios.

2.3. DSSAT Potato Model

The DSSAT model is a collection of independent application programs that operate together, developed by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT). There are 42 crop modules with tools to expedite the efficient use of the model [56–58]. The tools include a program database for weather, soil, crop management, experimental data, and applications. The CSM assesses crop growth and development as a function of the soil–plant–atmosphere dynamics related to soil, weather, crop experiment, management practices, genotypes, water, and nitrogen dynamics in the databases [58,70,71]. The DSSAT model comprises modules, databases, and applications controlled by software to aid in selecting and comparing alternatives to predict results [71]. It archives and supplies the data to the models for simulating the various kinds of experimental situations and assessing the risks or simulating yields on a long-term basis [58,72]. Simulation of Underground Bulking Storage Organ component (SUBSTOR) is a member of the sixteen computer software application programs that use Formula Translation (FORTRAN) language embedded within the DSSAT model. It assesses the potato's phenological effect, yield accumulation, and biomass in response to environmental factors [73–75]. It is basically used for various agroclimatic conditions and comprises modules that are used to input data, mathematical calculations of the process of growth and development, and, finally, interpretation of the potato simulation outputs [3,56]. The model considers several functions simultaneously to produce the actual structure of the soil–crop–atmospheric dynamic at different potato growth stages [75–77]. Potato development (Figure 4) occurs in various stages: sprout elongation, emergence, tuber initiation, bulking, and maturity [78].

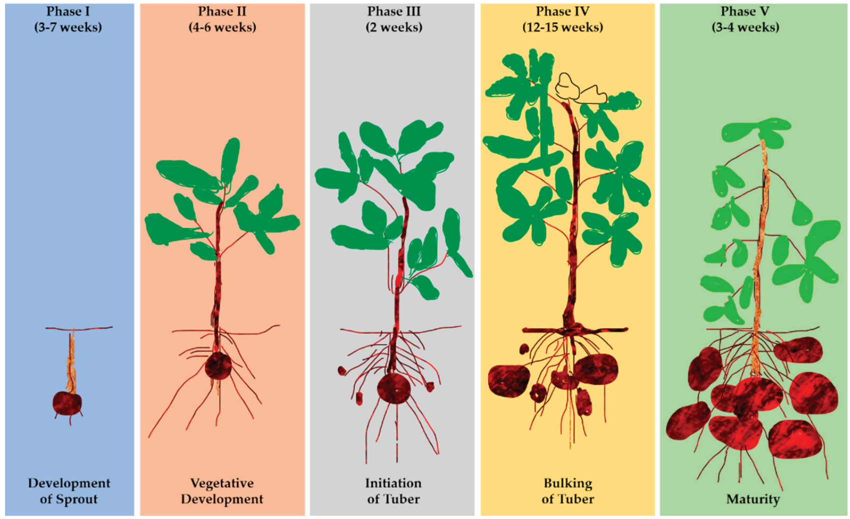

Figure 4. The development stages of potatoes.

SUBSTOR uses five genotype coefficients to define a potato cultivar's growth and development, which determines how the cultivar reacts to climatic conditions. The genetic coefficients include (1) G2—the rate of leaf area expansion, (2) G3—the rate of potential tuber growth, (3) PD—an index that suppresses tuber growth (dimensionless), (4) P2—sensitivity of tuber initiation to photoperiod (dimensionless), and (5) TC—tuber initiation upper critical temperature (Table 4). The varying genetic coefficients affect potato biomass accumulation [33,46,73,79–81]. SUBSTOR is partitioned into sub-sections simultaneously, modeling soil water, nitrogen balances, phenological development, partitioning, and biomass formation of potato crops, producing a real plant–soil–atmospheric system description [58,70]. TC and P2 are vital parameters at the tuber initiation stage; initiation and bulking are inhibited when the TC is exceeded, and a particular cultivar is less sensitive to long photoperiods the closer P2 tends towards 0. G2, G3, and PD influence biomass accumulation [74].

Table 4. Calibrated parameters in the DSSAT model.

Symbol	Parameter	Range	Iteration Interval	Calibrated Genetic Coefficient	Units
G2	Leaf area expansion rate after tuber initiation	900–2100	5	2100	$cm^2 \cdot m^{-2} \cdot day^{-1}$
G3	Potential tuber growth rate	21–26	0.02	21	$g \cdot m^{-2} \cdot day^{-1}$
PD	Suppression of tuber growth following tuber induction	0.5–1.0	0.01	0.500	relative index
P2	Tuber initiation sensitivity to long photoperiods	0.3–0.9	0.01	0.586	relative index
TC	The upper critical temperature for tuber initiation	5–22	0.02	22	°C

2.4. Model Calibration and Validation

The DSSAT model estimates potato yields in dry tuber weight using five genetic coefficients describing crop growth and development processes. Under different weather, soil, and management conditions, the potato coefficients aid the model in simulating the performance of the genotypes. An accurate simulation of tuber yields requires the correct genetic coefficients. We use the genotype coefficient calculator (GENCALC) module in the DSSAT model to calibrate model parameters in Table 4. Cultivar parameters are varied over a wide range to capture the behavior of the crop across a wide genetic range. Each parameter varies while holding the other four parameters constant at their calibration values. The potential of using a physically based (dynamic) crop simulation model (i.e., model performance) is evaluated by comparing the aggregated and reported tuber yields. The coefficient of determination (i.e., R^2), Nash–Sutcliffe efficiency (i.e., *NSE*), and index of agreement (i.e., *d*-stat) are used to ascertain the agreement between the observed and simulated values. R^2 ranges from 0 to 1; the closer the value to 1, the better the agreement between the observed yield and the simulated yield, and a value of 1 shows a perfect correlation, i.e., $0 \leq R^2 \leq 1$ [82]. R^2 is calculated using the following equation.

$$R^2 = 1 - \frac{SSE}{SST} \tag{1}$$

R^2 is the coefficient of determination, *SSE* is the sum of squared error, and *SST* is the sum of squares total. Equation (1) is used to confirm the R^2 generated by the model. Sensitivity analyses explore the variation of the genetic coefficient on potato yields to validate the model. *NSE* ranges from $-\infty$ to 1, where *NSE* is considered good between 0.75 and 1, satisfactory between 0.36 and 0.75, and unacceptable when below 0.36, i.e., $0.36 \leq NSE \leq 1$ [83,84]. *NSE* is calculated using the following equation.

$$NSE = 1 - \frac{\left(\sum_{i=1}^{n}(X_i - Y_i)^2\right)}{\left(\sum_{i=1}^{n}(X_i - \overline{X})^2\right)} \tag{2}$$

NSE is the Nash–Sutcliffe efficiency, X_i is the observed value, Y_i is the predicted value, $\overline{X}$ is the observed mean, and n is the number of observations. Equation (2) is used to calculate NSE. The d-stat value ranges from 0 to 1, where the closer the value to 1, the better the agreement between the observed yield and the simulated yield, where $d = 1$ shows a perfect agreement, i.e., $0 \leq d \leq 1$ [81,83]. The *d*-stat is calculated using the following equation.

$$d = 1 - \frac{\sum_{i=1}^{n}(Y_i - X_i)^2}{\sum_{i=n}^{n}\left(\left|Y_i - \overline{Y}\right| + \left|X_i - \overline{X}\right|\right)^2} \tag{3}$$

The *d*-stat is the index of agreement, X_i and Y_i are observed and simulated yield values, respectively, $\overline{X}$ and $\overline{Y}$ are the average observed and simulated yield values, respectively, and n is the observation numbers. Equation (3) is used to calculate the *d*-stat.

2.5. Measuring Climate Change Impacts on Potato Yields

The DSSAT model uses CMIP6 data to assess the impacts of changing climate on potato yields in PEI, with the coefficients validated in this study. The potato yields estimated under the baseline are compared to those under emission scenarios between 2045 and 2095, and the average of the seven GCMs was considered. The planting and harvest dates are fixed each year with rainfed conditions, considering the planting date that reports the most significant tuber yields. The entire PEI potato crop cycle is set to 130 days from planting to harvesting. The baseline (1995–2014) assessed the historical yields, and the assessment under each of the five emission classes captures the effect of climate variability on future yields. The percentage yield changes under future climates were evaluated by the average yield changes from the GCMs compared to the baseline yields. Under this approach, the changes in potato yield are calculated using the following equation:

$$\text{Change in Yield } (\%) = \left(\frac{\text{Future Yield} - \text{Baseline Yield}}{\text{Baseline Yield}}\right) \times 100\% \tag{4}$$

Emission scenarios reveal a future decline in potato yields compared to the baseline.

3. Results

The results for calibration, validation, and assessment of the impacts of climate change on potato yields are summarized and discussed below.

3.1. Model Calibration and Validation

The DSSAT model used PEI conditions (i.e., soil, weather, and crop management practices data) to successfully perform the genetic coefficient estimation (i.e., calibration and validation) by running the sub-model (GENCALC) to predict rainfed tuber yields for potato variety RB. Calibration and validation are vital for improving model performance and involve comparing field measurements (data) with the model outputs. In this study, the model was calibrated using ten years of "2000–2009" (Table 5) data and validated with eight years of "2010–2017" (Table 6) data in order to compare the observed to the simulated yield. The simulated data are generated through SUBSTOR (potato module) under the DSSAT model interface and compared to the observed yield. The observed yields are island-wide harvested potato yields from potato farms in PEI [50,85].

Table 5. Observed and simulated yield (2000–2009).

Year	Observed (t/ha)	Simulated (t/ha)
2000	29.8	32.6
2001	16.3	16.0
2002	32.7	29.4
2003	30.5	31.0
2004	33.1	30.7
2005	31.8	29.9
2006	33.2	32.5
2007	33.6	32.8
2008	26.8	25.7
2009	27.1	26.1

Table 6. Observed and simulated yield (2010–2017).

Year	Observed (t/ha)	Simulated (t/ha)
2010	29.8	30.1
2011	28.9	29.7
2012	28.2	27.7
2013	28.4	29.4
2014	31.1	31.5
2015	31.0	32.2
2016	32.0	33.3
2017	30.1	29.8

The R^2 with the intercept set to zero were 0.898 and 0.885 for calibration and validation, respectively (Figure 5), indicating a better and closer correlation. The results indicate a significant correlation between observed and simulated yields (i.e., the observed tuber yields corresponded well with the simulated tuber yields), representing a good performance. Additionally, the *NSE* and *d*-stat are 0.87 and 0.92, respectively, indicating a good correlation between observed yield and simulated yield.

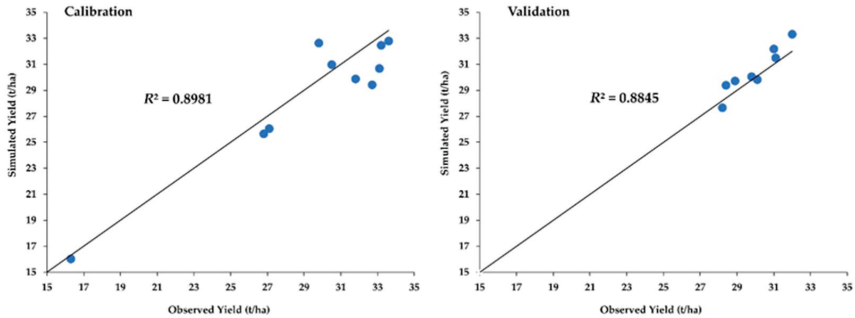

Figure 5. The results for model calibration and validation.

The derived genetic coefficients are used to quantify the development responses of rainfed tuber yields of RB to the changing climate. The mean observed and simulated yields for calibration are 29.5 t/ha and 28.7 t/ha, respectively, and for validation, they are 30.0 t/ha and 30.5 t/ha, respectively. The validated calibration shows that the DSSAT model can accurately assess potato yields under different management conditions in different climatic regions.

3.2. Impacts of Future Climate Change on Potato Yields

The DSSAT model assesses the impacts of climate change on potato yields, showing that the high-emission scenario could result in a significant decline. Future potato yields were assessed using CMIP6 data for the 2050s, 2070s, and 2090s compared with the baseline period (1995–2014) for SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5. The yield assessment using T_{max}, T_{min}, precipitation, and CO_2 was compared among the generated climate scenarios and the baseline period "1995–2014." The results indicated that the projections were based on combinations of seven GCMs under five SSP scenarios. Across the seven GCMs, CanESM5 shows the most significant decline, while the least decline is observed in the FGOAL-G3 (Figure 6 and Table 7). Overall, there is a significant decline in high emission scenarios, especially towards the end of the century when the average of the seven GCMs projection is considered.

Table 7. PEI's future potato yields (units: t/ha) under SSP scenarios.

GCM	Period	SSP Scenario				
		SSP1–1.9	SSP1–2.6	SSP−4.5	SSP3–7.0	SSP5–8.5
CanESM5	Baseline			15.1		
	2050s	12.3	8.6	9.2	3.9	5.9
	2070s	10.8	7.0	3.3	2.5	4.6
	2090s	12.4	10.7	2.8	2.0	0
GFDL-ESM4	Baseline			15.2		
	2050s	14.1	15.3	15.5	17.4	15.7
	2070s	14.1	14.8	16.0	9.0	7.5
	2090s	13.9	14.9	13.1	6.6	3.3
MRI-ESM2	Baseline			15.2		
	2050s	13.6	13.8	15.4	16.1	9.8
	2070s	12.3	143	11.0	7.7	4.4
	2090s	13.8	15.1	10.1	5.0	3.1

Table 7. *Cont.*

GCM	Period	SSP Scenario				
		SSP1–1.9	**SSP1–2.6**	**SSP−4.5**	**SSP3–7.0**	**SSP5–8.5**
MIROC6	Baseline			15.1		
	2050s	15.2	14.7	16.2	16,8	16.0
	2070s	14.8	15.4	15.4	8.6	4.8
	2090s	14.2	14.9	9.8	4.4	2.6
FGOAL-G3	Baseline			15.1		
	2050s	15.5	17.2	16.6	17,5	17.6
	2070s	15.4	16.3	17.3	15,6	13.9
	2090s	15.0	16.2	17.6	14.8	7.6
IPSL-CM6A-LR	Baseline			15.1		
	2050s	13.5	14.4	14.5	16.0	11.0
	2070s	14.2	14.5	9.6	6.4	2.7
	2090s	14.3	14.1	7.2	2.6	1.7
EC-Earth3-Veg	Baseline			15.1		
	2050s	14.1	15.3	16.1	15.7	10.0
	2070s	13.6	13.5	14.0	5.4	4.5
	2090s	12.7	13.3	6.8	3.7	2.9
Model Average	Baseline			15.1		
	2050s	14.0	14.2	14.8	14.8	12.3
	2070s	13.6	13.7	12.4	7.9	6.1
	2090s	13.7	14.2	9.6	5.6	3.0

There is a considerable variation in observed temperature, precipitation, and CO_2 for future climate scenarios. T_{max}, T_{min}, precipitation, and CO_2 are estimated to increase compared to the baseline over the century until the worst emission scenario (SSP5–8.5). Overall average yield decline is expected as simulated by the seven GCMs for the five SSPs, which projects to be significant towards the end of the year. The model average projected that it is likely to have the most significant yield decline under SSP5–8.5, followed by SSP3–7.0 and then SSP2–4.5, with medium to low yield decline in SSP1–1.9 and SSP1–2.6.

Extensively, the average potato yields in the future, under SSP1–1.9, will likely decline from 14.0 t/ha in the 2050s to 13.6 t/ha in the 2070s and 13.7 t/ha in the 2090s. Under SSP1–2.6, the yields are expected to decline from 14.2 t/ha in the 2050s to 13.7 t/ha in the 2070s and increase to 14.2 t/ha in the 2090s. In addition, under SSP2–4.5, the yields suggest a decline from 14.8 t/ha in the 2050s to 12.4 t/ha in the 2070s and 9.6 t/ha in the 2090s. Furthermore, yields under SSP3–7.0 are expected to decline from 14.8 t/ha in the 2050s to 7.9 t/ha in the 2070s and 5.6 t/ha in the 2090s. The most significant yield decline is expected under SSP5–8.5, from 12.3 t/ha in the 2050s to 6.1 t/ha in the 2070s and 3.0 t/ha in the 2090s.

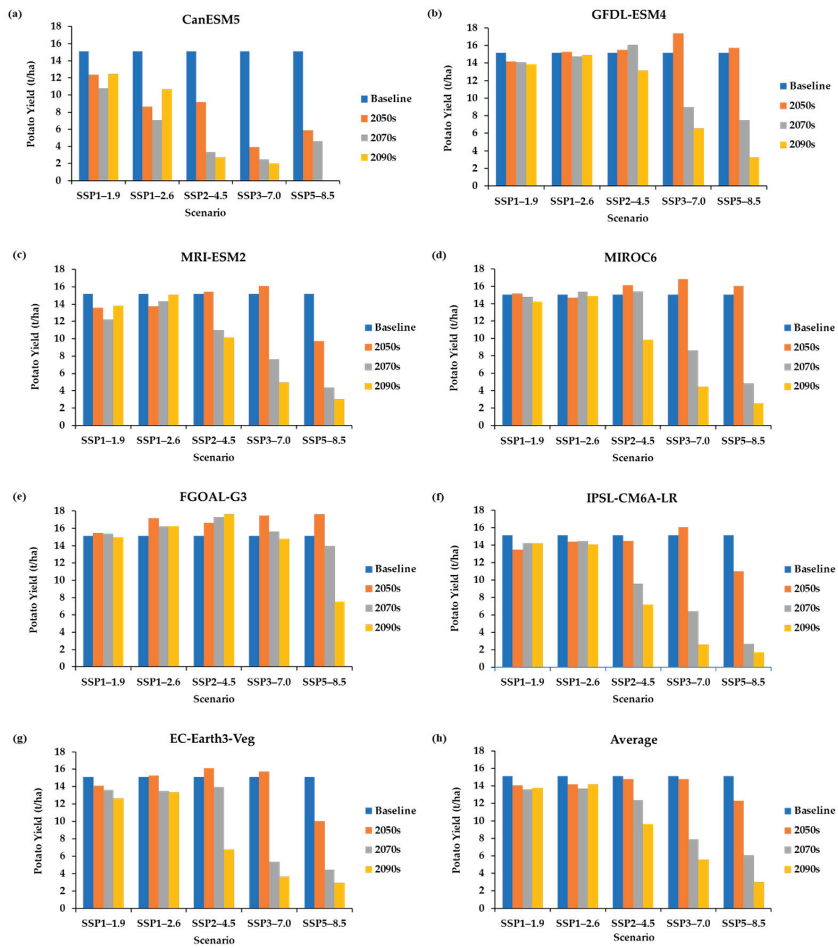

Figure 6. PEI's future potato yields under CMIP6 scenarios. (**a**) CanESM5, (**b**) GFDL-ESM4, (**c**) MRI-ESM2, (**d**) MIROC6, (**e**) FGOAL-G3, (**f**) IPSL-CM6A-LR, (**g**) EC-Earth3-Veg, and (**h**) multi-model average.

Compared to the baseline, yields under the SSP1–1.9 suggests a decline of 7.2% in the 2050s, 10.2% in the 2070s, and 9.2% in the 2090s. Under the SSP1–2.6, the yields are expected to decline by 6.4% in the 2050s, 9.6% in the 2070s, and 6.4% in the 2090s. Under the SSP2–4.5, the yields suggest a decline of 2.2% in the 2050s, 18.3% in the 2070s, and 36.4% in the 2090s. Yield decline of 2.3%, 47.8%, and 63.2% is likely under SSP3–7.0 in the 2050s, 2070s, and 2090s, respectively, while a decline of 18.8%, 60.0%, and 80.1% are expected in the 2050s, 2070s, and 2090s under SSP5–8.5 (see Figure 7 and Table 8).

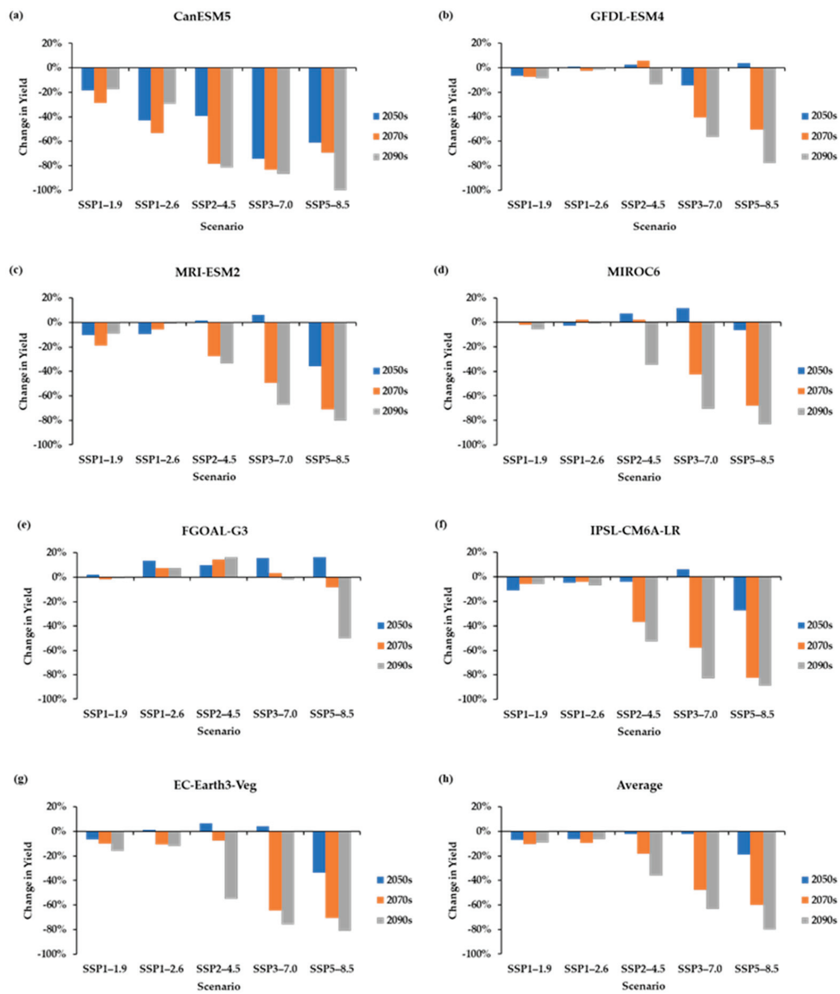

Figure 7. Percentage change in PEI's potato yields under CMIP6 scenarios. (**a**) CanESM5, (**b**) GFDL-ESM4, (**c**) MRI-ESM2, (**d**) MIROC6, (**e**) FGOAL-G3, (**f**) IPSL-CM6A-LR, (**g**) EC-Earth3-Veg, and (**h**) multi-model average.

However, the results were inconsistent between the different GCMs; there were mixed results, including decreases (red cells in Table 8) and increases (green cells in Table 8) in yields under the periods and SSPs.

Table 8. Percentage change in PEI's potato yields under SSP scenarios.

GCM	Period	SSP Scenario				
		SSP1–1.9	SSP1–2.6	SSP−4.5	SSP3–7.0	SSP5–8.5
CanESM5	2050s	−18.3%	−43.0%	−39.2%	−74.3%	−60.9%
	2070s	−28.8%	−53.5%	−78.2%	−83.4%	−69.5%
	2090s	−17.7%	−29.3%	−81.6%	−86.6%	−100%
GFDL-ESM4	2050s	−6.8%	+0.8%	+2.4%	−14.6%	+3.6%
	2070s	−7.5%	−2.7%	+5.7%	−40.8%	−50.6%
	2090s	−8.6%	−1.8%	−13.5%	−56.8%	−78.1%
MRI-ESM2	2050s	−10.4%	−9.4%	+1.5%	+6.2%	−35.6%
	2070s	−19.1%	−5.7%	−27.7%	−49.5%	−71.1%
	2090s	−9.3%	−0.7%	−33.3%	−67.3%	−79.9%
MIROC6	2050s	+0.6%	−2.7%	+7.2%	+11.8%	−6.3%
	2070s	−2.0%	+2.0%	+2.2%	−42.7%	−67.9%
	2090s	−5.5%	−1.3%	−34.9%	−70.5%	−83.1%
FGOAL-G3	2050s	+2.0%	+13.5%	+9.9%	+15.5%	+16.4%
	2070s	−1.8%	+7.5%	+14.3%	+3.2%	−8.1%
	2090s	−1.1%	+7.3%	+16.4%	−2.2%	−50.1%
IPSL-CM6A-LR	2050s	−10.8%	−4.9%	−4.2%	+6.1%	−27.3%
	2070s	−5.8%	−4.1%	−36.8%	−57.4%	−82.4%
	2090s	−5.7%	−6.9%	−52.6%	−83.0%	−88.8%
EC-Earth3-Veg	2050s	−6.7%	+1.2%	+6.7%	+4.1%	−33.8%
	2070s	−9.8%	−10.8%	−7.4%	−64.3%	−70.5%
	2090s	−16.2%	−11.9%	−55.2%	−75.9%	−80.7%
Model Average	2050s	−7.2%	−6.4%	−2.2%	−2.3%	−18.8%
	2070s	−10.2%	−9.6%	−18.3%	−47.8%	−60.0%
	2090s	−9.2%	−6.4%	−36.4%	−63.2%	−80.1%

Note that the red cells showed percentage decrease in PEI potato yields while the green cells showed percentage increase in PEI potato yields, across the periods and GCMs under SSP scenarios.

4. Discussions

The current study showed that potato yields are expected to decrease in PEI toward the end of the century when we consider the combined effect of T_{max}, T_{min}, precipitation, and CO_2. The seven GCMs projected increased temperature in the future, i.e., in the 2050s–2090s, T_{max} and T_{min} are expected to increase by 1.2 °C to 5.6 °C and 1.4 °C to 6.1 °C, respectively, depending on the climate scenario and period. CO_2 increased by 2.4% to 140.9%, while precipitation increased by 3.4% to 12.8% compared to the baseline values. There is instability in precipitation patterns across the scenarios and period; hence, the yield decline can be attributed to precipitation variation because the significant potato yield changes correlate with precipitation changes.

Our study result showed that future yields decrease under rainfed conditions, compared to Brassard and Singh's (2007) [47] studies, which reported a decrease in future potato yields in Quebec. In addition, Vashisht et al.'s (2015) [83] studies showed that future potato production under rainfed conditions in Minnesota, US, is projected to decrease due to climate change. Nevertheless, other studies showed that climate change might increase future potato yields. For instance, Tooley et al. (2021) [86] reported increased future potato yields in Maine, US, due to climate change, while some studies projected increased future potato yields under rainfed conditions compared to irrigated conditions [87,88]. Furthermore, Tubiello F. N. et al. (2002) [89] projected that climate change would increase future potato yield in the northern United States of America (US) while it will be reduced in the southern areas of the US. The observed variations in the projected future potato yields are due to differences in geographical area and management practices. The variation could also be caused by the differences in the GCMs used [74]. Our study suggests that the potato yield decrease correlates with an increase in future temperature and CO_2 concentration with varying precipitation patterns. Overall, our results indicate the potential negative impacts of climate change on future potato yields under rainfed conditions in PEI. It is worth mentioning that the crop yields determinant is not only limited to temperature, precipitation, and CO_2 but also depends on other factors, such as pests, soil salinity, and other parameters which play an essential role in crop growth processes and the harvested yields but are not included in our study's scope [26,29,30,90,91]. Although temperature and CO_2 changes influence the yields, their reaction with precipitation significantly influences tuber yields under rainfed conditions in PEI. The amount of precipitation and distribution within a specified temperature range drives potato development. Precipitation affected the yields simulated, which mostly declined from decreased precipitation with some compensation through elevated atmospheric CO_2. Our results suggest that future potato yields are expected to decrease in PEI, which could be attributed to the future drought effect under rainfed potato production systems. Considering that PEI potato cultivation is significantly rainfed [13,92], and since the decrease in precipitation decreases our simulated yield, we attributed the decline in potato yields to the drought effect, which could be compensated through supplemental irrigation. This study is a foundation to examine further and ascertain proper adaptation strategies to increase potato yields, which can be recommended to farmers. Ultimately, this study methodology can be applied to assess the impacts of climate change on potato yields in any geographical region worldwide.

5. Conclusions

In this study, we used the DSSAT model to assess the potential impacts of future climate change on potato yields in PEI. In particular, we used the IPCC CMIP6 data under five GHG emission scenarios, SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5, to assess the effects of climate change on potato yields in PEI. GCMs (CanESM5, FGOAL-G3, GFDL-ESM4, MIROC6, MRI-ESM2, IPSL-CM6A-LR, and EC-Earth3-Veg) were used to generate emission scenarios for the study. The assessment evaluates the combined impacts of climate variables, T_{max}, T_{min}, precipitation, and $CO_{2,}$ on potato yields.

This study calibrates and validates the DSSAT model using dry tuber weight as the parameter to evaluate the model's performance. The observed and simulated values were in close agreement and fell within the statistical significance limit. Using the average of the GCMs, the potato yields suggested a gradual decline under SSP1–1.9 and SSP1–2.6, with a distinct decline under SSP2–4.5. The most significant decline is expected under high-emission scenarios SSP3–7.0 and SSP5–8.5. The reduction is expected to be enormous towards the end of the century, indicating significant negative impacts on the yields due to climate change. Adapting to climate change's impacts requires exploring various strategies to guarantee food security. These strategies are crucial to improve crop and soil management and enhancing potato production. The results from this study can provide farmers and policymakers with a scientific basis to develop coping mechanisms for climate change impacts which can be adopted for optimal and quality potato yields to ensure food security.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/foods12061176/s1, Supplementary Information S1: Survey Form on PEI Potato Farming Practices.

Author Contributions: Conceptualization, X.W.; Methodology, X.W.; Software, X.W.; Validation, T.A. and X.W.; Formal analysis, T.A. and X.W.; Investigation, T.A.; Resources, T.A.; Data curation, T.A. and X.W.; Writing—original draft, T.A.; Writing—review & editing, T.A., X.W., S.B., R.A.N., T.P., Y.H. and S.L.; Visualization, T.A. and X.W.; Supervision, X.W.; Project administration, T.A., X.W., S.B., R.A.N., T.P., Y.H. and S.L.; Funding acquisition, X.W. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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Climate Change and Food Security Prioritizing Indices: Applying Analytical Hierarchy Process (AHP) and Social Network Analysis (SNA)

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Abstract: Food security and climate change are multidimensional issues. Therefore, a lack of knowledge about the most essential variables made these concepts more complex for decision-making and highlighted the need for credible decision support methods. Here, we aim to develop an accurate tool by using the analytic hierarchy process (AHP) method to explore the priority indicator of food security under climate change in Iran and social network analysis (SNA) to support decisions. The following steps were conducted for the AHP approach: a literature review, a Likert questionnaire and experts' interviews for variable selection and the variables' weight determination and prioritization by pairwise comparison questionnaire, designed based on the hierarchy matrix of the criteria and sub-criteria of food security and climate change. The SNA was employed to understand the robustness of the informants' points of view for indicator selection. After the analysis, 61 criteria were extracted. Sustainability was the important criterion, weighted 0.248. The most important sub-criteria (indicators): groundwater sources, household income, underweight adolescent ratio, food wastage and an annual average of precipitation, weighted 0.095, 0.091, 0.125, 0.227 and 0.236, respectively. The SNA showed that professionals with academic origins focused on the sustainability component. The AHP tool is a credible technique to distinguish the most important criteria. The results might be employed to estimate or predict food security under climate change and simplify decision making in Iran.

Keywords: analytical hierarchy process (AHP); multi-criteria decision-making; weather extreme events; food security; social network analysis (SNA)

1. Introduction

Climate change, war and poverty are three critical drivers of global hunger [1]. The evidence showed global warming affects crop production directly, reducing the primary yields of crops by around 3.1–7.4% for each °C increase in the global mean temperature [2]. Rural and urban people felt the consequences of global warming, which disrupted the agricultural sector and supply chain, raised food prices, diminished purchasing power, endangered human health and demolished property and livelihood with no opportunity to deal with catastrophic impacts and poverty; therefore, all dimensions of food security are in jeopardy [3–6]. Therefore, researchers and policymakers desired more than before to estimate the climate change uncertainty and risks that threaten the environment, agriculture, water, economic and political stabilities [3,4,7,8]. They conducted studies to apply context-specific, precise and reliable tools to enlist the essential variables and estimate the harmful impacts of climate change on different dimensions (availability, accessibility, utilization and sustainability) of food security [9–13]. After a preliminary literature review, we found that previous studies in different countries addressed the acceptable validity of the AHP method to identify the important indicators with accurate weights and use these indicators to predict the uncertainties in various subjects, e.g., environment or food and agriculture [14–20]. Moreover, lessons learned from other countries which tried to improve their adaptation policies evidenced that the development of tools to measure leading climate change and food security indices by the AHP questionnaire is helpful [21–25].

Thus, we developed a reliable and accurate tool by applying the AHP method to prioritize and rank the important variables of food security and climate change in the context of Iran. Moreover, a network analysis of experts' roles and positions in their institutes was conducted to support the indicators' validity prioritization of the AHP questionnaire [26,27].

Evidence showed that some areas in the world are more vulnerable to climate change disturbances, e.g., Middle East countries [28,29]. Iran, located in this region, faces severe weather anomalies in the following decades, for instance, mean temperatures will increase by 2.6 °C in 2035 in comparison to 1961–1990 and precipitation will decline by around 35% in 2016–2030 in comparison to 1982–2009 [30,31]. In addition, due to the geographic profile, Iran stands on the tenth rank of disastrous countries and the fourth rank of flood-experienced countries in Asia, with a total of 11 million Iranians affected by floods in recent years; in addition, Iran experiences prolonged and frequent drought due to water crises and groundwater depletion [32–34]. Therefore, food security is a challenge [35–38]. In recent years, several studies have been conducted to estimate food security and identify the criteria that have a principal role in every dimension of food security in Iran with different methods and tools (AHP, TOPSIS, and PROMETHEE) [39–42]. Nevertheless, those studies did not pay enough attention to the significant role of extreme weather event indicators in their estimation of food security and the limited identification of indicators in each dimension of food security [39–42].

To the best of our knowledge, there is no reliable tool to discover the most essential criteria that contributed to food security under climate change in Iran. Also, policymakers requested to know the weight of each important criteria of food security under climate change to make decisions accurately for 85 million people in Iran [43–46]. In summary, we designed this study to distinguish the most important indicators of food security under climate change with the aim to help policymakers in Iran.

Literature Review

Climate change has different socio-economic, health, cultural and environmental impacts, and there are several criteria explored in previous studies which are drivers of climate change [14,47–49]. Furthermore, climate change and food security are multidimensional issues; many stakeholders with different preferences present many ideas and sophisticated decision-making [26,50–53]. To overcome this complexity multi-criteria analysis (MCA) approaches are presented [54–56]. The two types of this approach that were invented by Thomas L. Saaty are the analytic hierarchy process (AHP) and analytic network process (ANP) techniques which are applied in many fields, e.g., engineering, the energy industry, environmental management and agriculture [47,57–60]. These methods have benefits compared to other multi-criteria decisions (MCDs), e.g., comprising numerous qualitative and quantitative factors, flexibility and simplicity of the tool, calculating the importance of each criterion, estimation and control of the internal consistency [61,62]. The AHP and ANP provide decisionmakers with a transformation of subjective judgments on objective estimation. However, there are some differences between the AHP and ANP [62].

The AHP derives relative priorities on absolute scales through paired comparisons in multilevel hierarchic structures [63]. Thus, researchers use primarily straightforward hierarchic foundations consisting of a top-down structure of goal, indicators and sub-indicators [18]. Although, the ANP uses a network that spreads out in all directions and involves cycles between clusters and loops within the same cluster [62,64]. The feedback structure does not have a hierarchical foundation but is similar to a network. Decisions provided from a network could be considerably different from those provided from a hierarchy [62,65]. In the present study, the network connection of indictors was not noteworthy because we made a decision to estimate only the weight of indicators. Consequently, we decided to carry out the AHP technique to develop the AHP questionnaire for prioritizing and ranking the indicators in four dimensions of food security under climate change in the context of Iran. In addition, we applied a social network analysis to support and increase the robustness of informant's decisions which are answering the AHP questionnaire [26,66–68]. Social network analysis (SNA) is a quantitative technique that could express the patterns of interactions between criteria or subjects by graphical features or statistical outputs in complex systems such as networks. SNA has been used to explore the network's structure and functions or the relationship strength between people and organizations and the flow of information between various actors in a network [68].

2. Methods

We conducted this part of study in three phases. First, a literature review and document analysis were conducted in Iran to select the sufficient and suitable food security criteria under climate change. Then, in the second phase, the criteria prioritization by the AHP method was performed, and it was followed in the third phase by the robustness of expert opinions by SNA.

2.1. Tools Assessment

Both climate change and food security are multidisciplinary aspects that need to integrate a wide range of scientific knowledge, such as politics, social sciences, health, natural sciences and skills [6,69]. Therefore, several stakeholders with diverse precedencies over these subjects and different points of view have to deal with a complex situation for decision making and reach a consensus on a single opinion for prioritizing the problems [64]. Scientific evidence demonstrated that humans are poorly equipped to solve these complicated issues in this context [60], because most people, when confronted with such occasions, make an effort to use an intuitive or heuristic approach for clarifying obscure problems and aim to manage the issues. Usually, in this complex situation and with multi-stakeholders, decision making will be difficult because of their value tradeoffs or uncertainty due to lost crucial information or ignored opposite points of view [56].

In such conditions, multi-criteria decision analysis (MCDA) tools will be applied to estimate the value judgments of individual decisionmakers. MCDA is used to quantify value judgments by risk-based decision analysis [56]. Various project alternatives will be scored according to the criteria of interest. In addition, the desirable course of action will be simple in electing. The optimization methods are multi-attribute utility theory or multi-attribute value theory (MAUT/MAVT) and the analytical hierarchy process (AHP) [54]. They apply numerical scores to communicate the competence of 1 option in comparison to others on a single scale. Other MCDA approaches such as Fuzzy Theory, ELECTRE and PROMETHEE are employed for weighing or evaluating decision making [53,56]. In this study, we employ the AHP approach.

2.2. Building the AHP Model

The intuitive judgments of a decisionmaker and consistency in comparing pairwise variables in the decision-making process are fundamental parts of this technique. Researchers [70] suggested that the "strength of this approach is its organizes tangible and intangible factors in a disciplined way and offers a structured, simple solution to decision-making problems" [59,71].

2.3. AHP Scoring

The nine-point scale method was designed for AHP model [60]. This scaling method operates to compare the importance of criteria and sub-criteria (indicators) pairwise. Furthermore, each pair represents the priority of the target options. The priority among criteria is rated between 1 and 9, which is defined and presented in Table 1.

It helps experts concentrate on two indicators or criteria and select one without paying attention to other variables [15,60,64]. By calculating the consistency ratio (CR), the consistency of judgments was checked.

Find the formula below:

$$C.R. = C.I./R.I.$$

where CI is consistency index and RI is random index. With:

$$C.I. = (\lambda max - n)/(n - 1)$$

where λmax is the eigenvalue of the matrix and n is the size of the matrix.

The consistency rate is an indicator that shows possible inconsistencies in the pairwise comparison matrix. It takes the value 0 (complete consistency) when λ¬max = n. The random index takes the values 0, 0, 0.58, 0.9, 1.12, 1.24, 1.32, 1.41, 1.45, 1.49, corresponding to the number of criteria n = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, respectively. The acceptable C.R. level should exceed 10%. Normally, C.R. > 0.10 is acceptable (CR indicates the amount of allowed inconsistency (0.1 or 10%)). However, an inconsistency ratio of up to 10% is tolerable, yet slight deviations do not pose a problem. Large deviations, however, imply that the judgments are not optimal and have to be improved [60]. The expert choice software calculates an inconsistency ratio (IR) and the ratio of under 0.1 in this study was acceptable. Hence, the CR was not calculated by researchers.

AHP Tool.

Table 1. The scale of priority and definitions.

Intensity of Importance	Definition
1	Equal importance both elements
3	Weak importance of one indicator over another
5	Substantial importance of one indicator over another
7	Very strong or demonstrated importance of one indicator over another
9	The extreme importance of one indicator over another
2, 4, 6, 8	Intermediate values between two adjacent judgments

2.4. Data Collection and Analysis

It is necessary to employ credible approach for selecting the essential criteria because it could be beneficial to apply a decision-making tool such as the AHP. However, before assessing the priority, it is essential to select the proper variables of food security and extreme weather events in Iran. Therefore, a literature review and document analysis were conducted in the first phase. Then, the important criteria used to assess food security and climate change were listed. Later, the Likert questionnaire, was designed and sent to 120 experts; then, 50 experts answered and completed this tool. Finally, 61 indices were selected in this stage. The AHP model was formulated to prioritize these criteria by AHP pairwise questionnaire in the second phase. The sample of the questionnaire which is designed for scaling and criteria priority was presented in Table 2.

Table 2. Questioner design of scaling and criteria priority (sample).

Criteria A	9	7	5	3	1	3	5	7	9	Criteria B
Climate change	9	7	5	3	1	3	5	7	9	Food availability

2.5. AHP Development and Data Analysis

We developed an AHP questionnaire to calculate the most important indicators to predict food security under climate change: 5 indicators were addressed as criteria. Moreover, at the sub-criteria level, 61 indicators were categorized, containing 54 indicators for four dimensions of food security (availability 17, accessibility 18, utilization 12, sustainability 7) and 7 indicators for climate change (extreme weather events).

Hence, we asked two questions according to this systematic procedure. The first: what is the hierarchy matrix of variables, the criteria and sub-criteria? Then, the second, what is the weight of each index in the pairwise selection stage? Consequently, we first designed the hierarchical matrix between food security and climate change indices. Then, designed a pairwise questionnaire for 66 variables with gradation in 3 levels [60]. (Figure 1). In this study, there was no alternative to define. Therefore, the hierarchical framework was made by 3 levels: goal, criteria, sub-criteria.

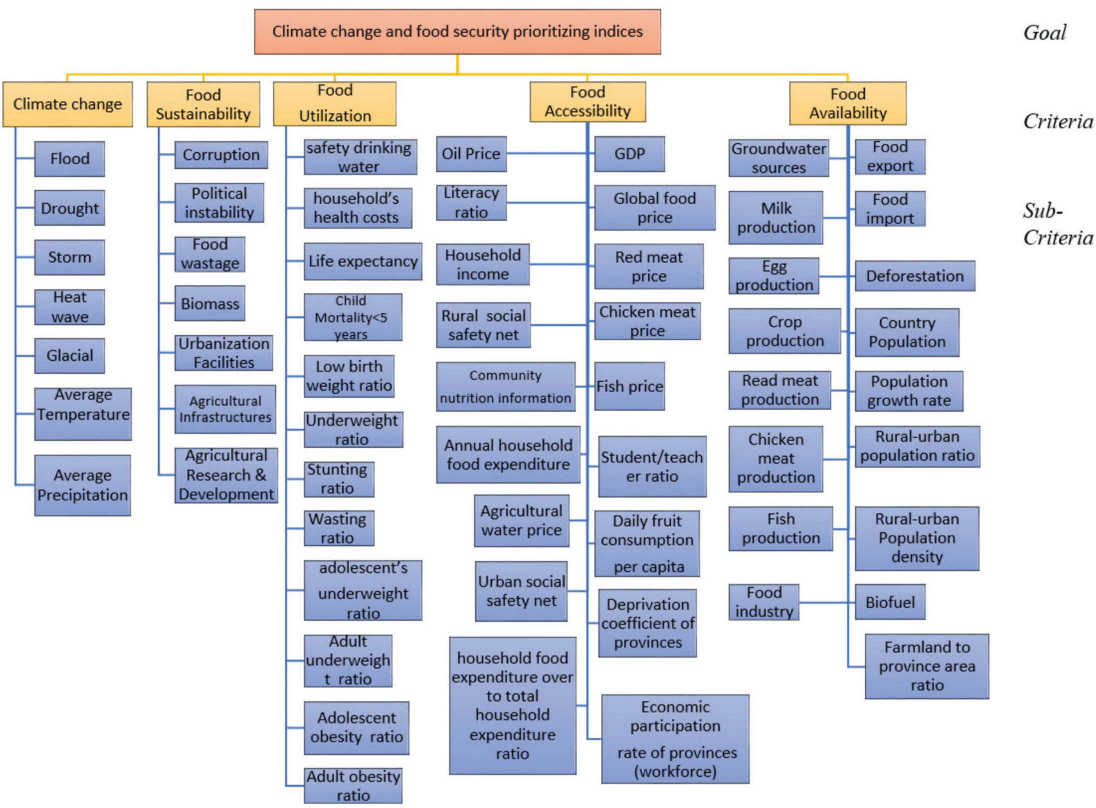

Figure 1. The hierarchical framework of criteria, sub-criteria (indices) prioritization for food security under climate change in Iran.

We sent an AHP questionnaire to all 50 informants from different parts of the food system, climate change (weather center) and other organizations with enough related responsibility, experience or academic knowledge in governmental, official, unofficial, NGOs and private sectors. Ultimately, criteria were all weighted based on 11 experts who filled in the AHP questionnaire and were interviewed. Supplementary File S1, AHP Questionnaire.

Expert Choice software (version 11) was applied to analyze the pairwise criteria (indices) of the AHP tool.

2.6. Social Network Analysis

Roles and workplaces conducted network analyses on data collected from 11 experts who participated in the AHP development tool. The characteristic of experts is presented in Table 3.

Table 3. The experts' characteristics, answered AHP questionnaire.

Person	Workplace	Education Level	Work Experience (Year)	Sex	Role of Institute (Actors)
P1	MoHME	PhD	10	M	Supportive
P2	IRIMO	PhD	29	M	Responsible
P3	MSRT	PhD	7	M	Cooperative
P4	MoHME	MSc	25	M	Supportive
P5	MAJ	MSc	15	M	Responsible
P6	MoHME	PhD	30	M	Supportive
P7	DoE	MSc	12	F	Cooperative
P8	MAJ	PhD	23	M	Responsible
P9	MAJ	PhD	18	M	Responsible
P10	DoE	PhD	29	M	Cooperative
P11	SCHFS	MSc	28	F	Supportive

Note: MoHME (Ministry of Health and Medical Education), IRIMO (Islamic Republic of Iran Meteorological Organization), MSRT (Ministry of Science, Research and Technology), MAJ (Ministry of Agriculture Jihad), DoE (Department of Environment), SCHFS (Supreme Council for Health and Food Security). M (Male), F (Female).

The questionnaire was distributed to subject matter experts in climate change and food security from various official and unofficial organizations and universities, including the food and nutrition faculties, the agricultural ministry departments, environmental and geography departments.

Table 4 shows the sample types of questions used for data collection.

We address the substantial experts' role in 3 categories, according to their formal responsibility and positions of their institute in this study: 1—supportive, 2—cooperative, 3—responsive. Gephi (version 9) software was administered to analyze the expert criteria and design network graphs. The network analysis and graphs are presented in the Section 3.

Table 4. The questionnaire used for the position and role of institute data collection.

Institute (Actors)	Role of Institute (Actors)		
	Supportive	Cooperative	Responsible
Ministry of Health and Medical Education (MoHME)	✓		
Islamic Republic of Iran Meteorological Organization (IRIMO)			✓
Ministry of Science, Research and Technology (MSRT)		✓	
Ministry of Agriculture Jihad (MAJ)			✓
Department of Environment (DoE)		✓	
Supreme Council for Health and Food Security (SCHFS)	✓		

3. Results

According to the hierarchical framework in Figure 1, the sixty-one indicators were categorized into 5 criteria and 56 sub-criteria matrixes based on the weights of criteria and sub-criteria (indicators) for food security components and climate change extreme events. The weights and ranks of each indicator and the estimated value of inconsistency were presented in Figures 2 and 3 and Table 5. The definition and source of the indicators were mentioned in this table. These are also mentioned in Figure 4 and Supplementary Figure S1. The social network analysis of food security and climate change experts' decisions according to their organizations was shown in Figure 4, parts B1–B6, and the social network analysis of food security and climate change stakeholders according to the role of the institute was showed in Supplementary Figure S1, parts G1–G6.

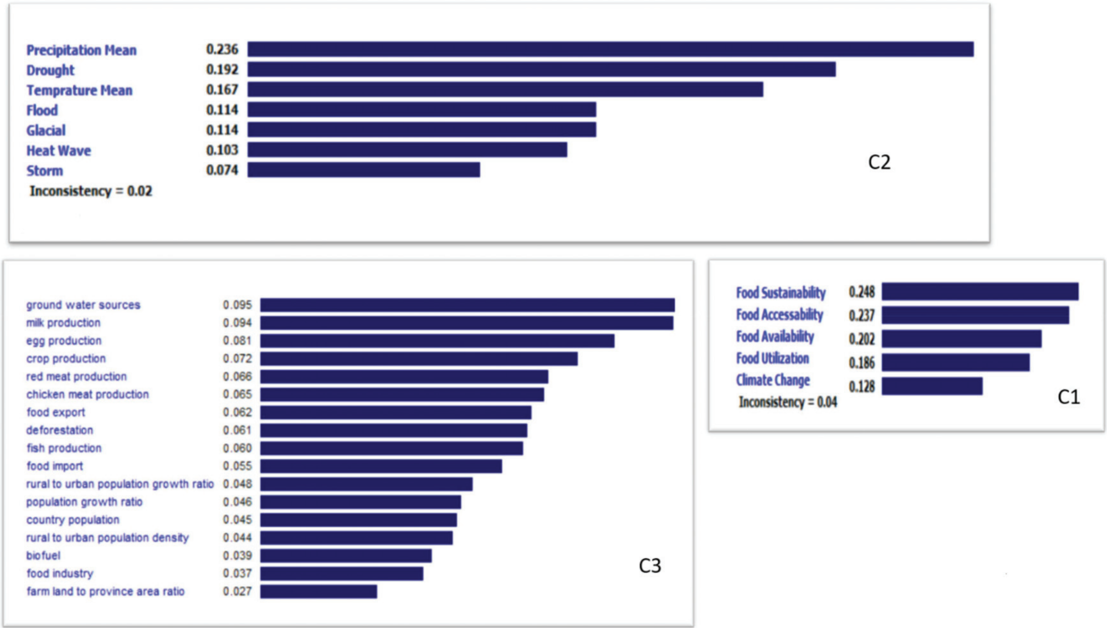

Figure 2. Relative Weights of Criteria and Sub-Criteria of Food Security under Climate Change by AHP Tool. **C1**: Criteria Weights of Food Security and Climate Change. **C2:** Indices' Weight of Climate Change. **C3**: Indices' Weight of Food Availability Criteria.

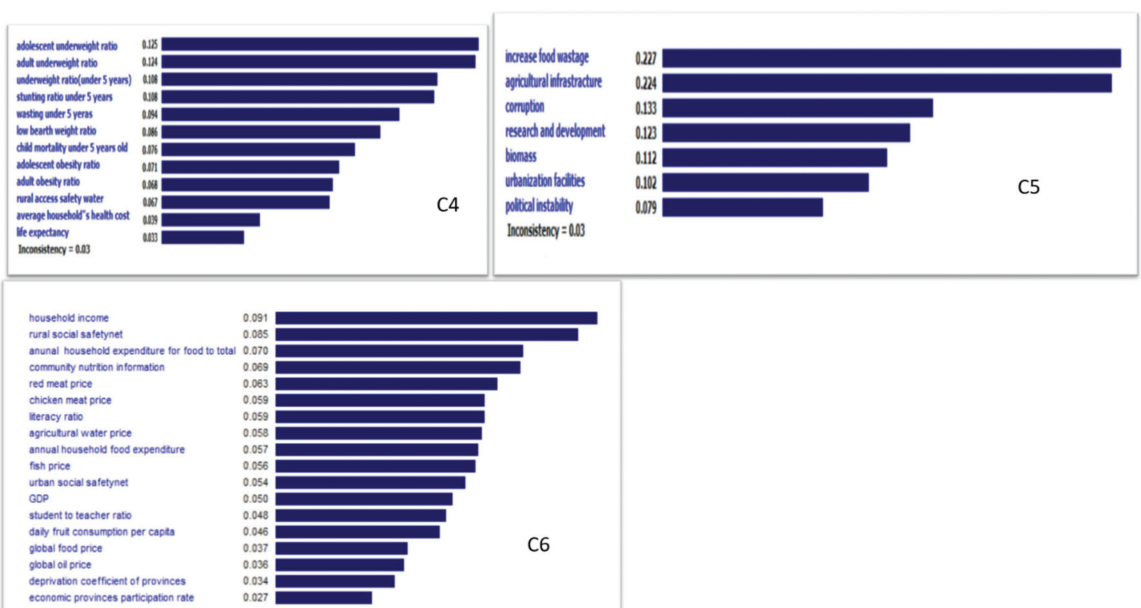

Figure 3. Relative Weights of Food Security under Climate Change Sub-Criteria by AHP Tool. **C4**: sub-criteria indices weight of food utilization. **C5**: indices' weight of food sustainability. **C6**: indices' weight of food accessibility criteria.

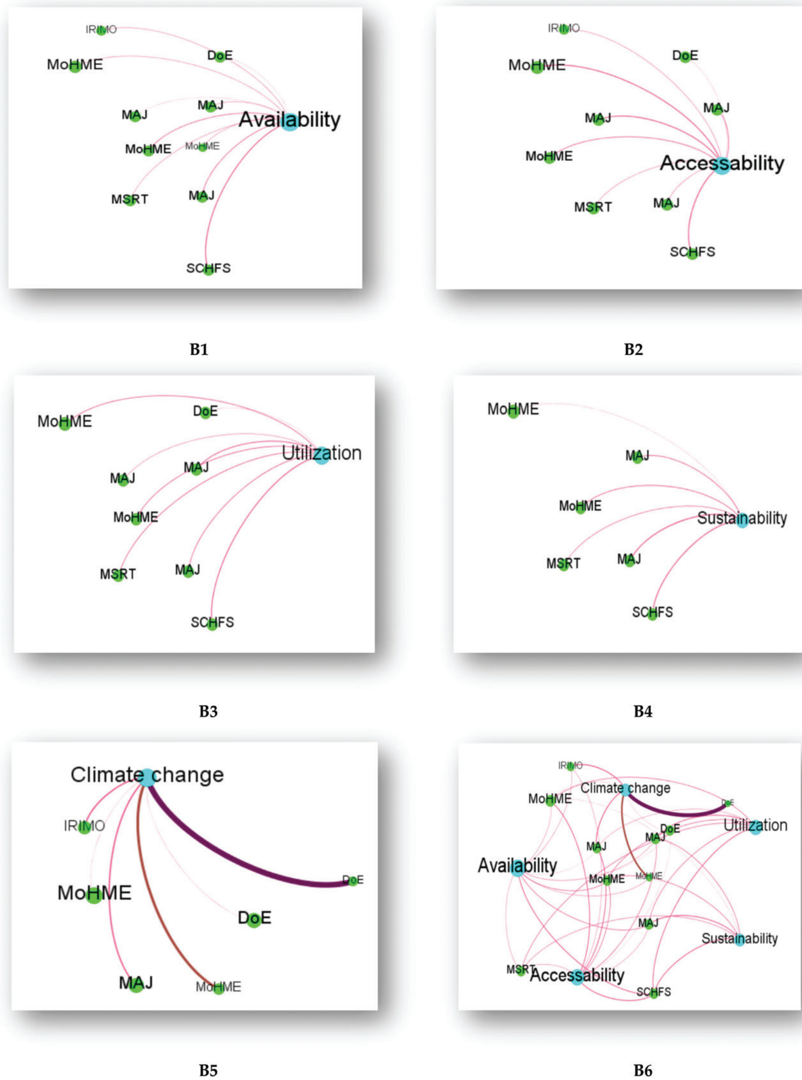

Figure 4. Social network analysis of food security and climate change experts' decisions according to their organizations (institute), parts **B1**–**B6**. Categories and colors: blue, food security components and climate change index; green, organizations. Note: MoHME (Ministry of Health and Medical Education), IRIMO (Islamic Republic of Iran Meteorological Organization), MSRT (Ministry of Science, Research and Technology), MAJ (Ministry of Agriculture Jihad), DoE (Department of Environment), SCHFS (Supreme Council for Health and Food Security). Authors' contribution.

Relative Weights of Indicators

The first category of indicators in the hierarchical framework (the criteria level in the matrix) and relative weights for food security components and climate change are depicted in Figure 2-part C-1. The second category in the hierarchical framework (the sub-criteria level in the matrix) and the relative weights of climate change and the four sub-criteria of food security (availability, accessibility, sustainability and utilization) are presented in Figure 2-part C2–C3 and Figure 3-part C4–C6. Figure 2, part C1—show the weight of the criteria (climate change, availability, accessibility, sustainability and utilization), and the highest weight was assigned to food sustainability (24.8%). Figure 2-part C2—shows that the mean precipitation and drought had the highest relative weights among the sub-criteria (indices) of climate change. Figure 2-part C3 indicates the sub-criteria indices' weight of the food availability criteria, with the highest index's weight on groundwater sources.

Figure 3-part-C4 presents the relative weights of the sub-criteria indices' weight of food utilization, with the highest rank of adolescent undernutrition ratio. Furthermore, Figure 3-part C5—shows the sustainability sub-criteria indices' weight with the first rank of increased food wastage (22.7%). In Figure 3-part C3, the indices' weight of the food accessibility criteria is showed, and the household income indicator was on the first rank with a weight of 9.1%.

The details of the priorities and weights are indicated in Table 5, presenting the relative weights of the criteria and sub-criteria (indicators). In each of the five categories, the values introduce the weight of each indicator which is relative to other indicators. In the definition column in this table, all national indicators are described and the international (well-known) indicators are addressed by reference. In another column, the priorities of each indicator according to its weight are presented. The last column shows the inconsistency ratio; the inconsistency ratios for all pairwise matrixes were less than 0.1.

The social network analysis (SNA) is used to understand: who choose which criteria, or which criteria is necessary for whom? This network showed the informants' decisions for prioritizing criteria according to their organization's positions on food security and climate change policy making in Iran. These are displayed in Figure 4 and Supplementary Figure S1.

Table 5. Relative weights, priorities by weights of criteria and sub-criteria (indicators) in AHP tool.

Criteria	Definition/Source	Of Criteria and Sub-Criteria	Weight	Priority	Inconsistency
Food sustainability		[72]	0.248	1	0.04
Food accessibility		[72]	0.237	2	
Food availability		[72]	0.202	3	
Food utilization		[72]	0.186	4	
Climate change		[73]	0.128	5	
Criteria	**Sub-Criteria**	**Definition/Source**	**Weight**	**Priority**	**Inconsistency**
Food Sustainability	Food wastage ratio	Percentage of national food waste in 12 months [73].	0.227	1	0.03
	Agricultural infrastructure	This is a composite indicator that measures the ability to store and transport crops to market [73].	0.224	2	
	Corruption ratio	[74]	0.133	3	
	Agricultural research and development	[73]	0.123	4	
	Biomass	Percentage of plant-based material used as fuel to produce heat or electricity.	0.112	5	
	Urbanization facilities (urban absorption capacity)	This indicator measures the capacity of a country to absorb the stresses placed on it by urban growth and still ensure food security [73].	0.102	6	
	Political instability	[74]	0.079	7	
Food Accessibility	Household income	[72]	0.091	1	Less than <0.1
	Rural social safety net	[72]	0.085	2	
	Annual household food expenditure over to total household expenditure ratio	[73]	0.07	3	
	Community nutrition information	Percentage of the knowledge of food and nutrition consumption that is monitored annually in Iran by the ministry of health.	0.069	4	
	Red meat price	Mean red meat price (national currency/Kg) a year.	0.063	5	
	Chicken meat price	Mean fish price (national currency/Kg) a year.	0.059	6	
	Literacy ratio	[73]	0.059	7	
	Agricultural water price	[73]	0.058	8	
	Annual household food expenditure	[72]	0.057	9	
	Fish price	Mean fish price (national currency/Kg) in a year.	0.056	10	
	Urban social safety net	Presence of urban food safety-net programs [73].	0.054	11	
	GDP	Gross domestic production.	0.05	12	
	Student/teacher ratio	The number of students over teachers number nationally.	0.048	13	
	Daily fruit consumption per capita	Percentage of daily fruit consumption per capita (national survey).	0.046	14	
	Global food price	[73]	0.037	15	
	Global oil price	USD for one barrel. Based on Organization of the Petroleum Exporting Countries (OPEC)	0.036	16	
	Deprivation coefficient of provinces	Estimated by the Gini coefficient [73].	0.034	17	
	Economic participation rate of provinces (workforce)	The proportion of the older 10-years-old population over to total population of the country that works and makes money in each province according to the national statistic center of Iran [73].	0.027	18	

Table 5. *Cont.*

Criteria	Sub-Criteria	Definition/Source	Weight	Priority	Inconsistency
Food Availability	Groundwater sources	[73]	0.095	1	Less than <0.1
	Milk production	Average national milk production (tones/year).	0.094	2	
	Egg production	Average national egg production (tones/year).	0.081	3	
	Crop production	Average national crop production (tones/year).	0.072	4	
	Read meat production	Average national red meat production (tones/year).	0.066	5	
	Chicken meat production	Average national chicken meat production (tones/year).	0.065	6	
	Food export	[73]	0.062	7	
	Deforestation	[73]	0.061	8	
	Fish production	Average national fish production (tones/year).	0.06	9	
	Food import	[73]	0.055	10	
	Rural–urban population ratio	Proportion of rural population over urban population in country.	0.048	11	
	Population growth rate	[73]	0.046	12	
	Country population	Total amount of population living in country + refugees and immigrants.	0.045	13	
	Rural–urban population density	[73]	0.044	14	
	Biofuel	Percentage of national biofuel production annually [72].	0.039	15	
	Food industry	Total national industrial food production annually. Tones/year.	0.037	16	
	Farmland-to-province area ratio	Proportion of farmland over total land in country.	0.027	17	
Food Utilization	Adolescent's underweight ratio	[72]	0.125	1	0.03
	Adult underweight ratio	[72]	0.124	2	
	Underweight ratio (under 5 years old)	[72]	0.108	3	
	Stunting ratio (under 5 years old)	[72]	0.108	4	
	Wasting (under 5 years)	[72]	0.094	5	
	Low birth weight (under 2500 g)	[72]	0.086	6	
	Child mortality under 5 years	[72]	0.076	7	
	Adolescent obesity ratio	[72]	0.071	8	
	Adult obesity ratio	[72]	0.068	9	
	Rural accessibility to safe drinking water	Access to potable water is the proportion of people using improved drinking water sources: household connection; public standpipe; borehole; protected dug well; protected spring; rainwater [73].	0.067	10	
	Average household's health costs	[73]	0.039	11	
	Life expectancy	[72]	0.033	12	
climate change	Annual average precipitation	Mean precipitation during 12 months [73].	0.236	1	0.02
	Drought	[73]	0.192	2	
	Annual average temperature	Mean temperature during 12 months [73].	0.167	3	
	Flood	[73]	0.114	4	
	Glacial	[73]	0.114	5	
	Heatwave	[73]	0.103	6	
	Storm	[73]	0.074	7	

4. Discussion

The results of this study clearly showed that the AHP is a credible tool to prioritize the criteria and indicators of food security under climate change in the context of Iran. This is because the AHP technique as a multidisciplinary approach enables us to identify the most important factors that play a role in food security under extreme weather events in this country. Moreover, the social network analysis helps us to reveal that the technique allowed for confidence indicator selection; this is because the experts' point of view did not relate to their roles in the organization or the position of their institutes. Our efforts to present the evidence led us to understand that in the second level of the hierarchy matrix, the highest weight was assigned to food sustainability (0.248), among the other four food security and climate change criteria. Zarei et al. [42] pay attention to food sustainability and the prioritization of the indicators by applying the AHP; however, in that research, food security was categorized in the sub-criteria level with weight (0.034) and the weight was not noticeable. Likewise, other researchers have made efforts to distinguish the essential indicators of food security in Iran, although they did not define the sustainable component of food security in their AHP hierarchical matrix [40,41].

It is necessary to explain that researchers employed the results of food security prioritizing and weights in their modeling of food security in Iran, and they proposed that the area in central parts of Iran has the higher food security score [75]. However, there is the most food-insecure area in the central parts of Iran, and it faces drought, water stress and other socio-economic impacts of extreme weather events [41]. Hence, what we aimed to indicate was the proper criteria and indicator selection and a credible weighting method that are indispensable for future food security under climate change estimation or prediction. It would be more comprehensive when paying attention to the FAO, the Paris Agreement (PA) and the 2030 Agenda for Sustainable Development announcement in which there was call for a produce policy framework to understand: (1) how disasters impact food systems and (2) what is the extent of extreme weather events on food and agriculture sectors. Consequently, identifying the most important factors that threaten food sustainability was highlighted. In other words, climate change places food sustainability at risk, not only by damaging agricultural products and increasing food loss and waste but also indirectly by soil erosion, decreased precipitation, farmers' economic damage and an increase in political instability and crisis [76]. The other evidence to raise the power of the indicator selection in this study is the sub-criteria regarding food sustainability: agricultural infrastructure, food waste, agricultural research and development, corruption ratio and political instability.

Ardakani Z. et al. [39] applied another MCDA approach named the TOPSIS technique, aiming to calculate a dynamic quantitative index of food and nutrition security in Iran. Interestingly, food stability reveals a higher weight among the four dimensions of food security in the context of Iran. This result from Ardakani Z. et al.'s study is in line with our research outcome [39], which is precisely revealed by employing the AHP technique and was further evidence for the power of the AHP method to prioritize the food security criteria in Iran.

According to the findings of this study, mean precipitation and drought take the higher importance weight, 0.236 and 0.192, among the climate change sub-criteria. It is reasonable to score higher for precipitation and drought in Iran because, during the last two decades, the average annual precipitation diminished and drought occurred with high frequency [31,38,77]. Again, Cheng J. et al. [78] employed the AHP to determine the weights of various relevant factors in the agricultural drought vulnerability in the Hubei Province of China. In fact, they investigated the indicators that contributed in regard to three aspects: the economic, social and political systems, on one hand, and on the other hand, the indicators that related to impacts of these aspects. Some of the indicators in that study looked like findings in this research, e.g., per capita GDP, infant mortality rate, the proportion of health care expenditure to total financial expenditure, the population natural growth rate and annual net income. Then, the drought evaluation with these indicators' weights shows the validity of this weight to find the most vulnerable county. These outcomes might show evidence of the suitable indicator selection in our study and increase our validity method. Also, the application of the Markov chain and Fuzzy modeling AHP to identify the linkage between climate change and food security in drought-sensitive agro-ecological zones in Ghana help us to understand that some indicators in our study related to drought factors or impacts are properly selected [49]. However, our hierarchy matrix is different from the Ghanaian study.

Further, researchers tried to document the climate change vulnerability assessment for agriculture by performing the AHP method in Vietnam. They constructed a hierarchy matrix with 3 primary indicators and 22 secondary indicators, whereas 6 climatic indicators were selected, including high temperature (0.153), heavy rain, meteorological drought (0.0157), hydrological drought (0.0166), flood (0.0221) and saline intrusion (0.0186), to determine the exposure of the agriculture sector. Moreover, they carried out consultations with ten experts to collect data and use the AHP technique for the analysis. The method and the number of experts were the same as in our study; we interviewed eleven informants. Likewise, the climate change indicators were almost similar to what we found in this study, albeit they categorized drought into two indicators: meteorological drought (0.0157) and hydrological drought (0.0166) [49]. This evidence proved that the AHP method would be a credible tool to prioritize climate change and food security indicators if the design is context-specific.

In the present study, among the 17 food availability indicators, the groundwater source with a weight of (0.095) was an important indicator. This evidence presented the validity of the informant's indicator prioritization by the AHP questionnaire because it is one of Iran's most essential elements for agricultural production [32–34]. Other researchers in the Middle East region documented the same results [19]. They applied the compound AHP-GIS model to evaluate the agriculture's suitability to achieve food security in an arid area; the water resource was the main criterion, with weight (0.314), and groundwater availability, weight (0.354). These results are in line with the present study findings and Li, Xiao et al.'s outcome [79] with a groundwater weight of (0.23) that prioritized water–energy–food indicators with the AHP technique in China.

The AHP questionnaire in the present study identified the highest weight for the increased food wastage (0.227) indicator in the context of Iran in the food sustainability criteria. It is reasonable, because the ratio of this index in the world and Iran is very high, according to scientific kinds of the literature, with approximately one-third of food production, with the highest 45% for fruit and vegetables and 20% for dairy products and meat production [80–82].

Social Network Analysis (SNA)

We tried to produce an overview of the connection between professionals or main stakeholders and their points of view to select the most important indicators by applying the social network analysis method. SNA can provide a perspective of collaboration among diverse informants and sectors of food security and climate change (e.g., researchers, knowledge producers and decisionmakers) [26,66,67].

In Iran, these issues experienced interdisciplinary challenges. Hence, giving a neutral opinion by experts without respect to their role or positions is valuable [68,83]. We indicated that all informants believe in the importance of food availability. The academics (MoHME, SCHFS and MSRT) selected sustainability criteria. Nevertheless, this component of food security was more important for the MAJ as the most responsible institute of food production in Iran. In addition, climate change was the most important threat to agricultural production in Iran, selected by the DOE and MOHME, who work in the disaster part in these organizations, and the IRIMO, responsible for estimating weather in Iran. In summary, utilization was the priority for food production (MAJ) and the MOHME. It is reasonable that the MOHME selected this component, but the higher weight by the MAJ shows that they understand the importance of food availability in health. In this study, we pay attention to the gender of professionals; a total of 2 out of 11 experts were female. They work at the SCHFS and DoE in decision-making positions. Their job revealed that, in Iran, women play a role as a food producer in rural areas and farms similar to other parts of the world [76]. They are also considered active as food security and climate change policymakers.

Finally, these results indicated that experts selected the food security component despite their responsibility in their institutes (Supplementary Figure S1). Therefore, this method might help the validity of indices weighting by the AHP.

5. Limitation

This AHP questionnaire is designed for prioritized food security with 61 indices, including 4 food security dimensions and extreme climatic weather events in the criteria level and 56 sub-criteria by our team. We had to provide a pairwise design for all indices. This means that the questionnaire was lengthy and time-consuming to answer. Furthermore, we could not receive an expert's viewpoint on food security and extreme climate change events weighting indices from other countries.

There might be mentioned some strengths of this research. Our team succeeded in distinguishing 11 knowledgeable professionals in different aspects, e.g., economic, health, agriculture, social and environment. These experts worked in different governmental organizations with acceptable diversity in responsibilities and experiences. Additionally, we supported their viewpoint by analyzing their position and roles in employing SNA. This method enabled us to improve the validity of the informants' opinions to score the AHP questionnaire.

6. Conclusions

Food security is endangered by extreme climate events because both climate change and food security have a multidimensional nature. Therefore, researchers should focus on employing the multidisciplinary approach (MCA) to understand the factors most related to these issues. In this study, we focused on the AHP technique, which is one of the multidisciplinary approaches aimed to design tools for identifying the essential indicators that contribute to food security under extreme climate change events in the context of Iran. Further, we conducted the SNA to support the robustness of the informants' decisions about indictor prioritization. The potential property of the AHP to measure the essential criteria helped us to provide the set of important indices of extreme climate change events that contribute to food security in Iran. Our finding addressed the 61 priority indicators and the relative weight of the criteria from various subjects, e.g., socioeconomic, health, political and environment.

In addition, the dominant indicator among food security components in this study was food sustainability. This result shows that informants look out for the instability impacts of climate change on food security because the dominant indicator among the climate change criteria was the annual mean precipitation in Iran, and the second index was drought. These two weather and extreme events recognized the remarkable risk for agricultural food production in Iran [31,37,45]. Also, the expert's point of view in the SNA revealed that they selected and prioritized indicators without being biased to their job or organizational position because, for instance, academic informants have given the higher score to climate change compared to experts of agriculture institutes or environment organizations. In summary, we demonstrated that the AHP questionnaire could be a helpful tool to highlight the important indicators.

Furthermore, we provide insight into various indicators with different weights for policymakers to focus on various factors when making decisions about food security in their national context that might be vulnerable to extreme weather events. These causing factors are context-based. In addition, according to our survey, we have recommended the SNA technique to support and enhance the reliance on criteria prioritizations by the AHP tool.

7. Suggestions for Future Research

The authors offer the following recommendations to improve the situation of food security under extreme climate weather and attract the attention of academics and policymakers toward indicators that have previously received less consideration.

1. Applying the same questionnaire in other countries with different political, social and economic contexts to understand the most essential national indices contributing to their food security under climate change.
2. Reviewing and revising the food security indices, especially under extreme weather events, to develop an AHP questionnaire at the provincial level in Iran.
3. Developing such studies in other countries to explore methods like the SNA with aims to improve the validity of indices' weights.
4. These indicator weights might be helpful in models that were conducted to predict the risk of food security under extreme weather event uncertainty in the national context.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14148494/s1, Supplementary Figure S1—Network analysis of food security and climate change actors according to their roles show in G1–G6 parts. Categories and colors: Purple: food security components and climate change index. Red: Responsible role, Green: Supportive role, Blue: Cooperative role. Note: MoHME (Ministry of Health and Medical Education), IRIMO (Islamic Republic of Iran Meteorological Organization), MSRT (Ministry of Science, Research and Technology), MAJ (Ministry of Agriculture Jihad), DoE (Department of Environment), SCHFS (Supreme Council for Health and Food Security). Supplementary File S1, AHP Questionnaire. The prioritization of effective factors for prospecting the relationship between climate change and food security in Iran.

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Article

Indigenous Peoples' Perceptions of Their Food System in the Context of Climate Change: A Case Study of Shawi Men in the Peruvian Amazon

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Abstract: Biodiversity and ecosystem conservation in the Amazon play a critical role in climate-change mitigation. However, institutional responses have had conflicted and complex relations with Indigenous peoples. There is a growing need for meaningful engagement with—and recognition of—the centrality of Indigenous peoples' perceptions and understanding of the changes they are experiencing to inform successful and effective place-based adaptation strategies. To fill this gap, this study focuses on the value-based perspectives and pragmatic decision-making of Shawi Indigenous men in the Peruvian Amazon. We are specifically interested in their perceptions of how their food system is changing, why it is changing, its consequences, and how/whether they are coping with and responding to this change. Our results highlight that Shawi men's agency and conscious envisioning of their future food system intersect with the effects of government policy. Shawi men perceive that the main driver of their food-system changes, i.e., less forest food, is self-driven population growth, leading to emotions of guilt and shame. During our study, they articulated a conscious belief that future generations must transition from forest-based to agricultural foods, emphasising education as central to this transition. Additionally, results suggest that the Peruvian government is indirectly promoting Shawi population growth through policies linking population size to improved service delivery, particularly education. Despite intentional Shawi moves to transition to agriculture, this results in a loss of men's cultural identity and has mental-health implications, creating new vulnerabilities due to increasing climatic extremes, such as flooding and higher temperatures.

Keywords: food system; indigenous; climate change; food security

1. Introduction

Food systems are major contributors to, and are being impacted by, climate change, with implications for people's physical and mental health [1–4]. Approximately one-third of greenhouse emissions are attributable to food systems [1,2,5], reaffirming their centrality in current efforts to mitigate climate change [2,6]. At the same time, climate change is already impacting food systems. For example, food production, food supply chains, and food consumption are frequently affected by extreme events that negatively impact food quantity, prices, and quality [1,7,8]. These impacts are increasing malnutrition and the risk of food insecurity and hunger, and climate-driven ecosystem and biodiversity loss are also affecting mental health [1,2,6].

Climate-change risks are experienced differentially across the globe, disproportionally affecting people with already-vulnerable food systems, especially Indigenous peoples [1–3,9–11]. Indigenous peoples living in biodiversity hotspots like the Amazon have been particularly affected as their access to land has been compromised. This has been compounded by globalisation, ongoing colonisation, and environmental disruptions, causing rapid transitions in their food systems and resulting in modifications to diets, nutritional status, and physical activity [9,12–14]. This food transition is characterised by an increased dependence on external market foods, combined with decreased availability of food from the forest, with consequences for Indigenous peoples' well-being, health, nutrition, culture, and social networks [15–18]. Ongoing development underpins key drivers of this food transition, overlapping substantially with climate-change drivers, including deforestation, urbanisation, road construction, increasing agro-exportation, and pollution due to extractive industries that contribute to ecosystem and biodiversity loss [12,19,20].

Institutional responses focused on climate and food in the Amazon have had conflicted and complex relations with Indigenous peoples. In Peru, for example, government food-aid programs to reduce undernutrition have focused on supplying highly processed foods, which have been found to conflict with traditional food preferences; research found limited evidence of improvements in nutritional indicators among Indigenous peoples as a result of these programs, largely due to their misalignment with Indigenous cultures and customs [21,22]. Additionally, climate-change mitigation and conservation policies have made the Peruvian government increase the number of protected areas, limiting the access of Indigenous peoples to forest resources and aggravating Indigenous land dispossession [23,24].

Successful and effective place-based adaptation strategies to overcome food insecurity in a changing climate require meaningful engagement with—and recognition of—the centrality of Indigenous peoples' perceptions of the changes that they are experiencing [25,26]. Consideration of Indigenous peoples' perceptions, emotions, knowledge systems and worldviews, and the implications of all these factors for our understanding of climate-change impacts in food systems on biodiversity hotspots like the Amazon, is limited [27,28]. There is an urgent need for Indigenous peoples' voices and values to be taken into consideration and to recognise the emotional and psychological impact that climate change has on social and cultural values and ways of living [29–32].

To fill this gap, this research aims to identify, characterise, and assess Indigenous peoples' value-based perspectives on current and potential adaptation strategies and trade-offs related to food systems in a changing climate in the Amazon. We are specifically interested in Indigenous peoples' perceptions of how their food system is changing, why is it changing, what the consequences are of this change, and how/whether they are coping and responding effectively to it. Taking as our starting point their perceptions, we assess individual, communal, and societal determinants interacting with Indigenous food systems, following a collective health framework. This is done in collaboration with the Shawi Indigenous men of Nuevo Progreso, a community in the Peruvian Amazon.

2. Materials and Methods

2.1. Conceptual Framework

In this research, we first start with the perceptions of individual people about the changes they are currently experiencing in their food system in comparison with the past and their envisioned futures, seeking to identify what is worth preserving and achieving in the interaction with climate change and ecosystem changes [29,33]. By placing perceptions at the centre of our analysis, we seek to identify how people live and experience the world [34], privileging values that are subject to intangible or non-economic harm (e.g., sense of place, knowledge, dignity, self-determination) [30], as well as emotions affecting mental health and well-being related to climate change [35,36]. We do so in response to the recognition that Indigenous peoples' mental health is particularly affected by climate change, with well-documented evidence of ecological grief associated with current and future ecological, cultural, and identity loss [31,32,37]. Despite this emerging and growing literature, however, there are limited data on Amazonian Indigenous peoples [28].

Second, our approach is underpinned by the understanding that the foods people eat are determined and influenced by individual choices, rooted in family traditions and livelihoods, which in turn are embedded in societal and cultural contexts that condition an individual's relative autonomy [38–40]. Based on the collective health framework, this study is predicated on the understanding that there is a dialectical relationship between individuals and society structured according to three analytic dimensions: (a) societal: the socio-historical and political system at a local, national, and global level; (b) community: ways of living life embedded in social groups, cultural identities, and economic contexts; and (c) individual: the lifestyles and behaviours of individuals and the individual psycho-emotional conditions that influence health [39,40].

Finally, we additionally analyse how climate interacts with the three analytical dimensions that influence food systems (Figure 1) [3]. Vulnerability to climate change is assumed within this framework to be embedded and subsumed within complex and dynamic socio-ecological factors interacting across different spatial-temporal scales that put people at risk: where, how, when, and why certain groups are more vulnerable than others [11,41].

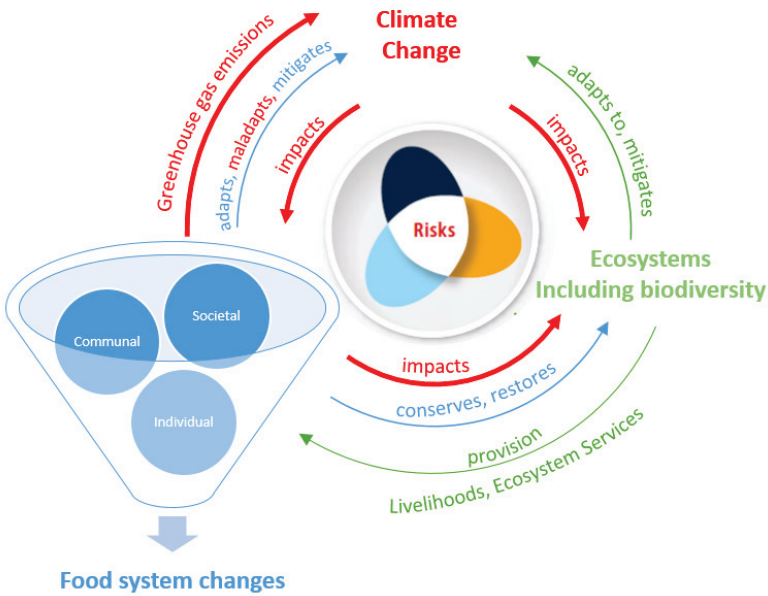

Figure 1. Conceptual framework of food systems and climate change. Source adopted from Pörtner et al. (2022) [1] and modified by the authors.

2.2. Study Area

We used a case-study approach to develop an in-depth and place-based understanding about the complexity of vulnerability and adaptation to climate change [42]. This research was possible due to an ongoing relationship between the Indigenous Health Adaptation to Climate Change Program "www.ihacc.ca (accessed on 7 December 2022)" and the Shawi people of the Peruvian Amazon that has lasted over 10 years. Our focus on the intersection of food, health, and climate was previously identified by community members as being one of the most pressing issues they face, and one that needs immediate attention in policy and research agendas [43–45]. Based on a household questionnaire in 2014, a study found that food insecurity and malnutrition levels among the Shawi were among the highest globally: 98% of Shawi households were food insecure, 66% of children had anaemia, 44% were stunted, 17% were underweight, and 19% of anaemic children had an overweight parent [22]. The aim of the study described in this paper is to complement current ongoing research with a deeper exploration of Indigenous peoples' narratives and perceptions of the changes experienced in their food system, reframing the research to centre Indigenous people's own voices more prominently alongside scientific research.

This paper focuses on a Shawi Indigenous community in the north-western Peruvian Amazon, Nuevo Progreso (Figure 2). This community is formed of three localities: Nuevo Progreso, Nuevo Yurimaguas, and Nuevo Belén. At the time of research in 2019, there were approximately 162 households (Nuevo Progreso: 97, Nuevo Belén: 50, and Nuevo Yurimaguas: 56). Nuevo Progreso did not have electricity, but Nuevo Belén and Nuevo Yurimaguas had solar energy. None of the communities had access to potable water. In 2010 the Peruvian government built the first road connecting Nuevo Progreso with the largest nearby city, Yurimaguas.

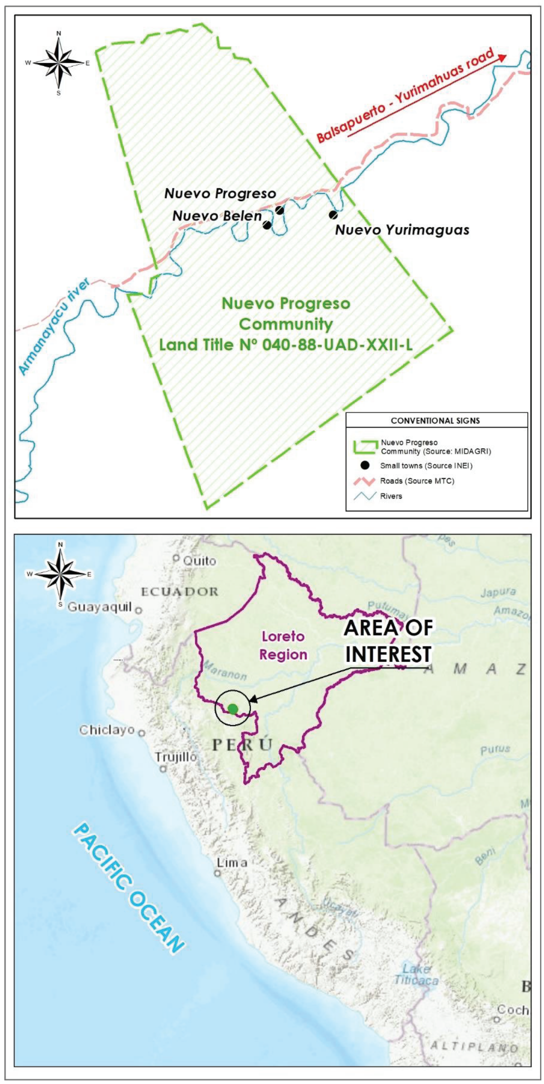

Figure 2. Map outlining the study area made by Paul Castro for this manuscript with ArcGis 10.8.1 software. Source: official database from the Ministry of Agriculture of the Peruvian Government (community limits), National Institute of Statistics and Informatics (town locations), Ministry of Transport and Communications (roads).

The Shawi people comprise more than 20,000 people living in 185 communities in the Loreto and San Martín regions [46]. As a result of the extended presence of Jesuits (1638–1768) and Christian missionaries (since 1945), there is Christian–Shawi worldview syncretism in their understanding of everyday life [47–49]. Gonzales-Saavedra [47] noted, however, that the Shawi transformed the belief that they were among the easiest Indigenous peoples to be Christianised into a survival strategy, designed to preserve their identity, culture, and traditional practices in colonial and postcolonial times.

Spiritualism is a cornerstone of the Shawi worldview and is key to understanding their relationship with nature [48,50,51]. Traditionally, the Shawi understand the world as being "round as a honeycomb wasp" with nine specific spaces ruled by sentient spirits (Figure 3). The third space is Nu´paru´te, where the Shawi people live in harmony with plants, animals, and the forest's spirits [50]. The Shawi understand that their relationship with every spirit (mountains, trees, plants, etc.) must be in balance to live well; diseases and ecological changes are, therefore, sometimes understood as a punishment for breaking this balance [47,48,50,52,53].

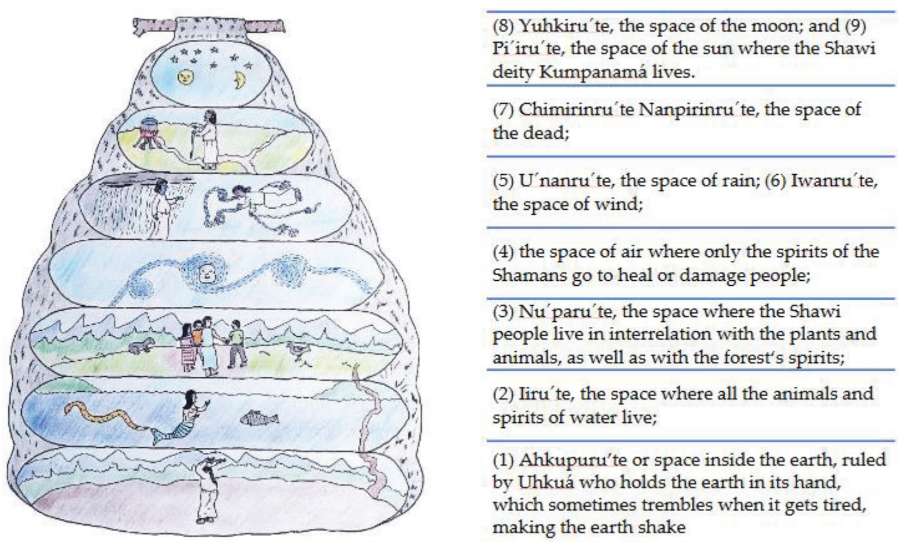

Figure 3. Shawi worldview, drawn by Alberto Chanchari from the Shawi people of Nuevo Progreso for this manuscript.

2.3. Methods

Fieldwork was conducted in Nuevo Progreso in January and February 2019 by the lead author (I.A.-R.), accompanied by a young Shawi man designated by the community as a gatekeeper following customary law. Research characteristics were debated and approved in a community assembly. Following the assembly, each participant had the right to decide whether to participate. By request of the community assembly, the community's name was not anonymised as a strategy to promote their historical records for future generations.

All interviewees were adults, heads of their families, and active participants in community assemblies. Our focus on men was not deliberate but rather emerged from the dynamics of community gender roles. In many Indigenous cultures in the Amazon like the Shawi people, women are not allowed to participate in public spaces, and they are less likely to attend schools or to speak Spanish in comparison to men [54].

We undertook 23 semi-structured, in-depth interviews with Shawi men, 5 participant-observation activities, and a male-only focus group. Interviews were conducted by I.A.-R. primarily in Spanish, as preferred by participants, with translator assistance when questions were unclear. Interviews were primarily located in Nuevo Progreso (n = 14), with some in Nuevo Belén (n = 4) and Nuevo Yurimaguas (n = 2). In Yurimaguas, the closest city, we interviewed the community's school representative and two representatives of the Shawi Indigenous organisation (n = 3). Only three interviews were not recorded, respecting the interviewees' decision.

The Interviews covered issues related to food and health changes. First, we asked about food consumption on the day of the interview and the week before. Men were asked to compare their current diet with their childhood diet. We also explored Indigenous knowledge to discuss important and dominant foods consumed and how access and consumption had changed over time. We asked participants to explore and characterise their perceptions of the drivers of these changes, considering the three analytical dimensions of the conceptual framework: individual, collective, and societal drivers of change. When weather variability was not mentioned, we probed further to inquire whether/how weather interacts with the changes they are experiencing around food. The last part of the interview focused on visions of the future, both desired and foreseeable. Regarding their desired future, we asked participants to choose three things they would change/improve in their community if they had the power to and to explain their reasoning. In the case of the foreseeable future, we asked them to describe what the community might look like in 5 and 10 years if things continued without intervention. If food was not mentioned, we asked directly about what they might eat in that future and how activities around food were perceived to have evolved. In many cases, discussions around food led to a broader discussion on well-being and health. These discussions also included a focus on spiritual dimensions.

I.A.-R. joined and observed food- and health-related activities with community members, including participation in fishing and gathering fruits from the forest, family farming and crop production, cooking wild food from hunting, preparing Masato (a local beverage), and preparing plant-based medicines. During the field research, a diary was kept to document activities, feelings, and observations, which served as an additional data source for our research findings.

Following the initial phase of interviews, a focus group was conducted with men (n = 12) to collectively discuss overall results. We first asked participants to identify food-related activities, and then to explain how they had changed over time and how they thought these activities would evolve. Additionally, we explored characteristics of Indigenous knowledge by asking them about abilities that they felt the Shawi people have that other people do not. We also explored their approaches to seeking medical attention.

All recorded interviews and group discussions were transcribed verbatim and hand-checked for accuracy. This process also included making a note of the speaker's emotions, something that can be lost in audio transcription. Here we followed the principles of thematic analysis [55]. For this research, inductive codes (data-driven) were created (e.g., changes in hunting), which were then organised into broad theory-driven families of code to sort findings (e.g., food-system changes, climate-change perceptions, envisioned futures). The coding was completed using nVivo data-analysis software. All results met data saturation (i.e., were reported by all or most respondents) or were otherwise reported explicitly as divergent or outlier findings.

2.4. Positionality

The fieldwork and primary analysis were conducted by I.A.-R., a Quechua female based at a UK university, with the help of a young Shawi male research assistant. We acknowledge that the work's focus on men may have biased participant responses and researcher interpretations of the results. This research was intentionally framed to focus on the voices of Indigenous Shawi men to minimise bias from researcher interpretation. Our results, therefore, are primarily descriptive, aimed at centring the voice of Shawi men with limited analytical interpretation or filtering. Complementing this, in the discussion we undertake a more interpretive and researcher-driven analysis consistent with scientific axioms and epistemology.

3. Results

3.1. Individual Dimension

All interviewers highlighted that the Shawi food system is based on three sub-systems, composed of wild food from the forest, sourced through hunting, fishing, and gathering; food cultivated through farming; and food acquired from external sources, from shopping or government aid (Figure 4). Food scarcity has become a significant challenge in everyday life for this group and is directly associated with reductions in wild foods available from the forest. Most interviewees explained that they usually eat only once a day. To cope with hunger, the Shawi constantly drink Masato, a fermented cassava drink that even small children consume, which makes them "feel full".

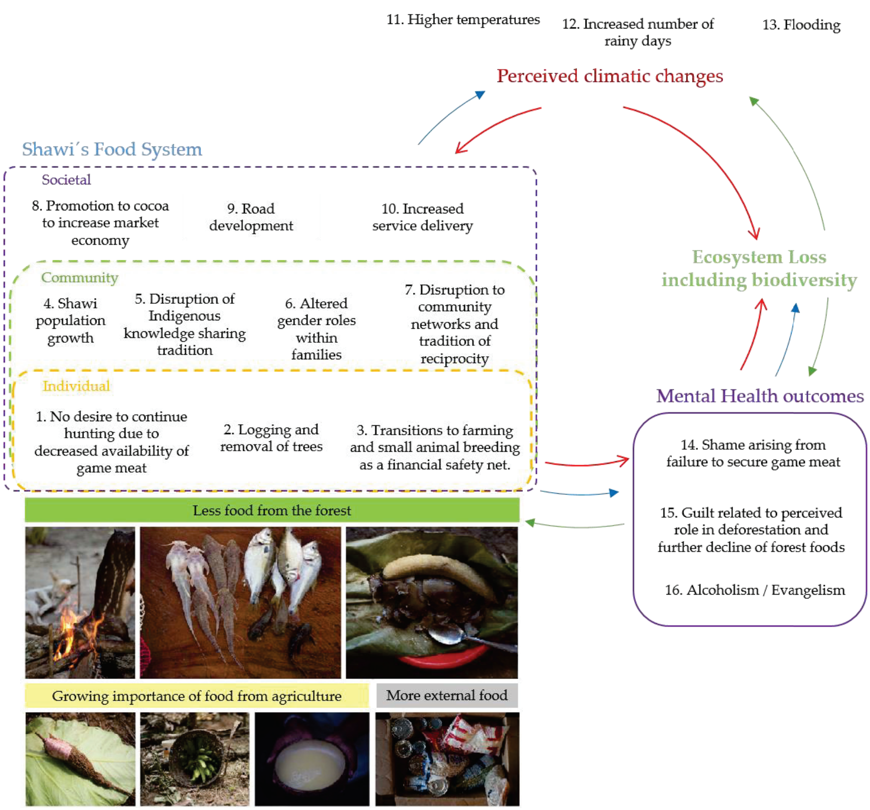

Figure 4. Shawi men's narratives of changes of their food system. Source: pictures taken by Matthew King for the IHACC program.

Forest foods are still the most preferred but also the scarcest; fish and game meat are highly preferred, although they are largely acquired from external sources. Food from farming, such as cassava or plantain, is the most readily available, but preference for these foods is declining since they are often the only thing people eat for many days. Hens have also been identified as a preferred food. Other domestic animals and crops like cocoa are less preferred among the Shawi and are considered, rather, as a means to obtain food from the market.

"Our women tell us to go find something to feed our kids. (. . .) sometimes when I go hunting, I cannot find anything, I even go further in the forest and nothing! Then I have to come back late, and I feel upset . . . You can no longer find anything here." –Shawi adult.

Many men recalled that the last time they had hunted large animals such as deer or collared peccary was several years before. Nowadays, their perception is that the difficulties associated with hunting do not depend on their skills but on luck. Most men explained that they no longer hunt because it requires dedicating whole days to going far into the forest, and even then it is difficult to find animals. Many men prefer not to go hunting to avoid the potential embarrassment of returning home without any prey (1 in Figure 4). The inability to hunt regularly and effectively affects Shawi men's well-being.

Nowadays, men tend to carry a shotgun in case they find small wild animals such as partridge (*Cripturellus cinereus*) while farming. However, hunting requires cartridges only available in the nearest city, generating a dependency on money, and making it even more challenging to continue hunting. During research visits in Nuevo Belén, one of the interviewees captured a small peccary but reported that it was only by luck because, although he did not have a cartridge and so could not shoot it, the small bird was with its mother and he was able to grab the baby.

With less availability of game meat, the Shawi diet relies on fish (fresh or salted) as the main protein source. However, interviewees noted that fish is no longer obtained from the river but is increasingly acquired from external sources. All participants explained that there are only small fish available in their territory, so they prefer to buy from vendors on the road from the city of Yurimaguas. External purchasing of fish could reflect a strategy to recover local fish stocks but was mainly reported to reflect resignation in the face of meagre fishing in local waters. Money to buy fish came from selling domestic animals, crops, or seasonal wild fruits.

Given the absence of game meat and fish, food predominantly coming from the forest included wild fruits, mushrooms, edible plants, and small animals like suri, a worm that lives in the aguaje or palmito trees. However, many strategies for collecting forest food involve cutting down trees, which further reduces forest-food availability (2 in Figure 4). For example, to obtain aguaje fruit, men must cut down an entire tree. This fruit is used to complement meals and has recently become an important source of seasonal income. Thus, whenever a family needs protein, they go to the forest where an aguaje tree has fallen, peel a part of the stem, and remove the suri worms. Given the increased need for cash to purchase external foods, many aguaje trees have been cut down, leading to worries about the future availability of the aguaje fruit and suri worms.

"We have quantity in the forest, it is our natural farm, there is a lot of wealth there! (...) now there is less because sometimes people are destroying a lot to sell at the market. Our people are doing it, and it is no longer like before, (. . .) they chop the trees down, and they are killing them. For it to grow up, how many years? (. . .). Our next generation, what are they going to eat now?" –Shawi adult.

Due to the decline of forest food, Shawi men are changing their livelihood activities. All participants recognised that because the forest has changed so rapidly, they now rely more heavily on farming and domestic animals for food (3 in Figure 4). Farming combines subsistence crops with cash crops, such as cocoa, to generate income. Subsistence crops are traditionally cassava and plantain and are available all year. These tubers are sometimes sold when a harvest is abundant. It is now easier to travel to Yurimaguas given the recent establishment of a road to the city, and men reported selling crops at the market and using the income to purchase other items. Men also reported growing corn for sale and feeding hens. Bred domestic animals, such as hens, pigs, cows, guinea pigs, and sheep, are perceived as important complements to the Shawi diet. Particularly important for the men was the fact that this allows them to add eggs to their diet, albeit in low quantities. Additionally, selling domestic animals was considered a safety net for emergencies when cash is needed to pay for food, school supplies, or medical care.

Many men perceived that the solution to food scarcity is tied to learning new ways to produce diverse crops, building fish farms to have reliable access to this food, and improving their skills in breeding domestic animals. They reported high expectations from formal schooling to supply this knowledge to younger generations, thereby promoting more reliable access to food.

> *"I told my son: 'you must work, you must make a fish farm so that you can feed your family'. I told him that, and asked him to raise chickens, pigs (. . .) There are no more animals in the forest, no more fish either. The forest will not recover. New generations will not know how to find food in the forest (. . .) I told them to raise domestic animals so they could eat. I raise my children telling them that."* –Shawi adult.

Logging in the Shawi community also affected forest-food availability (2 in Figure 4). Men explained that they allowed external loggers to enter the community as a source of income to purchase food and school supplies and pay for medical costs or transportation to the nearest city. They recognised that logging contributes to "making animals flee" due to noise and disruptions to their natural habitat, making it harder to hunt game meat. However, many Shawi men still depend on logging, as it provides a substantial income to feed their families, exceeding the amount obtained by selling farm animals or wild fruits in small quantities at the market.

> *"On Sunday I had a little money; the loggers paid me 200 PEN. And I said, 'I am going to buy soap'; we do not have soap and I walked with my little daughter. So I bought my soap and there was a little money left. Then I bought a kilo of collared peccary; 25 soles buys a kilo of collared peccary in Yurimaguas (. . .). Nowadays this is a luxury we can only afford a few times."* –Shawi adult.

3.2. Community Dimension

All the participants reported that they believe the main reason for a decrease in forest-food availability is their own population growth, articulating that there are now more people to feed. This, they suggested, is resulting in higher demand on forest resources, which in turn incentivises them to take logging deals for cash income to supplement diets as well as cut down trees to sell fruits, all of which are combining to exacerbate a decline in forest access and wild-food availability (4 in Figure 4). This reinforces their perception that they are the cause of the changes they are experiencing and are active agents driving the decline in food from the forest. While assuming responsibility as primary drivers of changes in the availability of forest food, Shawi men also articulated a desire for their community to become more urbanised, supporting continued population growth. The rationale behind this was linked to the expectation of population growth leading to improved access to government services in their communities, such as electricity, drinking water, health services, and education. However, they recognised that this would also mean the continued decline or disappearance of the forest-food sub-system.

> *"I want the population to grow. There will be more people, more young people, more children. (. . .) There will be less game meat, but what can we do? (. . .) There is not going to be anything anymore (. . .). This little girl would not know the taste of agouti or deer . . . . This is what is happening now. My son has eaten deer and collared peccary, but this little girl has never, and she won't."* –Shawi adult.

The decline of forest food plays a central role in the transmission of traditional knowledge (e.g., hunting and fishing techniques) from Shawi men to younger generations (5 in Figure 4). Male disengagement from hunting is disrupting the knowledge sharing that the Shawi have preserved as a critical element of their cultural heritage, in which children would go with the family's men to hunt and learn to differentiate animal tracks, make hideouts, and shoot. Additionally, because hunting now requires more time, it conflicts with school attendance, making it more challenging to continue the intergenerational transmission of knowledge. During research visits in Nuevo Progreso, for example, we observed two boys going out with a slingshot every day to hunt birds. Only once did we observe the smallest of the boys catching a bird, allowing him to provide breakfast for his family (Figure 5). It was a very proud moment for the family, as they explained that the only knowledge commonly transmitted to younger generations today is how to use a slingshot.

Figure 5. The day A (9 years old) proudly caught a bird with his slingshot to feed his family. Source: picture taken by I.A.-R. and shared with the permission of A and his parents.

Second, the reduced availability of forest food that has led to male disengagement with hunting has also altered gender roles within Shawi families (6 in Figure 4). Changes and disruptions in the availability of forest food have meant that men can no longer fulfil their traditional role as hunters, leading many of them to transition to market-related activities (farming and logging) to provide food for their families.

Third, the declining availability of food from the forest was reported to be affecting community networks traditionally based on reciprocity through food sharing (7 in Figure 4). Nowadays, since there is negligible game meat and the population has grown, it is difficult to share food with others, altering the traditional community customs of caring for vulnerable people, particularly elders. For example, during our visit, some interviewees reported the recent death of an older woman whose husband had died and who was dependent on her children for food. With less food in the community, her children could not share much because they had their own families to feed. The older woman presented general discomfort or malaise and did not have enough energy to leave her bed or eat. Some men believed that the woman died because of "revenge disease" or "damage," a disease caused by the envy of others; however, one person suggested that it was hunger and not "damage" that killed this person.

3.3. Societal Dimension

The Peruvian government has played a role in the food-system changes that the Shawi men are experiencing. In farming, cocoa cultivation has been extended in the communities because it is part of the regional government's plan to improve connections to the market economy (8 in Figure 4). Interviewees made it clear that families received free seeds, ploughing tools, and technical support. The cocoa project was advertised in the Shawi communities as a way to overcome poverty and promote economic inclusion. Many Shawi men reported that this program was unsuccessful since they were unable to obtain a fair income to cover their monetary needs to buy food and other items. They specified that chocolate factories in the region only buy cocoa in large amounts, which requires Shawi men to sell cocoa to intermediaries at a cheaper price.

Additionally, changes in the forest have expanded and increased in recent years because of logging, facilitated by the completion of a road connecting Balsapuerto to Yurimaguas in 2016, constructed by the Peruvian government to promote road connectivity in the Amazon (9 in Figure 4). Many Shawi men were pleased with the road because it made selling crops in the market more accessible and created opportunities for tourism. It was unclear whether they associated road construction with impacts on the forest; there was, however, general resignation that they had very little agency in influencing development trends. Along with logging, another dominant activity in the area attributed to the road was the development of papaya plantations. Interviewees mentioned that when the road was built, some men had rented their land to papaya plantations. However, the plantations moved further into the forest in search of more adequate land and so the community soon lost this income stream. During our visit, papaya plantations were located near Balsapuerto. Logging and papaya plantations were perceived to be compounding changes in forest cover, affecting the availability of game meat for the Shawi.

Despite a push by the government for family planning [56], our research also showed that population growth is indirectly encouraged by the Peruvian government. For Shawi men, population growth is perceived as the only way to mobilise governmental provision of social services to the community, such as electricity, clean water, and schools (10 in Figure 4). For example, during our visit, authorities from Nuevo Yurimaguas reported that they had persistently requested that provincial authorities provide an elementary school in the community, as children struggled to cross the river alone to attend the closest school. They reported that the authorities based their decision on the number of local pupils, and Nuevo Yurimaguas did not meet the required minimum, so they were denied this provision. In this sense, population growth represents a key strategy among the Shawi to increase their influence on the government's service planning and provision.

3.4. Perceived Climatic Changes

Climatic conditions and changing weather exacerbate Shawi food-system vulnerabilities by affecting food obtained from the farming and breeding of small animals. Shawi men observed that temperatures are increasing, impacting their regular activities (11 in Figure 4). Higher temperatures, for example, reduce the time men can dedicate to farming because of the absence of cool zones to seek shelter and rest. Temperatures are also changing the timing of farming activities, making it preferable to work early in the morning when the heat is considered more bearable. Furthermore, Shawi men reported that increasing air temperatures are associated with increasing water temperatures in rivers and streams. Some men reported that the increase in water temperatures also affects the availability of fish.

Many men reported observing precipitation changes, with an increase in the number of rainy days in winter (12 in Figure 4). When it rains, they do not go out to hunt and prefer not to farm, since they feel that they could get sick. Additionally, rain increases streamflow, which, they reported, makes it more challenging to fish and difficult for them to manoeuvre canoes, since the river can rise rapidly under these conditions. A month before our visit, a woman and her small children died trying to cross the river at night with a canoe after heavy rain.

Shawi men recognised that since 2014, flooding had been a recurrent event affecting them every two years (13 in Figure 4). Many men explained that flooding mainly affects crops and small animals like hens, generally considered their safety net to cope with rapid changes in their food systems. Flooding in the study area can last several hours, damaging food sources. Many men recalled losing their breeding animals, especially hens, and losing corn and cassava crops. Flooding has motivated Shawi men to identify the most at-risk places in the community so they can avoid planting in those areas. Nonetheless, higher-altitude areas are scarce, and only some areas are considered suitable for relocation and farming.

> *"When it floods, sometimes it takes our things (. . .). In the first flood, it was 2014, that time was at dawn, 1 am, so it was flooded when we were sleeping, so many chickens were taken."* –Shawi adult.

Participants reported that flooding had caused changes in the river, leading to the loss of land on the riversides and putting houses and farms close to the river at risk. Some of the men suggested that they needed to plant forest species such as yacushimbillo, or guava tree (*lnga marginata Willd.*), to reduce soil erosion on riverbanks; however, they did not have sufficient resources.

3.5. Mental-Health Implications

Changes in the Shawi food system were also reported to affect Shawi men's well-being and mental health. Within the individual dimension, no longer being able to hunt creates feelings of shame (14 in Figure 4) and guilt (15 in Figure 4), which has increased alcohol consumption (16 in Figure 4) in communities like Nuevo Progreso. During fieldwork, we frequently observed men drinking distilled alcohol at any time of the day. In Nuevo Belén and Nuevo Yurimaguas, Shawi men shared that many of them had decided to turn to evangelism because they needed order in their life to stop abusing alcohol (16 in Figure 4), reflecting the mental-health implications of food-system transitions. Within the community dimension, the perception that their own population growth is the main driver of the reduction of food from the forest is a source of guilt. For Shawi men, the forest is a space that connects the physical with the spiritual world, where people are interdependent with the forest. Any disruption in the plants and animals is often attributed to people, as in this case, where they positioned themselves as the cause of reduced availability of forest food.

Perceptions suggested that changes in forest-food availability are causing an increase in anaemia and malnutrition among the Shawi. Many interviewees reported that they knew about anaemia because they attended a public health centre one hour away on foot. Services at the health centre are only available in Spanish and, according to the interviewees, are not provided respectfully. Iron tablets are given freely to treat anaemia; however, many participants reported that they did not take them. Men recalled that when they visited the public health centre, the health worker told them to hunt more, increasing pressure and burden on the men to hunt despite challenging conditions. Furthermore, rain also interferes with attendance at health centres for nutritional check-ups due to difficult travel conditions. The men explained that treating anaemia at health centres was a long process, and they were given appointments that they were sometimes unable to attend due to heavy rains. They reported that health workers did not recognise the legitimacy of this reason for absence and took it as disrespect or imprudence.

> *"The physician does not recognise reason like weather or increase of water streams. How can we go to the hospital if it's a bad day? When the river is growing, I'm not going to go to the health service, I have to respect the river . . . The doctor wants you to come even when there is rain. He does not understand because in the city it is different. In the city you can go when it is rainy because there are motorbikes, there is public transport but here in the community, you have to walk, so you can't get there, it's very different."* –Shawi adult.

Spirituality is central to the Shawi perceptions of well-being, health, and nutrition. Despite the Peruvian government's promotion of an intercultural approach to healthcare services [57], the Shawi worldview and cultural characteristics are widely considered to be neglected in Peruvian formal health systems. Interviewees expressed a preference for community healers (vegetalistas) to identify the origin of their ill health. The vegetalista then suggests that people visit a healthcare centre when they recognise a disease that they cannot treat effectively. Where an illness is believed to be treated locally, they produce medicine based primarily on local plants, sometimes mixed with paracetamol or other medicine they are familiar with and feel may be beneficial. Additionally, in Nuevo Progreso, people reported seeking the services of shamans for illnesses related to the soul.

4. Discussion

Consideration of Indigenous peoples' perspectives of their food system in relation to climate change has shown clear connections between (mal)adaptation strategies and the actions of the Peruvian government, as well as the consequences for their mental health. Our results indicate that Shawi men have been forced to shift from relying on forest foods towards agriculture to provide for their families and maintain their food sovereignty.

In doing so, Shawi men recognise a need for new skills and livelihood strategies for younger generations, expressing hope that government-provided education will provide them and, in doing so, overcome undernutrition and hunger. The desire to obtain new knowledge through public schooling and other public services has driven an increase in Shawi population growth while at the same time contributing to further deforestation in the Amazon, in turn increasing biodiversity loss.

Previous research highlighted that Shawi population growth and desire for education might reflect maladaptive strategies that increase pressures on the forest, increase food insecurity, and constrain adaptation to climate change [45]. However, Shawi's male perspectives expressed in our study indicate that population growth is an intentional response to systematic and historical exclusion perpetuated by the Peruvian government. The government's logic behind service delivery is perceived not as rights-based but situated in inflexible economic efficiency: the worthiness of a community to receive educational services is based on the number of pupils, regardless of differential access and unique geographical or cultural contexts. Despite Shawi men acknowledging that a growing population is detrimental to forest and biodiversity conservation, it is considered to be a necessary step in their strategy if they are to address their current food scarcity, creating a circle of guilt and shame affecting Shawi men's well-being and mental health. Shawi male participants provided a vivid conceptualisation of Indigenous knowledge and strategies that are dynamic, adaptable to change, practical, and often reflecting conflicting priorities.

The analysis and consideration of Indigenous peoples' perceptions within climate-change research draw on growing epistemological calls to take into account the diverse ways in which people and institutions observe, understand, value, and respond to climate change [58–61]. This is important for navigating conflicting development perspectives between communities and policymakers. Our results show that government programs have been focused on producing food to sell at the market (i.e., cocoa), conditional cash transfers, or food-aid programs based on external food sources to reduce food insecurity in Indigenous communities. However, a better way to address these issues might be to change how services are delivered in rural communities. The government´s development and adaptation strategies are embedded in capitalist and neoliberal approaches, which in many cases are unsuited to those who perceive the world differently [58]. Converging these different value systems with an intercultural approach should be a priority in food and climate policy. Consideration of pluralism and acknowledging other worldviews should therefore underpin the conceptualisation of what is meaningful for people and worth being preserved, their envisioned futures, and the best strategies to achieve these futures [29,30,58].

Attention to mental health is needed, in particular given the close relation Indigenous peoples have with place and how rapid socio-ecological changes are causing compounded emotional trauma that reflects—and emerges from—the Shawi worldview. Nu´paru´te is the space where the Shawi people live in harmony with plants, animals, and forest spirits [50]. Consequently, any ecosystem and biodiversity disruption is often associated with their own actions, generating feelings of guilt. Acknowledging the role that worldviews play in driving mental-health outcomes is critical to understanding Shawi food transitions. New research has called attention to the impacts of climate change on mental health, especially emotional responses related to ecosystem loss, which have been conceptualised in the literature as "ecological grief" [31]. This loss is linked to the value people place on the things they are dispossessed of and for which there can be no substitute in the future [29]. This is particularly important in Indigenous contexts such as that of the Shawi because Indigenous peoples often perceive nature as sentient. The emotional trauma expressed by Shawi men in our study arising from the loss of forest food is a manifestation of their worldview. This reflects the grief associated with anticipated future losses of species, their knowledge of accessing food, and their role in the Shawi's traditional social and cultural practices around food, as well as their identity.

Consideration of Indigenous peoples' worldviews also broadens research attention to the spiritual dimension of the forest by reinforcing interdependency relationships: the Shawi depend on the forest for survival, and the forest depends on Shawi traditions to be preserved. Similarly, Indigenous peoples in Ecuador have demanded an understanding of the Amazon as Kawsak Sacha, or living forest. This concept challenges the perception of the Amazon as uninhabited and untapped, full of resources open for exploitation, and of Indigenous peoples as guardians of "an imagined and mythical space, but as reproducers of human and non-human relations and defenders of a territory that is crucial for their lives" [62]. Concepts like Kawsak Sacha or Nu´paru´te question the mitigation of climate-change policies by calling for a reconceptualisation and broadening of their understanding of the Amazon.

5. Conclusions and Recommendations

This study highlights the importance of ecosystem conservation for addressing Indigenous food insecurity and climate change in biodiversity hotspots like the Amazon. By understanding Shawi men's perceptions of their food system and how important the forest is for their well-being, we conclude with recommendations for effective adaptation strategies. First, there is a need to re-evaluate the way the Peruvian government is approaching service delivery in Indigenous Amazonian communities, particularly the extent to which it may be increasing deforestation and contradicting efforts to mitigate climate change by indirectly promoting population growth. Second, adaptation initiatives should prioritise agriculture, as Shawi men are actively transitioning towards livelihood dependence on agriculture. However, this activity leaves them highly vulnerable to climate change. Finally, the mental-health implications of current food-system changes and biodiversity loss in Indigenous peoples require urgent attention.

This study also highlights priorities for further research moving forward. First, given the emphasis placed on education by Shawi men as a key component of their envisioned future, further research could evaluate how public schooling is responding to Indigenous peoples' expectations vis a vis food insecurity and climate change. Second, research targeting Indigenous women and youth is critical to complement the presented results. Finally, interdisciplinary research is needed that complements the narratives of Shawi men with an assessment of competition-resource tenure, distribution systems, and foraging behaviours in the past and the present versus agricultural work.

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Data Availability Statement: The datasets generated and analysed during the current study are not publicly available due their sensitive nature, but an anonymised version of the interviews (in Spanish) are available from the corresponding author on reasonable request.

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Article

Time-Varying Elasticity of Cyclically Adjusted Primary Balance and Effect of Fiscal Consolidation on Domestic Government Debt in South Africa

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Abstract: This paper investigates the impact of the time-varying elasticity of the cyclically adjusted primary balance (CAPB) and fiscal consolidation on government debt. The time-varying parameter structural vector autoregression (TVP-VAR) model is used on a time series of data from 1979 to 2022. The contribution of this paper is on the understanding of the impact of fiscal consolidation on domestic government debt and the need to use time-varying elasticity when calculating the cyclical adjusted primary balance to provide a more accurate representation of discretionary actions taken by fiscal authorities. It is found that there is more variation in the CAPB with time-varying elasticity than with constant elasticity. Constant elasticity is not effective in capturing fiscal consolidation episodes, and time-varying elasticity is a better alternative. There is evidence that fiscal consolidation increases domestic government debt. The shocks of fiscal consolidation through government expenditure cuts reduce domestic government debt in the long run, while taxes increase domestic government debt. It is recommended that fiscal authorities use fiscal consolidation to reduce government expenditure that is related to inefficient expenditure. In the event of government expenditure, this expenditure needs to be in productive sectors of the economy that will bring about an increase in revenue rather than an increase in the tax rate. Given the result, a tax increase should be something that fiscal authorities are not using in the effort to stimulate economic growth or reduce domestic government debt.

Keywords: fiscal consolidation; domestic government debt; cyclically adjusted primary balance (CAPB); time-varying parameter structural vector autoregression (TVP-VAR)

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1. Introduction

The debate on fiscal consolidation and measures has been of interest to the Organisation for Economic Co-operation and Development (OECD), the Internal Monetary Fund (IMF), and other scholars (Alesina and Perotti 1995; Alesina and Perotti 1997; Alesina et al. 2015; Yang et al. 2015) among other. However, there is no agreement on the impact of fiscal consolidation on government debt. The thinking around fiscal consolidation is that government expenditure cuts and tax increases will result in a fall in government debt. This is because forward-looking economic agents will anticipate a reduction in tax and interest rates. This will increase permanent income, crowd-in investment, increase economic activities, and result in higher tax collection that can be used to reduce government debt (Alesina and Ardagna 2010; Mankiw 2019). One of the broad measures of discretionary government intervention to reduce the government debt that defines fiscal consolidation episodes is the cyclically adjusted primary balance (CAPB). This measure is concerned with the identification of discretionary fiscal policy changes in taxes and government expenditure by filtering out changes due to economic fluctuations in taxes as well as government expenditure (Alesina and Perotti 1995).

There are five main developments of the CAPB. The first is the primary approach, concerned with differences in government expenditure and taxes to find fiscal consolidation (Alesina and Perotti 1995). The second is the Blanchard approach, which considers cyclical components (government expenditure and tax) in the CAPB to find fiscal consolidation (Blanchard 1990). The third is the asset price approach, which filters out the asset price impact on government revenue and expenditure (Yang et al. 2015). Fourth and fifth are the OECD approach as well as the IMF approach, which uses deviation from the output gap from government expenditure and taxes to find fiscal consolidation. Both the OECD and IMF approaches use the constant elasticity of government expenditure and taxes to reflect the responsiveness required to find fiscal authorities' actions or the discretionary actions of fiscal authorities that can be attributed to fiscal consolidation espisodess (Zhang et al. 2022).

The OECD and IMF assume constant tax revenue and government expenditure elasticities throughout the analysis in the compositions of the CAPB (Mourre et al. 2013). These elasticities are used to identify discretionary actions by fiscal authorities that are to reduce domestic government debt through an increase in taxes and a cut in government expenditure. This paper identifies this as a problem because constant elasticity in the CAPB does not account for responsiveness to changes in these economic variables over time. The applicability of constant elasticity in government expenditure does not capture well government interventions over time or the fiscal framework that may be used to reduce domestic government debt. On the other hand, there is an economic dynamic in government revenue, and constant elasticity ignores every change in the tax system and taxes. In this regard, the assumption of constant elasticity in tax revenue and government expenditure categories by the OECD and IMF approaches can have significant biases. This leads to the incorrect composition of the CAPB as well as the identification of fiscal consolidation episodes.

In South Africa, domestic government debt was high at a rate of 71.72% in 2021 (SARB 2022). This rate of 71.72% is above the 60% threshold advocated by Southern African Development Community (SADC) countries, of which South Africa is one (Buthelezi and Nyatanga 2018). On the other hand, in 2014, the Financial and Fiscal Commission (FFC) recommended more fiscal consolidation stances to restore the fiscal position and reduce government debt (BR 2014). The FFC recommendation outlined that "Fiscal consolidation can no longer be postponed. Ensuring continued progress toward a better life obliges the government to safeguard public finances by acting within fiscal limits that can be sustained over the long term. To do otherwise would risk exposing the country to a debt trap, with damaging consequences for development for many years to come" (MTBPS 2014). The question this paper poses is as follows: what is the difference between the CAPB with time-varying elasticity and time-invariant elasticity as a proxy for fiscal consolidation? The second concern of this paper is the impact of fiscal consolidation on government debt in South Africa. The time-varying parameter structural vector autoregression (TVP-VAR) model following Nakajima (2011) was used on data from 1979 to 2022. The economic variables used were domestic government debt, money supply, total government revenue, debt service ratio, and fiscal consolidation, proxied by the CAPB, among others.

The significance of this paper lies in its contribution to the understanding of the impact of fiscal consolidation on domestic government debt and the need to use time-varying elasticity when calculating the cyclical adjusted primary balance (CAPB) to provide a more accurate representation of discretionary actions taken by fiscal authorities. The paper highlights the limitations of using constant elasticity when calculating the CAPB, which can result in an inaccurate representation of discretionary actions taken by fiscal authorities. The paper also demonstrates the significant impact of fiscal consolidation on government debt levels, particularly in the short term, and the need for careful planning and consideration of potential negative impacts on government debt levels. The paper provides important policy implications and recommendations for future research and policy decisions, including the need for the IMF and OECD to adopt time-varying elasticity when calculating the CAPB, the importance of examining the short-term benefits of fiscal consolidation, and the need to consider the impact of fiscal consolidation on other economic variables beyond government debt levels. The paper contributes to the ongoing debate and discussion surrounding fiscal policy and its impact on government debt levels, providing important insights for policymakers and researchers alike.

It is found that the CAPB calculated with constant elasticity has a lower period compared with that calculated with time-varying elasticity. There is less variation in the CAPB with constant elasticity, while the CAPB with time-varying elasticity reflects more variation (more discretionary action) and covers 43 years. The IMF reflects that the CAPB has a non-upwards trend that reflects increasingly less discretionary action. However, when time-varying elasticity is accounted for, fiscal consolidation episodes are found. There is a 56.26% variation in the CAPB with time-varying elasticity, and there is a 2.36% variation in the CAPB of the IMF data. Fiscal consolidation government expenditure is found to increase domestic government debt, while tax-increase fiscal consolidation results in a slight fall in domestic government debt and quickly return to equilibrium. It is recommended that the IMF and OECD move away from constant elasticity and start to utilise time-varying elasticity to capture the fiscal consolidation variation over time. Fiscal consolidation has no positive impact on reducing domestic government debt. Fiscal authorities need to use government expenditure in productive sectors of the economy that will bring about an increase in revenue rather than an increase in the tax rate, as advocated in the fiscal consolidation policy. Moreover, fiscal authorities need to develop a tax system that generates optimal tax revenue with the adjustment of the tax rates.

The rest of this paper is outlined as follows. First, Section 2 outlines a review of fiscal consolidation measures. Second, Section 3 outlines an empirical review measure of fiscal consolidation. Third, Section 4 discusses this paper's methodology. Fourth, Section 5 discusses the empirical results. Finally, Section 6 outlines the conclusion of the paper.

2. Review of Fiscal Consolidation Measures

Scholars have been interested in how to measure fiscal consolidation, which reflects discretionary government intervention to reduce government debt (Alesina and Perotti 1995; Romer and Romer 2010; Leigh et al. 2011). The use of the CAPB has been proposed to identify discretionary fiscal policy changes in taxes and government expenditure by filtering out changes that are due to economic fluctuations (Alesina and Perotti 1995). There are five main developments of the CAPB, outlined below.

2.1. Primary Approach

The primary approach rationale is that the CAPB can be presented by the changes in the primary deficit as advocated by (Alesina and Perotti 1995). The primary approach is shown in Equation (1).

$$\Delta CAPB_t = (TGR_t - G_t) - (TGR_{t-1} - G_{t-1}) \tag{1}$$

where TGR_t is total government revenue, G_t is total government expenditure, and t reflects the time. The thinking is that a positive difference between the current budget balance $(TGR_t - G_t)$ and the previous budget balance $(TGR_{t-1} - G_{t-1})$ reflects the discretionary actions of the government.

2.2. Blanchard Approach

Blanchard (1990) notes that economic variables that show changes or deviation from full employment are critical in the calculation of the CAPB. Blanchard (1990) points out that unemployment triggers cyclical movement in taxes and government expenditures. Unemployment changes were proposed to be filtered out in the CAPB calculation to find discretionary changes in fiscal policy that can be attributed to fiscal consolidation. The primary approach was developed into the Blanchard approach, as shown in Equation (2).

$$\Delta CAPB_t = (TGR_t - G_t(UNE_{t-1})) - (TGR_{t-1} - G_{t-1}) \tag{2}$$

where UNE_{t-1} is unemployment for the prior year and other economic variables are as indicated above. The drawback of this approach is that unemployment in a country may be affected by external factors.

2.3. Asset Price Approach

The asset price approach affects the CAPB and needs to be filtered out in the CAPB. This is because a boom in the stock market improves the CAPB by increasing capital gains and cyclically adjusted tax revenues (Yang et al. 2015). The asset price approach advocates that asset prices need to be filtered out and fiscal authorities need to consider time trends as well as unemployment, as shown in Equation (3).

$$G_t = \alpha_0 + \alpha_1 Tremd + \alpha_2 UNE_t + e_t \tag{3}$$

where *Tremd* is the government expenditure and e_t is the residuals. To find the primary adjusted government expenditure for business cycles and changes in unemployment, Equation (4) is followed.

$$G_t(UNE_{t-1}) = \alpha_0 + \alpha_1 Tremd + \alpha_2 UNE_t + e_t \tag{4}$$

where $(\alpha_0,\ \alpha_1,\ \alpha_2)$ are estimated coefficients and the asset price index is added as in Equation (5).

$$TGR_t = \alpha_0 + \alpha_1 Tremd + \alpha_2 UNE_t + \alpha_3 Assetprice_t + e_t \tag{5}$$

where $Assetprice_t$ is the asset price index and the discretionary revenue changes as shown with the account of the previous year's asset price difference $(t-1)$, as shown in Equation (6).

$$TGR_t(UNE_{t-1}, Assetprice_{t-1}) = \alpha_0 + \alpha_1 Tremd + \alpha_2 UNE_t + \alpha_3 Assetprice_t + e_t \tag{6}$$

Finally, the changes in discretionary fiscal policy are obtained in Equation (7).

$$\Delta CAPB_t = (TGR_t(UNE_t, Assetprice_t) - G_t(UNE_t)) - (TGR_{t-1}(UNE_{t-1}, Assetprice_{t-1}) - G_{t-1}(UNE_{t-1})) \tag{7}$$

2.4. OECD Approach

The OECD approach focuses on the elasticity of government expenditures and taxes to find the discretionary action of fiscal consolidation. The OECD approach rationale is that discretionary changes are best presented when the present primary deficit would have prevailed if expenditure in the previous year had grown with potential GDP and revenues had grown with actual GDP (Mourre et al. 2013). The OECD approach is reflected in Equation (8).

$$\Delta CAPB_t = \frac{\left[\left(\sum_{j=1}^{4} TGR_t{}^{\varepsilon_{tgr}} - G_t^{\varepsilon_g}\right) - \left(\sum_{j=1}^{4} TGR_{t-1}{}^{\varepsilon_{tgr}}(1+y_t) - G_{t-1}^{\varepsilon_g}(1+y_t)\right)\right]}{Y_{t-1}} \tag{8}$$

where y is nominal GDP and Y is the nominal GDP potential, which is estimated based on country-specific production functions. The OECD approach offers a much broader scope of the CAPB because it involves a disaggregated approach and the elasticity of ε_{tgr} (tax revenue) and ε_g (government expenditure) (Mourre et al. 2013). There are four tax revenue categories, which are shown in Equations (9)–(12).

$$\Delta CIT_t = \beta_0 + \beta_1 CIT_t\left(\frac{y_t}{Y_t}\right) + \mu_t \tag{9}$$

$$\Delta PIT_t = \beta_0 + \beta_1 PIT_t\left(\frac{y_t}{Y_t}\right) + \mu_t \tag{10}$$

$$\Delta SSC_t = \beta_0 + \beta_1 SSC_t \left(\frac{y_t}{Y_t} \right) + \mu_t \tag{11}$$

$$\Delta IT_t = \beta_0 + \beta_1 IT_t \left(\frac{y_t}{Y_t} \right) + \mu_t \tag{12}$$

where CIT is corporate income tax, PIT is personal income tax, SSC is social security contributions, and IT is indirect taxes. On the expenditure side, $umplb$ is unemployment benefits, as shown in Equation (13).

$$\Delta \frac{UNE_t}{UNE_{t-1}} = \beta_0 + \beta_1 unmplb_t \left(\frac{y_t}{Y_t} \right) + \mu_t \tag{13}$$

where UNE_t reflect the unemployment and UNE_{t-1} is the unemployment in the last period while represents the Δ change. The CAPB reflects the cyclically adjusted tax revenue and cyclically adjusted government expenditure accounting for elasticity as well as the output gap, as shown in Equation (14).

$$\Delta CAPB_t = \sum_{j=1}^{4} TGR_t \left(\frac{y_t}{Y_t} \right)^{\varepsilon_r} - G_t \left(\frac{y_t}{Y_t} \right)^{\varepsilon_g} \tag{14}$$

The CAPB is derived from constant cyclically adjusted tax revenue ε_{tgr} and government expenditure ε_g accounting for elasticity as well as the output gap (Alesina and Perotti 1997; Alesina and Ardagna 2013; Alesina et al. 2015; Alesina et al. 2019). The OECD approach uses generalized least squares (GLS) to estimate the elasticity for each country and the seemingly unrelated regression procedure (SURE). This estimation is reflected in Equations (15)–(18).

$$\varepsilon_{tgr} \mid = \mid TGR_t = \beta_0 + \beta_1 \sum_{j=1}^{4} TGR_t \left(\frac{y_t}{Y_t} \right) + \mu_t \tag{15}$$

$$\varepsilon_{tgr} = \beta_1 = cnstnt\_elstcy\_tgr \tag{16}$$

$$\varepsilon_g \mid = \mid G_t = \beta_0 + \beta_1 G_t \left(\frac{y_t}{Y_t} \right) + \mu_t \tag{17}$$

$$\varepsilon_{tgr} = \beta_1 = cnstnt\_elstcy\_tgr \tag{18}$$

where $cnstnt\_elstcy\_tgr$ and $cnstnt\_elstcy\_tgr$ reflect the constant elasticity.

2.5. International Monetary Fund Approach

Similar to the OECD, the IMF follows a similar approach to finding the CAPB, as shown in Equation (19).

$$\Delta CAPB_t = \frac{\left[\left(\sum_{j=1}^{4} TGR_t{}^{\varepsilon_{tgr}} - G_t^{\varepsilon_g} \right) - \left(\sum_{j=1}^{4} TGR_{t-1}{}^{\varepsilon_{tgr}} (1 + y_t) - G_{t-1}^{\varepsilon_g} (1 + y_t) \right) \right]}{Y_{t-1}} \tag{19}$$

The only difference is that the OECD uses GMM to find elasticity to obtain the potential output, while the IMF utilizes the Hodrick–Prescott (HP) filter, which is a data-smoothing technique, over all the data points (Mourre et al. 2013).

2.6. Narrative Approach

The narrative approach rationale is that historical documents that outline the intentions of fiscal authorities to increase taxes and reduce government expenditures are those that fully reflect discretionary changes by fiscal authorities that can be attributed to fiscal consolidation (Romer and Romer 2010; Leigh et al. 2011). Romer and Romer (2010) and Leigh et al. (2011) build fiscal consolidation episodes, which are shown in Equation (20):

$$FC_t = FC_t^G + FC_t^T + \epsilon_t \tag{20}$$

where FC_t is narrative fiscal consolidation episodes FC_t^G is a government expenditure cut and FC_t^T is a tax increase. The fiscal consolidation episode follows policy documents advocate that outline a tax increase and a cut in government expenditure.

2.7. Definition Approach

The definition approach is based on thresholds or specific changes in fiscal variables such as government debt, CAPB, and deficit (Bergman and Hutchison 2010). The intuition is that a fall in government debt, which is the ultimate objective of fiscal consolidation, best presents a discretionary action. The definition approach to the threshold is shown in Table 1.

Table 1. Definition approach to the threshold.

Economic Variables	Fiscal Consolidation Definition
Government debts share to gross domestic product	A 4.5% decrease in government debt share to gross domestic product (GDP) in $(t+1)$, $(t+2)$, and $(t+3)$ (Alesina and Ardagna 2010). The Mean is less than 5% of the initial government debt share to GDP for 3 successive years (Alesina and Perotti 1995; Alesina and Ardagna 2010).
Government deficit	A fall of 2% below the initial rate for government deficit in $(t+1)$, $(t+2)$, and $(t+3)$ (Alesina and Perotti 1995; Alesina and Ardagna 2010).
Economic growth	Economic growth is higher for 2 consecutive years for the growth rate means of cases where there was fiscal consolidation (Alesina et al. 1998). The average economic growth rate, at (t), is higher than $(t-1)$ and $(t-2)$ (Giudice and Turrini 2007).
The cyclically adjusted primary balance	If there is a 1% change in the cyclically adjusted primary balance over 3 years (Tavares 2004). The cyclically adjusted primary balance improves by 1.5% in (t) (Alesina and Perotti 1997; Alesina et al. 1998; Gupta et al. 2005; Alesina and Ardagna 2010; Hernández De Cos and Moral-Benito 2013; Schaltegger and Weder 2014). The cyclically adjusted primary balance improves by 1.5% in $(t+1)$ and $(t+2)$ (Alesina et al. 1998). The cyclically adjusted primary balance increases by 2% in $(t+1)$ (Alesina et al. 1998). The cyclically adjusted primary balance improves by mean (μ) plus standard deviation (σ) in (t) (Yang et al. 2015).

Composed by the authors.

3. Literature Review of Fiscal Consolidation Measures

Giorno et al. (1995) used the OECD methodology of CAPB elasticity from 1978 to 1992. The tax revenue elasticity function is $\varepsilon_{tgr} \mid = \mid TGR_t = \beta_0 + \beta_1 \sum_{j=1}^{4} TGR_t\left(\frac{y_t}{Y_t}\right) + \mu_t$ and the government expenditures categories are represented by $\varepsilon_g \mid = \mid G_t = \beta_0 + \beta_1 G_t\left(\frac{y_t}{Y_t}\right) + \mu_t$. Using ordinary least squares (OLS), it was found that the elasticity of 2.55% for corporate tax, 1.14% for personal income tax, 1% for indirect tax, 0.74% for security contributions, and 0.35% for government expenditure. Van den Noord (2000) used the method of Giorno et al. (1995) by using the aggregated shares of each in total revenue as weights to derive the elasticity of the total revenue. It was found that the average elasticity of 1.3% for corporate tax, 10.0% for personal income tax, 0.9% for indirect tax, 0.8% for social security, and −0.3% for current expenditure, and the aggregated CAPB reflected a positive elasticity of 0.49%. The main contribution of Bouthevillain et al. (2001) was based on the analysis of elasticity using the TB tax-based approach share, which is contrary to the traditional approach. Therefore, the elasticity of tax revenue was given by $\epsilon_{tgr} = \sum_{j=1}^{4} TR\left(\frac{TB}{Y}\right)$, and government expenditure was given by $\epsilon_g = G\left(\frac{TB}{Y}\right)$. The time-invariant elasticities of the CAPB on government revenue and expenditure were 1.4% and 0.7%, respectively.

Girouard and André (2006) re-estimated and respecified the elasticity of the CAPB using the OECD framework. Their specification was $\epsilon\_taxw = \left(\sum_{i=1}^{n} \gamma_{iMA_i}\right) / \left(\sum_{i=1}^{n} \gamma_{iAV_i}\right)$, where γ denotes the weights of different income distributions, MA_i is the marginal income tax rate, and VA_i is the average income tax rate for each country. It was found that there was an average of -0.10% sensitivity in the CAPB. Fedelino et al. (2009) used the IMF methodology of constant elasticity concerning the output gap. It was found that government expenditure elasticity was 20.4%, whereas fiscal consolidation negatively impacted demand and growth targets.

Afonso (2010) found that fiscal consolidation harms private consumption. Moreover, budgetary spending categories, including the general government, finally provided support for expansionary fiscal consolidations. Princen et al. (2013) used time-varying parameters to find discretionary tax measures (DTMs). It was found that the average elasticity of the CAPB was -0.1%. Mourre et al. (2014) proposed share tax deviations from the output gap to be used in the CAPB of the OECD, given by $\epsilon_{tgr} = \sum_{j=1}^{4} \frac{TB}{Y}(y - \hat{y})$, and government expenditure was given by $\epsilon_g = \frac{G}{Y}(y - \hat{y})$. It was found that semi-elasticity for revenue was -0.03%, contrary to the positive value of 0.42% obtained using the traditional approach. Dang Price et al. (2014) estimated new tax and expenditure elasticity estimates in the data of Girouard and André (2006). They found that elasticity changes in different tax brackets affect fiscal consolidation episodes. Breuer (2019) adopted the data and methodology of Giorno et al. (1995) and found that the CAPB, which reflects fiscal consolidation results, showed a 0.067% fall in the gross domestic product. Moreover, the authors noted that the CAPB used in the literature has erroneous assumptions that produce flawed results in support of expansionary austerity.

Mourre and Poissonnier (2019) argue that CAPB fiscal semi-elasticities are structural, country-specific, and long-lasting characteristics that are strongly correlated with budgetary variables such as the amount of public spending, spending related to unemployment, and the progress of the tax system. Braz et al. (2019) account for the lag effect in tax and government expenditure data. They found that tax elasticity was 1.07% and the elasticity of direct taxes paid by corporations was 1.95%. They proposed that there is a need for improvements in CAPB output elasticities. Afonso et al. (2022) found that "tax revenue" elasticities have positive Ricardian behaviour, whereby they perceive an increase in taxation to be a sign of future government spending.

No consensus has been reached on the impact of fiscal consolidation on domestic governments. Giavazzi and Pagano (1995), the IMF (2010), Afonso (2010), and Alesina and Ardagna (2010), among others, found that fiscal consolidation of government expenditure reduces government debt and stimulates economic growth. On the other hand, scholars such as Baldacci et al. (2013) and Yang et al. (2015) have shown evidence that fiscal consolidation results in an increase in government debt. Blanchard (1990) outlines that in times of low government debt, fiscal consolidation is successful. Swanepoel and Schoeman (2003) note that when there are high levels of government debt, fiscal consolidation reduces government debt. Müller (2014) argues that fiscal consolidation is self-defeating during financial crises. Monastiriotis (2014) notes that fiscal consolidation leads to unprecedented recessions. Jordà and Taylor (2016) found that a 1% fiscal consolidation translates into a loss of 3.5% of real GDP. Burger and Jimmy (2006) provide evidence that there are two regimes of government debt with a mean of 27.4% and a value of 67% when there is the adoption of fiscal consolidation. Auerbach and Gorodnichenko (2017) note that fiscal consolidation of a government expenditure cut was found to result in a 2.80% fall in government debt. Heimberger (2017) notes that fiscal consolidation has a strong negative association with deep economic crises.

Alesina et al. (2017), in their standard new Keynesian model, demonstrate how sustained expenditure cuts caused by fiscal shocks influence wealth. Under sticky pricing, static distortions brought on by ongoing tax increases result in more significant changes in aggregate supply. Brady and Magazzino (2018) find that in different regimes of high government debt, fiscal consolidation is successful. They found that even when differentiating between different tax types, base broadening during fiscal consolidations resulted in fewer production and employment reductions than rate increases. Ardanaz et al. (2021) point out that in nations with flexible fiscal rules, the adverse impact of fiscal adjustments on public investment disappears, suggesting that flexible rules shield public investment during episodes of consolidation. The consequence is that assuming productive public investment, the design of fiscal rules can add a growth-friendly dimension to the budgetary sustainability target that has traditionally been the emphasis of fiscal rules. The fiscal rule investigated by Nakatani (2021) used a fiscal reaction function. It was found that natural disasters and climate change affect long-term debt dynamics. The expenditure rule, on the other hand, is based on non-resource and non-grant revenue, which is interdependently defined by budget balance objectives and government debt levels, taking into account projected catastrophe shocks. The implementation of a difference-in-discontinuities was undertaken by Marattin et al. (2022), to investigate revenue- and expenditure-based fiscal consolidation with evidence for the pass-through from federal cuts to local taxes. They note that local governments typically increase taxes as a response to the decline in intergovernmental funding, rather than cutting spending.

4. Methodology

This paper uses quantitative analysis to investigate the impact of fiscal consolidation on domestic government debt and measures of the CAPB in South Africa from 1979 to 2022. The theoretical framework of the OECD as well as the IMF extended to the government budget constraint framework, is adopted. The time-varying parameter structural vector autoregression (TVP-VAR) model was used by Primiceri (2005), (Nakajima 2011), and (Koop and Korobilis 2018), among others. There are limitations in this paper in that there are other economic variables that may have not been included in the model. However, Primiceri (2005), (Nakajima 2011), and (Koop and Korobilis 2018) have used a model for monetary policy in this paper for fiscal consolidation analysis. The data were sourced from the South African Reserve Banks (SARB), the IMF, and the Department of the National Treasury Report. The economic variables considered are as follows: $CAPB$ is the cyclically adjusted primary balance, y_t is the potential gross domestic product, Y_t is the gross domestic product, TGR_t is government revenue, G_t is government expenditure, $CAPB\_tgr_t$ is the cyclically adjusted primary balance for government revenue, $CAPB\_g_t$ is the cyclically adjusted primary balance for government expenditure, rD_t is the government debt service payment, $M3_t$ is the money supply proxied, and GD_t is domestic government debt. The framework of the OECD and IMF is shown in Equations (21)–(23).

$$\Delta cnstnt\_elstcy\_\_CAPB\_tgr_t = \sum_{j=1}^{4} TGR_t\left(\frac{y_t}{Y_t}\right)^{\varepsilon_{tgr}} \tag{21}$$

$$\Delta cnstnt\_elstcy\_CAPB\_g_t = G_t\left(\frac{y_t}{Y_t}\right)^{\varepsilon_g} \tag{22}$$

$$\Delta cnstnt\_elstcy\_CAPB_t = \sum_{j=1}^{4} TGR_t\left(\frac{y_t}{Y_t}\right)^{\varepsilon_{tgr}} - G_t\left(\frac{y_t}{Y_t}\right)^{\varepsilon_g} \tag{23}$$

where elasticity is given by ε_{tgr} and ε_g is the constant elasticity of government revenue as well as government expenditure. The time-varying elasticity is reflected in Equations (24)–(26).

$$\Delta tvp\_elstcy\_CAPB\_tgr_t = \sum_{j=1}^{4} TGR_t\left(\frac{y_t}{Y_t}\right)^{\varepsilon_{tgr_t}} \tag{24}$$

$$\Delta tvp\_elstcy\_CAPB\_g_t = G_t\left(\frac{y_t}{Y_t}\right)^{\varepsilon_{g_t}} \tag{25}$$

$$\Delta tvp\_elstcy\_CAPB_t = \sum_{j=1}^{4} TGR_t\left(\frac{y_t}{Y_t}\right)^{\varepsilon_{tgr_t}} - G_t\left(\frac{y_t}{Y_t}\right)^{\varepsilon_{g_t}} \tag{26}$$

where $\varepsilon_{tgr} = \varepsilon_{r_t}$ and $\varepsilon_g = \varepsilon_{g_t}$, with the key distinction being the t time subscript reflecting the time-varying elasticity. The theoretical framework is then expanded to the government budget constraint framework to investigate the impact of fiscal consolidation proxied by time-varying CAPB on domestic government debt, as shown in Equations (27) and (28).

$$G_t + rD_t = TGR_t + GD_t + M3_t \tag{27}$$

$$GD_t = G_t + rD_t - TGR_t - M3_t \tag{28}$$

The theoretical framework of the OECD and IMF with time-varying CAPB and the government budget constraint framework is shown in Equations (29)–(31).

$$GD_t = G_t + rD_t - TGR_t - M3_t + tvp\_elstcy\_CAPB\_tgr_t \tag{29}$$

$$GD_t = G_t + rD_t - TGR_t - M3_t + tvp\_elstcy\_CAPB\_g_t \tag{30}$$

$$GD_t = G_t + rD_t - TGR_t - M3_t + tvp\_elstcy\_CAPB_t \tag{31}$$

Model Specification

The TVP-VAR model was adopted because it is effective in answering the question of this paper, which is related to finding the time-varying elasticities within the CAPB. TVP-VAR provides time-varying coefficients (Koop and Korobilis 2018) reflecting the responsiveness of the CAPB components that can be attributed to fiscal consolidation. Sims (1980) developed the basic VAR model that was extended by Primiceri (2005), which incorporates time-varying parameters. Nakajima (2011) further improved the framework. The TVP-VAR model is built from the framework of the structural vector autoregressive (SVAR) model, which can then be reduced to the vector autoregressive (VAR) model. The SVAR model is reflected in Equation (32).

$$Ay_t = \beta_0 + \beta_1 y_{t-1} + \beta_1 y_{t-2} + \beta_1 y_{t-3} + \ldots \beta_p y_{t-p} + Ce_t \tag{32}$$

where A shows the contemporaneous relationships between the endogenous variables $n * n$ matrix and p shows the number of variables in the system. The subscripts y_t, y_{t-1}, y_{t-2}, and y_{t-p} reflect a matrix $n * 1$ vector of endogenous variables, β_0 is the intercept, β_1, β_2, β_3, and β_p reflect time-invariant coefficients explained by the matrix $n \times n$, $t - p$ indicates the order of autoregression or several lags, and structural shocks in the system are denoted by $E(e_t = 0)$ of the vector that has uncorrelated or orthogonal structural disturbances with a zero mean in the matrix $n \times 1$ (Equation (33)).

$$E\left(e_t,\ e_t'\right) \sum_e = \begin{bmatrix} \sigma^2_{e_{t1}} & 0 & \cdots & 0 \\ 0 & \sigma^2_{e_{t2}} & \cdots & \vdots \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & \sigma^2_{e_{tn}} \end{bmatrix} \tag{33}$$

where σ is the standard deviation, and it is assumed that structural shocks follow a recursive identification pattern with A taking on a lower triangular matrix (Equation (34)).

$$A = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ a_{2,1} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ a_{n,1} & \cdots & a_{n,p-1} & 1 \end{bmatrix} \tag{34}$$

The SVAR model is transformed through the multiplication of the contemporaneous matrix A^{-1} across all perimeters and is expressed in Equations (35)–(37).

$$A^{-1}Ay_t = A^{-1}\beta_0 + A^{-1}\beta_1 y_{t-1} + A^{-1}\beta_2 y_{t-2} + A^{-1}\beta_3 y_{t-3} + A^{-1}\beta_p y_{t-p} + A_t^{-1}C_{e_t} \tag{35}$$

$$A^{-1}Ay_t = F_0 + A^{-1}F_1 y_{t-1} + A^{-1}F_2 y_{t-2} + A^{-1}F_3 y_{t-3} + A^{-1}F_p y_{t-p} + A^{-1}\sum_e t \tag{36}$$

$$\varepsilon_t \sim (N0, I_n) \tag{37}$$

where $A^{-1}F_i = \beta_1$ for $i = 1\cdots p$ and $\sum_e t$ is the diagonal matrix denoting the disturbance term. This study uses the rationale of Primiceri (2005) by describing $X_t = I_s \otimes \left(0, y'_{t-1,} y'_{t-2,}, \ldots, y'_{t-p}\right), \beta = \left(F_0, F_1, F_2, F_3 \ldots F_p\right)$, where $\otimes$ denotes the Kronecker product. The reduced form, VAR, is reflected in Equation (38).

$$y_t = \beta_0 + \beta X_t + A^{-1}\sum_e t \tag{38}$$

The dynamic characteristics of variable interaction and the specification in Equation (38) are further extended to the TVP-VAR model, allowing for the parameters in Equations (39)–(42).

$$y_t = \beta_t X'_t + A_t{}^{-1}\sum_e t \tag{39}$$

$$\beta_t = \Phi\beta_{t-1} + v_t \tag{40}$$

$$a_t = a_{t-1} + \varsigma_t \tag{41}$$

$$h_t = h_{t-1} + \xi_t \tag{42}$$

where $y_t = X'_{t-1}$ indicates that the variables of interest are explained by the lag function itself, and β_t, a_t, and h_t is indicate the evolution of time-varying parameters following the first-order random walk process, as proposed by Primiceri (2005) and Koop and Korobilis (2018). β_t is the time-varying coefficient, Φ is phi, a_t is the evolution sequence of structural information, and h_t is the evolution sequence of stochastic volatility. On the other hand, $v_t \sim N\left(0, \Omega_\beta\right)$, $\varsigma_t \sim N(0, \Omega_a)$, and $\xi_t \sim N(0, \Omega_h)$ denote a new error term note correlated with the matrix shown in Equation (43).

$$V = Var = \begin{bmatrix} t \\ v_t \\ \varsigma_t \\ \xi_t \end{bmatrix} = \begin{bmatrix} I_n & 0 & 0 & 0 \\ 0 & \Omega_\beta & 0 & 0 \\ 0 & 0 & \Omega_a & 0 \\ 0 & 0 & 0 & \Omega_h \end{bmatrix} \tag{43}$$

This paper follows Primiceri (2005) and Koop and Korobilis (2018) by selecting training samples to find the prior information using the ordinary least squares (OLS) algorithm. This information on coefficients factors in the Monte Carlo Markov chain (MCMC) to investigate time-varying parameters. In the MCMC, the Gibbs sampling algorithm is used to fix high-dimensional data. The MCMC discussed above can be expressed in Phases 1–5: Phase 1 has β, a, h, V, Phase 2 has $\beta|a, h, V, y;\ \Omega_\beta|\beta$, Phase 3 has $a|\beta, h, V, y;\ \Omega_a|a$, Phase 4 has $h|\beta, a, V, y;\ \Omega_h|h$, and Phase 5 returns to Phase 2. One of the variables in this paper is potential GDP, which is used in the CAB. This is calculated using the Hodrick–Prescott filter, as shown in Equation (44).

$$\frac{\text{Min}}{\{Y^p\}_{t=-1}^{T}} \sum_{t=1}^{T}(Y_t - Y^p{}_t)^2 + \lambda \sum_{t=1}^{T}(Y^p{}_t - Y^p{}_{t-1})^2 - (Y^p{}_t - Y^p{}_{t-2})^2 \tag{44}$$

5. Empirical Results

Table 2 shows the descriptive statistics of economic variables from 1979 to 2022. The gd was found to have a mean of 37.22%. The level of g was found to have an average of 27.94% between 1979 and 2022. The tgr has a growth rate mean of 14.32%. The $m3$ was found to have an index value of 12.79 over the period. The GDP was found to be 0.25% between 1979 and 2022 on averageLastly, the economic variable that is considered the $tvp\_elstcy\_CAPB\_tgr$, time-varying elasticity for total government revenue, and tvp_elstcy_g, time-varying elasticity for government expenditure, were found to have mean values of −0.29% and 0.76%, respectively. The average values are relatively low compared with those found in the case of time-invariant elasticity. For $tvp\_elstcy\_CAPB\_tgr$, $tvp\_elstcy\_CAPB\_g$, and tvp_elstcy_CAPB, time-varying CAPB was found to have mean values of −1.35%, 5.25%, and 6.61%, respectively.

Table 2. Descriptive statistics of the data sourced and estimated.

Variable	Obs	Mean	Std. Dev.	Min	Max
gd	44	37.22682	11.2063	21.99	73.18
g	44	27.94886	3.00313	23.3	37.5
tgr	44	14.32779	8.75437	−5.2537	36.8419
$m3$	44	12.795	6.12093	1.79	27.3
gdp	43	0.255814	2.60926	−7.7	4.4
Estimated data					
$tvp\_elstcy\_CAPB\_tgr$	44	−0.293636	12.2292	−47.3	49.72
$tvp\_elstcy\_CAPB\_g$	44	5.259546	45.5113	−247.4	67.85
tvp_elstcy_CAPB	44	6.616136	56.26286	−297.13	115.15

Composed by the authors.

Table A1 shows Dickey–Fuller and Phillips–Perron tests for the unit root with the result that at a level, the unit root null hypothesis could not be rejected, as it was not stationary at the level for all economic variables considered except for gdp. All variables were found to be stationary at the first difference. Table A2 shows the optimal length of three lags determined by the standard lag order selection criteria applied to a constant parameter, VAR, which was used in the estimation. The three lag lengths were found using three LR, FPE, and HQIC criteria out of the five criteria selected, while one SBIC criterion selected one and the other AIC criteria selected four.

In Figure 1 Graph (a)–(g) show the Hodrick–Prescott filter for GDP, dgp reflects the actual data shown in Graph (a), dgp_c is the cyclical component shown in Graph (b), and dgp_p reflects the trend component shown in Graph (c). To find a discretionary action that can be attributed to fiscal authorities' action, cyclical movement in economic variables needs to be filtered out (Alesina and Perotti 1995). This is shown in Graphs (e) and (g), and Graphs (d) and (f) show the actual data of government revenue and expenditure, respectively.

Table A3 shows the Johansen tests for cointegration, indicating that there is a long-run relationship between the economic variables and the validity of the use of the VAR model. Table A4 shows the VAR stability condition, reflecting stability in the estimation of the VAR model.

Table 3 shows that the VAR model results in tgr reflect a coefficient value of 0.06%, reflecting how responsive the South African fiscal policy authorities are. It was found that the g government expenditure output gap share to total output has a negative coefficient of 5.5%. These two elasticities are constant, as reflected in Figure 2 Graph (a) and (d).

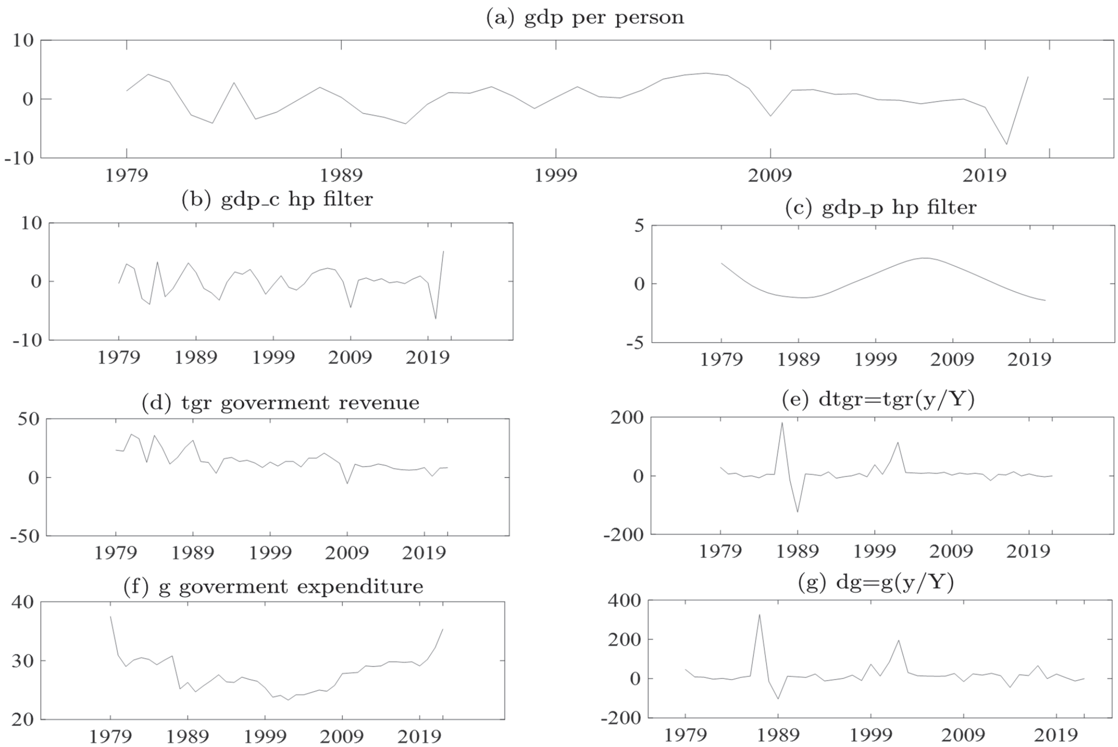

Figure 1. Graph (**a**–**g**) is the Hodrick–Prescott filter for GDP. Note Graph (**a**) and $gdp\ per\ person$ is the gross domestic product, Graph (**b**) and $gdp\_c\ hp\ filter$ is the gross domestic product cyclical component from the Hodrick-Prescott (HP) Filter, Graph (**c**) and $gdp\_c\ hp\ filter$ is the gross domestic product cyclical component from the Hodrick-Prescott (HP) Filter, Graph (**d**) and tgr is the total government revenue, Graph (**e**) and $tgr = tgr(y/Y)$ is the total government revenue times the proportion of the output gap, Graph (**f**) and g is government expenditure, Graph (**g**) and $g = g(y/Y)$ is government expenditure times the proportion of the output gap. Composed by the authors.

Table 3. VAR model.

Economic Variables	Estimation 1	Estimation 2
$L3.D.tgr$	0.330 * (−2.45)	0.330 * (−2.45)
$L2.D.tgr$	0.0646 ** (−2.65)	0.0646 ** (−2.65)
$L3.D.tgr$	0.038 (−1.45)	
$D.g$		−5.546 *** (−5.90)
$L.\ ce1$ $cons$	2.283 (1.02)	0.000500 (0.00)
N	41	43

t statistics in parentheses and * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Composed by the authors.

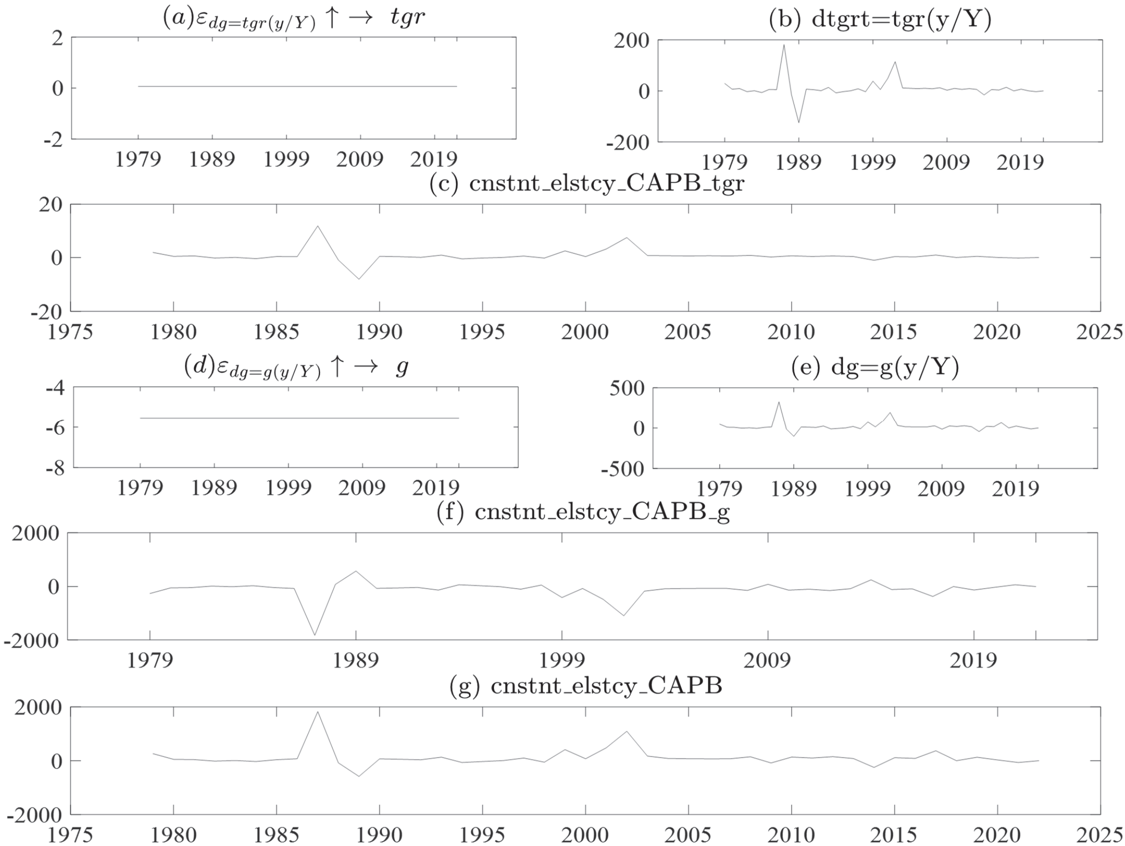

Figure 2. Graph (**a**–**g**) is the CAPB with constant elasticity. Note the economic variable that gdp is the gross domestic product, $gdp\_c\ hp\ filter$ is the gross domestic product cyclical component from the Hodrick-Prescott (HP) Filter, $gdp\_c\ hp\ filter$ is the gross domestic product cyclical component from the Hodrick-Prescott (HP) Filter, tgr is the total government revenue, $tgr = tgr(y/Y)$ is the total government revenue times the proportion of the output gap, g is government expenditure, and $g = g(y/Y)$ is government expenditure times the proportion of the output gap. Composed by the authors.

Figure 2 displays the constant elasticity of the cyclically adjusted primary balance (CAPB) obtained from the estimations presented in Table 2. The CAPB is a measure of a government's fiscal stance that is adjusted to exclude cyclical factors that affect the government's budget balance, such as changes in tax revenues and spending that are due to the economic cycle. The IMF and OECD frameworks use the constant elasticity of the CAPB as a measure of fiscal consolidation, which is the process of reducing a government's budget deficit or debt. Graphs (a) and (d) in Figure 2 show the constant elasticity of total government revenue and expenditure, respectively, which are calculated using the *cnstnt_elstcy_tgr* and *cnstnt_elstcy_g* estimations from Table 2. These elasticities are then multiplied by the output gap, which has been filtered to remove the cyclical component using Equations (21)–(23), resulting in Graphs (b) and (e). Graphs (c) and (f) show the product of the filtered discretionary actions of fiscal authorities $tgr = tgr(y/Y)$ and $dg = g(y/Y)$ and the corresponding constant elasticities. Finally, Graph (g) displays the time-invariant or constant elasticity of the CAPB. This elasticity represents the responsiveness of the CAPB to changes in the output gap, holding all other factors constant.

The analysis presented in Figure 2 has important policy implications for governments and policymakers. The constant elasticity of the CAPB is a measure of a government's fiscal stance that is adjusted for the effects of the economic cycle, and it provides a useful tool for assessing the effectiveness of fiscal policies in achieving budgetary consolidation. The results from Figure 2 can inform policy decisions by providing information on the appropriate mix of revenue and expenditure measures needed to achieve fiscal consolidation. Policymakers can use the constant elasticities of revenue and expenditure to identify the most effective measures for achieving their desired fiscal targets. For example, if the constant elasticity of revenue is higher than that of expenditure, it may be more effective to focus on revenue-raising measures, such as tax increases, rather than expenditure reductions. Furthermore, the time-invariant elasticity of the CAPB can be used as a benchmark to assess the sustainability of a government's fiscal stance over the long term. If a government's fiscal policy is not aligned with the constant elasticity of the CAPB, it may face challenges in achieving long-term sustainability.

The TVP-VAR results are shown in Tables A4 and A5, which shows the posterior means, standard deviations, 95% credible intervals, convergence diagnostics (CD) of Geweke (1992), and inefficiency factors computed using the MCMC sample. The CD statistics are less than unity, and the inefficiency factors are less than 100. In the estimated result, the null hypothesis of convergence to the posterior distribution is not rejected for the parameters at the 5% significance level based on the CD statistics, and the inefficiency factors are quite low except for *sh*2, which indicates efficient sampling for the parameters and state variables. Figures A1 and A2 shows the sample autocorrelation function, the sample paths, and the posterior densities for the selected parameters. After discarding the initial 2000 samples in the burn-in period, the sample paths appear stable, and the sample autocorrelations drop smoothly. Figures A3 and A4 show the posterior mean estimates for the stochastic volatility of the structural shock used for the estimation of government revenue and expenditure, respectively.

The TVP-VAR results are shown in Tables A5 and A6, which shows the parameters, 95% confidence intervals, convergence diagnostics (CD) of Geweke (1992), and inefficiency factors computed using the MCMC sample. In the estimated result, the null hypothesis of convergence to the posterior distribution is not rejected for the parameters at the 5% significance level based on the CD statistics, and the inefficiency factors are quite low except for sh2, which indicates efficient sampling for the parameters and state variables. Figures A5 and A6 show the time-varying elasticity of government revenue and time-varying elasticity of government expenditure respectively. In both Figures A5 and A6 the Graph of interest if (d), which time-varying elasticity of government revenue and time-varying elasticity of government expenditures noted. Figure A5 Graph (d) the time-varying elasticity of government revenue has been less elastic however the change is seen in the late 1980s to late 1990, thereafter the time-varying elasticity of government revenue inelastic. Figure A6 Graph (d) The time-varying elasticity of government expenditure is reflected with a downwards trend in the from 1790 to late 1990s. Thereafter, time-varying elasticity of government expenditure started to increase.

Figures A7 and A8 show the posterior estimates of stochastic volatility for total government revenue and government expenditure. For both economic variables, the coefficients have 95% credible intervals including the true values. The total government revenue shows again in momentum for volatility from the later 1980s till 2019. On the other hand, government expenditure volatility started to gain momentum of volatility in the early 1990's this was due to most of the government expenditure programs toward democracy in 1994. After 1994 the volatility subsided in 2009 and thereafter start to increase again. Figures A9 and A10 show the evolution sequence of structural information of the interest of total govetment revenue and government expenditure respectily. This will be starttting poing of the coeefection in the estimation of the cieffience over time.

Table 4 reflects the descriptive statistics of tvp_elstcy_CAPB, $CAPB\_IMF$, and CAB_IMF. The tvp_elstcy_CAPB has 44 observations, while the data from the IMF have 23 observations.

This reflects that the empirical work of this paper has gone to great lengths to find what can be used to analyse fiscal consolidation. In terms of variation and volatility, the tvp_elstcy_CAPB standard deviation is 56.26%. This reflects that there is a 56% variation in the cyclically adjusted primary balance using time-varying elasticity. The difference in the number of observations between the tvp_elstcy_CAPB variable and the IMF data suggests that different methods were used to generate these variables. This could have implications for the reliability and comparability of the data. The difference in the number of observations between the tvp_elstcy_CAPB variable and the IMF data could have important implications for the reliability and comparability of the data. This means that policymakers should be cautious when interpreting data from different sources and should take steps to ensure that the data they are using is as accurate and reliable as possible.

Table 4. Estimated CAPB for this paper and the IMF.

Variable	Obs	Mean	Std. Dev.	Min	Max
		IMF data of CAPB for South Africa			
tvp_elstcy_CAPB	44	6.616136	56.26286	−297.13	115.15
		IMF data of CAPB for South Africa			
$CAPB\_IMF$	23	0.3516041	2.361112	−4.687403	3.766418
CAB_IMF	23	−3.063716	2.552726	−9.054413	0.8080437

Composed by the authors.

Figure 3 Graph (a)–(g) shows the CAPB with time-varying constant elasticity. Graphs (a) and (d), show the time-varying elasticity of fiscal consolidation, which is in contrast to the constant elasticity applied in the IMF and OECD frameworks. To represent time-varying elasticity in fiscal consolidation for tgr government revenue, the data in Graphs (a) and (b) are multiplied to obtain $tvp\_elstcy\_CAPB\_tgr$, which reflects the CAPB with time-varying elasticity shown in Graph (c). The time-varying elasticity reflected in Graph (d) is for g, government expenditure. The time-varying elasticity for g (government expenditure) multiplied by the share of GDP deviation is shown in Graph (e), resulting in the $tvp\_elstcy\_CAPB\_g$ time-varying CAPB for government expenditure. The tvp_elstcy_CAPB has a range from −297.13% as the minimum value to 115.5% as the maximum value. In the first 8 years, the tvp_elstcy_CAPB was characterized by an average value of 26.36%. In the same period, the maximum value found was 45.85% in 1989, and the lowest value found was –11.06% in 1985. The tvp_elstcy_CAPB drastically fell to −297.13%, which is thought to be an outlier in the data. Observations of the data reflect that this could be related to the fall in the gross domestic product per person in the same year. The tvp_elstcy_CAPB, the next point, was found to be high in 1989, which recorded a value of 115.15%. After 1989, tvp_elstcy_CAPB started to become stable in terms of volatility. Between 1989 and 2022, the tvp_elstcy_CAPB recorded an average of 6.76% as well as a maximum value of 75.30% and a minimum value of −91.40%.

The comparison between the time-varying constant elasticity approach and the constant elasticity approach used in the IMF and OECD frameworks underscores the importance of considering the complexity of fiscal consolidation measures and the potential impacts of these measures over time. By using a more nuanced approach, policymakers can gain a better understanding of the potential benefits and drawbacks of different fiscal consolidation measures and can design policies that are more effective and sustainable over the long term. The range of values in the tvp_elstcy_CAPB variable, which includes both very high positive and negative values, reflects the high volatility and complexity of fiscal consolidation measures. The outcome sheds light on how the cyclically adjusted primary balance changes over time and emphasizes the value of employing time-varying elasticity methods to capture fiscal consolidation.

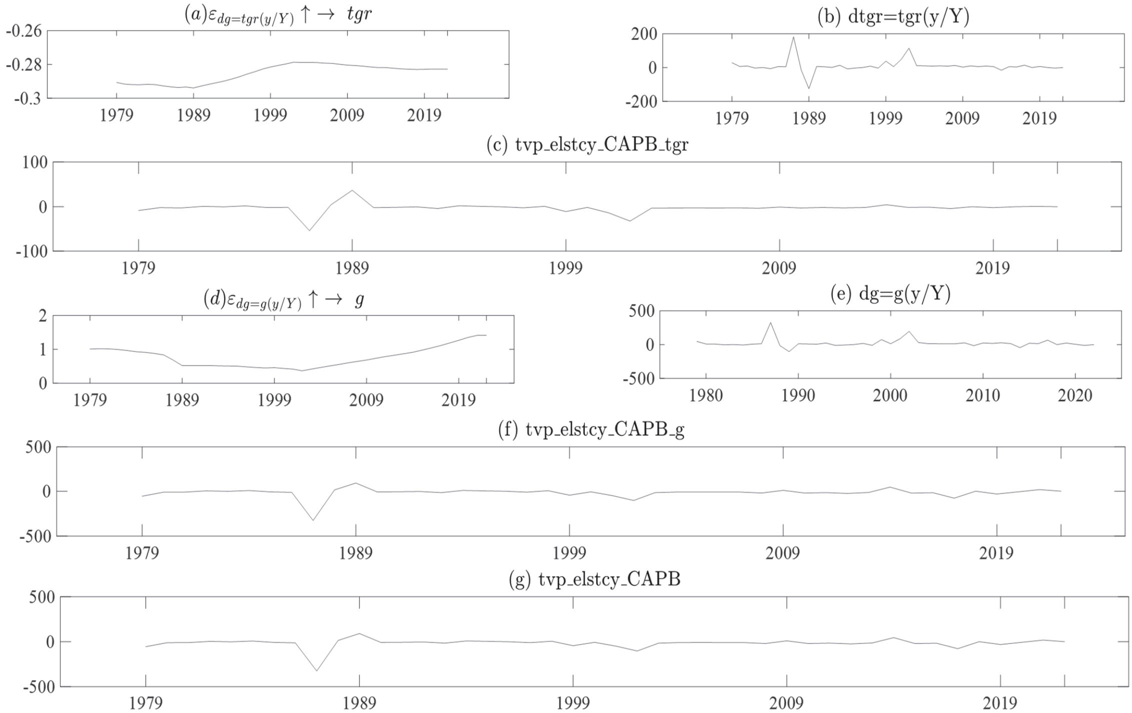

Figure 3. Graph (**a**–**g**) is the CAPB with time-varying constant elasticity. Where Graph (**a**,**d**) and $dg = g(y/Y)$ shows the government expenditure times the proportion of potation gross domestic product, Graph (**b**,**e**) and $tgr = g(y/Y)$ shows the g total government revenue times the proportion if potation gross domestic product, Graph (**c**) and $tvp\_elstcy\_CAPB\_tgr_t$ is the time-varying cyclically adjusted primary balance for government revenue, Graph (**f**) and $tvp\_elstcy\_CAPB\_g_t$ is the time-varying elasticity cyclically adjusted primary balance for government expenditure and Graph (**g**) and $tvp\_elstcy\_CAPB_t$ is the cyclically adjusted primary balance for government expenditure. Composed by the authors.

5.1. Comparison of the CAPB of This Paper and the IMF

The introduction of the cyclically adjusted primary balance calculation by the IMF in 2000 was a significant development in fiscal policy analysis. This measure is used to assess the sustainability of fiscal policy by removing the cyclical component of government revenues and expenditures and thus providing a clearer picture of the underlying structural fiscal position of a country.

Figure 4 Graphs (a) and (b) show the $tvp\_elstcy\_CAPB\_g$ with time-varying elasticity, which provides a more dynamic approach to analyzing the cyclically adjusted primary balance. The time-varying elasticity captures changes in the responsiveness of the primary balance to the output gap over time and is calculated using a state-space model. On the other hand, Graphs (c) and (d) show the cyclically adjusted primary balance using time-invariant elasticity for the methodology of the IMF, which is based on a fixed elasticity of government revenue and expenditure with respect to the output gap. It is worth noting that the IMF did not calculate the cyclically adjusted primary balance before 2000, as seen in Graphs (c) and (d). Therefore, the introduction of this measure by the IMF in 2000 was a significant step in providing a more comprehensive assessment of the fiscal sustainability of member countries. Both $CAPB\_IMF$ and CAB_IMF reflect downward information trends from 2000 to 2020. These data reflect that South Africa has been adopting a less discretionary fiscal policy or fiscal consolidation to reduce domestic government debt.

However, with the data that were calculated in this paper using time-varying elasticity from 2000 to 2020, the CAPB has a positive trend. Contrary to the IMF, this trend reflects that there has been a discretionary fiscal policy or fiscal consolidation in the effort to reduce domestic government debt.

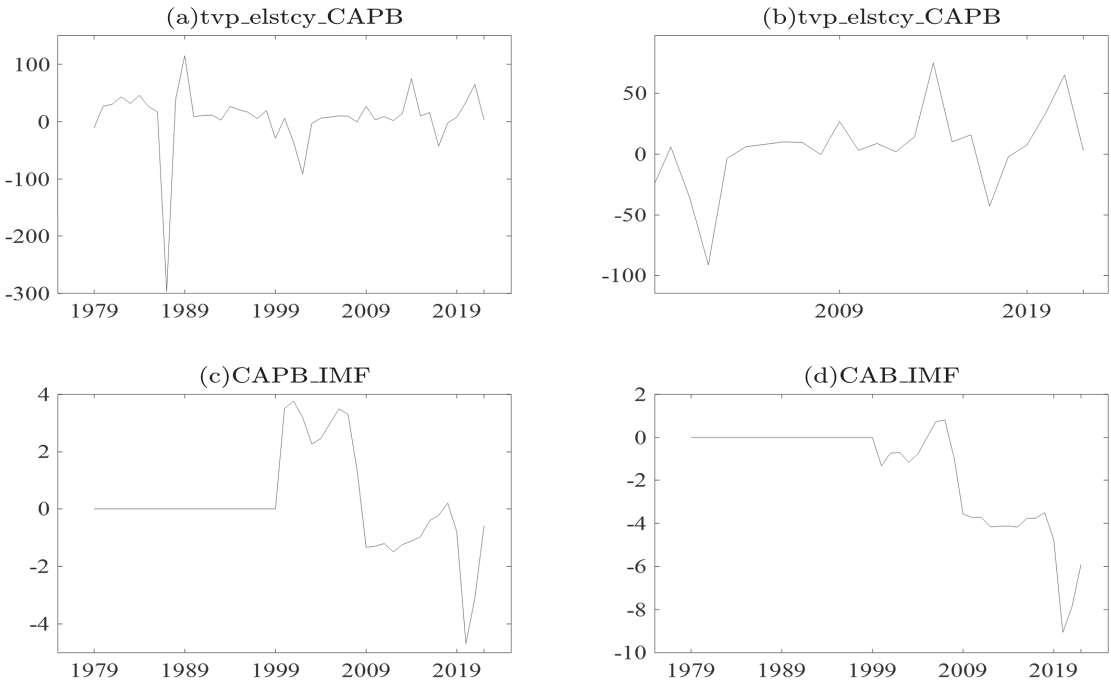

Figure 4. Graph (**a**–**d**) show the time-varying CAPB of this paper and time-invariant CAPB of the IMF. Where Graph (**a**,**b**) tvp_elstcy_CAPB show the cyclically adjusted primary balance with time-varying elasticity. While Graph (**c**,**d**), as well as $CAPB\_IMF$ shows the cyclically adjusted primary balance from the International Monetary Fund. Composed by the authors.

5.2. Impact of Fiscal Consolidation of Domestic Government Debt Using Time-Varying CAPB

Figure 5 shows a time-varying CAPB that proxies fiscal consolidation impact in the economic variables of interest. The $\varepsilon_{tvp\_elstcy\_CAPB\_tgr} \uparrow \rightarrow gd$ shock of fiscal consolidation through taxes or government revenue is anticipated to be implemented in 3 years, with the highest multiplier being -0.5% in Year 1. This results in a fall in gd in the following year.

After Year 1, gd starts to become unstable and increases above equilibrium. However, fiscal consolidation is anticipated to be implemented in 6 years, with a multiplier of 0.9%. The fiscal consolidation expected in 12 years has the highest multiplier at 0.5%. Fiscal consolidation has a detrimental effect on gd. On the other hand, the $\varepsilon_{tvp\_elstcy\_CAPB\_g} \uparrow \rightarrow gd$ shock of fiscal consolidation through government expenditure expected in 3 years increases gd in Year 1; after that year, there is a reduction in gd until Year 3, with a maximum multiplier value of 0.05%. After Year 3, gd increases and returns to equilibrium. The shock $\varepsilon_{tvp\_elstcy\_CAPB\_g} \uparrow \rightarrow gd$ expected in 6 years is found to reflect high volatility in gd. First, there is a drastic reduction in gd in Year 1 followed by a high increase in the following year and a high multiplier value of 0.025%. In Year 1, the results are similar to those of Giavazzi and Pagano (1995), the IMF (2010), and Afonso (2010), outlining that a government expenditure cut results in a reduction in gd. The shock of $\varepsilon_{tvp\_elstcy\_CAPB\_g} \uparrow \rightarrow gd$ expected in 12 years increases gd in the 1st year, with a maximum multiplier value of -0.022%. Thereafter, there is a reduction in gd at a level below equilibrium from Year 2 to Year 11, and in Year 12, it returns to equilibrium.

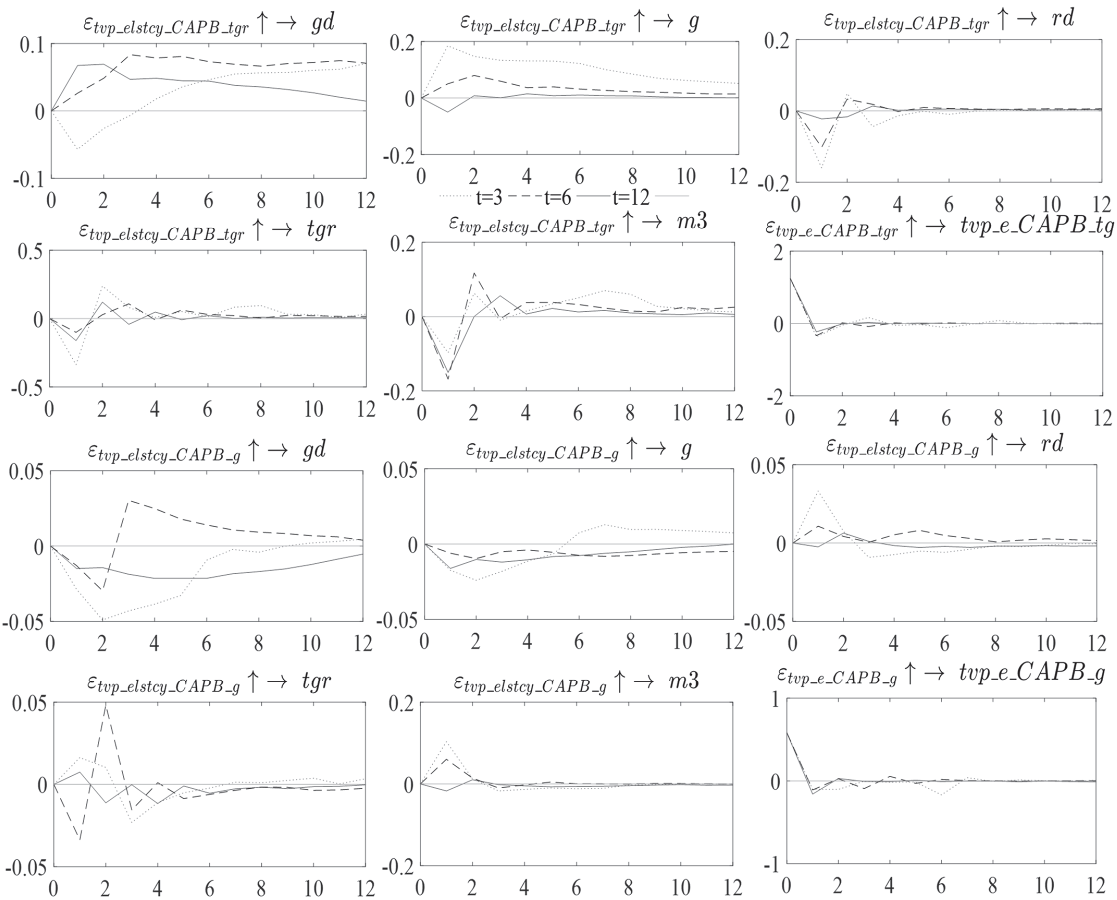

Figure 5. Time-varying impulse response functions. Where gd_t is the doedomesticvernment debt, g_t is government expenditure, rd_t is the government debt service payment, tgr_t is government revenue, $m3_t$ is the money supply, and $CAPB\_g_t$ is the cyclically adjusted primary balance for government expenditure. Composed by the authors.

6. Conclusions

This paper is based on the investigation of new measures of fiscal consolidation episodes with the use of the cyclical adjusted primary balance (CAPB) taking into account the time-varying elasticity. This investigation is based on the problem that is identified that IMF and OECD used constant elasticity when calculating the CAPB and not time-varying elasticity. Moreover, another broad question of the paper is to investigate what is the impact of fiscal consolidation on domestic government debt. The empirical work uses data from 1979 to 2020 and the Time-Varying Parameter Structural Vector Auto-Regression (TVP-VAR model) (Nakajima 2011) to find time-varying elasticity. The economic variables utilized in this empirical work are domestic government debt, money supply, total government revenue, debt service ratio, and fiscal consolidation proxied by CAPB. The empirical work found that IMF data for the CAPB ran over 23 years, but the one that is calculated in this study is 43 years. The IMF reflects that the CAPB has no upward trend, indicating that fiscal authorities have been taking less and less discretionary action toward stabilizing the economy. However, when the time-varying elasticity is accounted for, it is found that there is variation in the CAPB reflecting different times of discretionary action by the fiscal authority in the effort to stabilize the economy. There is a 56.26% variation in the CAPB with time-varying elasticity and there is a 2.36% variation in the CAPB of the IMF data.

Regarding the investigation of the impact of fiscal consolidation on domestic government debt, the time-varying cyclical adjusted primary balance is used to proxy fiscal consolidation. In the TVP-VAR model, it is found that fiscal consolidation is expected to occur in 3 years and 6 years resulting in a radical increase in domestic government debt in the first 3 years of implementation. Moreover, the domestic government debt remains at a high level from year 3 until year 12. If fiscal consolidation is expected in 12 years, this will result in a fall in the domestic government debt in the first 3 years when the fiscal consolidation has been implemented. However, after that, the domestic government debt will increase up until year 12. Given that the South Africa budgetary planning is done over 3 years, the empirical work of this study concludes that fiscal consolidation years will increase domestic government debt in South Africa. Moreover, it is recommended that the fiscal consolidation be planned 3 years to 6 years in advance. Nevertheless, fiscal authorities need to critically examine the benefit of fiscal consolidation in the short run. Future studies need to also investigate the long-run implication of fiscal consolidation.

The policy implication based on the finds of this paper is the value of employing time-varying elasticity when calculating the cyclically adjusted primary balance (CAPB) to provide a more precise evaluation of the independent steps taken by fiscal authorities to stabilize the economy. Because of the large short-term effects of fiscal consolidation on domestic government debt, careful planning is required, as is taking into account any long-term negative effects on government debt levels. Constant elasticity has drawbacks that can lead to an erroneous picture of the fiscal authorities' discretionary decisions when used to calculate the CAPB. Further research is required to evaluate the long-term effects of fiscal consolidation and its effects on other economic factors outside government debt levels. On the other hand, it is recommended that when computing the CAPB, the IMF and OECD should use time-varying elasticity to more accurately reflect the discretionary measures taken by fiscal authorities. The short-term advantages of fiscal consolidation should be carefully considered, and fiscal authorities should prepare for any potential negative effects on domestic government debt. To ensure adequate planning and prevent any negative effects on the level of government debt, budgetary planning should be done over a longer period. While deciding on a policy, fiscal authorities should take into account how fiscal consolidation may affect other economic factors outside government debt levels, such as economic growth and unemployment.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Dickey–Fuller and Phillips–Perron tests for unit root.

Variables		Dickey-Fuller Test for Unit Root				Phillips–Perron Test for Unit Root			
		Test	1%	5%	10%	Test	1%	5%	10%
d.gd	Z(t)	−3.902	−3.634	−2.952	−2.61	−3.924	−3.634	−2.952	−2.61
d.g	Z(t)	−7.018	−3.634	−2.952	−2.61	−7.124	−3.634	−2.952	−2.61
d.tgr	Z(t)	−9.221	−3.634	−2.952	−2.61	−3.506	−3.628	−2.95	−2.608
d.m3	Z(t)	−6.166	−3.634	−2.952	−2.61	−2.677	−3.628	−2.95	−2.608
gdp	Z(t)	−4.71	−3.634	−2.952	−2.61	−4.649	−3.634	−2.952	−2.61
d.rd	Z(t)	−9.403	−3.736	−2.994	−2.628	−10.045	−3.736	−2.994	−2.628

MacKinnon's approximate *p*-value for Z(t) = 0.0000. The number of obs = 42. Composed by the authors.

Table A2. Selection-order criteria.

Selection-Order Criteria for Variables								
Lag	LL	LR	df	p	FPE	AIC	HQIC	SBIC
0	−340.914				95795	17.1457	17.1762	17.2301 *
1	−336.294	9.2392	4	0.055	92,923.1	17.1147	17.2063	17.368
2	−330.807	10.974	4	0.027	86,443.4	17.0404	17.193	17.4626
3	−324.851	11.913 *	4	0.018	78,752.5 *	16.9425	17.1563 *	17.5336
4	−320.78	8.1412	4	0.087	79,135.9	16.939 *	17.2138	17.699

Sample: 1983–2022, number of obs = 43. * denotes rejection of the hypothesis at the 0.05 level. Composed by the authors.

Table A3. Johansen test for cointegration.

Maximum Rank	Parms	LL	Eigenvalue	Trace Statistic	5% Critical Value
0	6	−368.913		36.9264	15.41
1	9	−353.482	0.52042	6.0628	3.76
2	10	−350.45	0.13442		

Trend: constant, number of obs = 42, sample: 1981–2022, lags = 3. Max eigenvalue test indicates 0 cointegrating equation(s) at the 0.05 level. Composed by the authors.

Table A4. VAR stability condition.

Eigenvalue Stability Condition		
Eigenvalue	Eigenvalue	Modulus
0.8781253		0.87813
−0.391861	+0.6125297i	0.72715
−0.391861	−0.6125297i	0.72715
0.0827303	+0.5868185i	0.59262
0.0827303	−0.5868185i	0.59262
0.0545967		0.0546

Composed by the authors.

Table A5. Estimated parameters in the TVP-VAR model for government expenditure.

Parameter	Mean	Stdev	95% U	95% L	Geweke	Inef.
sb1	0.0029	0.0006	0.002	0.0043	0.157	9.97
sb2	0.0028	0.0006	0.002	0.0042	0.346	6.59
sa1	0.0056	0.0016	0.0034	0.0097	0.912	12.51
sa2	0.0058	0.0022	0.0034	0.0109	0.319	26.66
sh1	0.0056	0.0017	0.0034	0.01	0.995	14.81
sh2	1.5984	0.4177	0.9125	2.5323	0.42	11.63

TVP-VAR model (Lag = 1), Iteration: 20,000 and Composed by the authors.

Table A6. Estimated parameters in the TVP-VAR model total government revenue.

Parameter	Mean	Stdev	95% U	95% L	Geweke	Inef.
sb1	0.1937	0.1175	0.0298	0.4728	0.409	206.57
sb2	0.5593	0.2142	0.202	1.0391	0.841	148.62
sa1	0.0055	0.0017	0.0034	0.0096	0.119	9.93
sa2	0.0024	0.0003	0.0019	0.0031	0.12	0.54
sh1	0.0024	0.0003	0.0019	0.0031	0.762	1.11
sh2	0.1937	0.1175	0.0298	0.4728	0.409	206.57

TVP-VAR model (Lag = 1), Iteration: 20,000 and Composed by the authors.

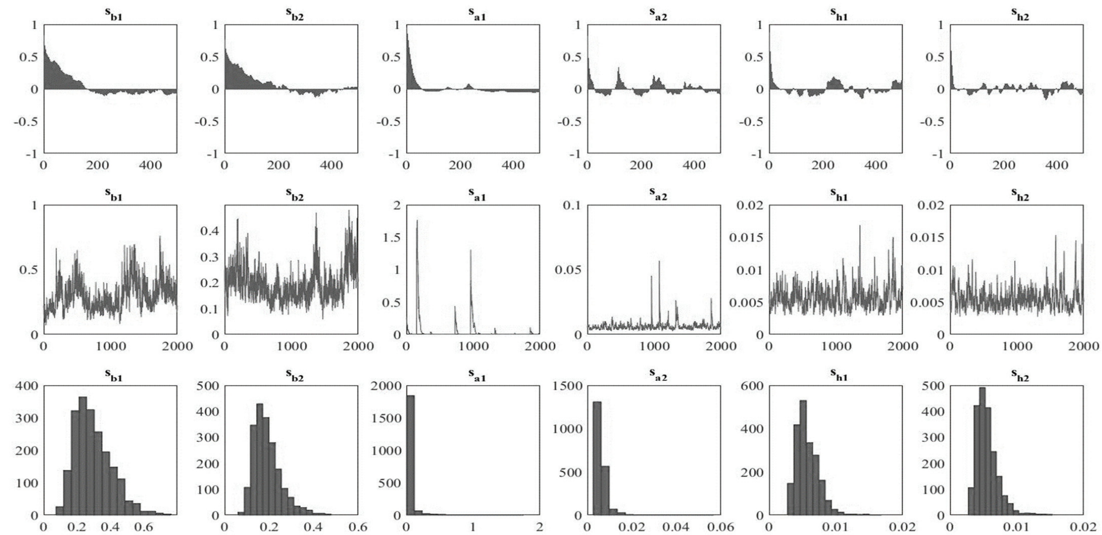

Figure A1. Estimates of the moments and posterior distributions of the model for G. Note: The estimates of Σ_a and Σ_β are multiplied by 100. Composed by the authors.

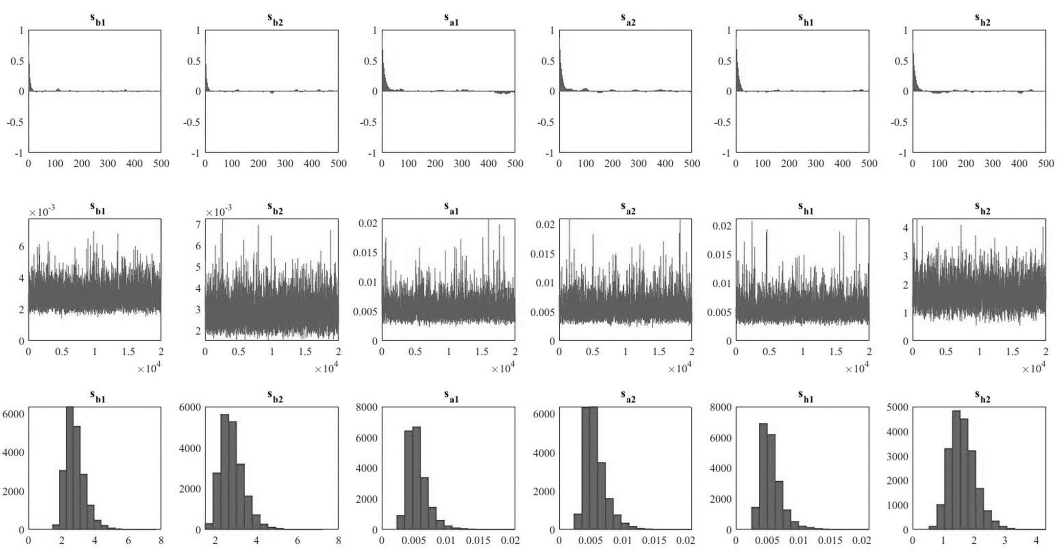

Figure A2. Estimates of the moments and posterior distributions of the model for TGR. Note: The estimates of Σ_a and Σ_β are multiplied by 100. Composed by the authors.

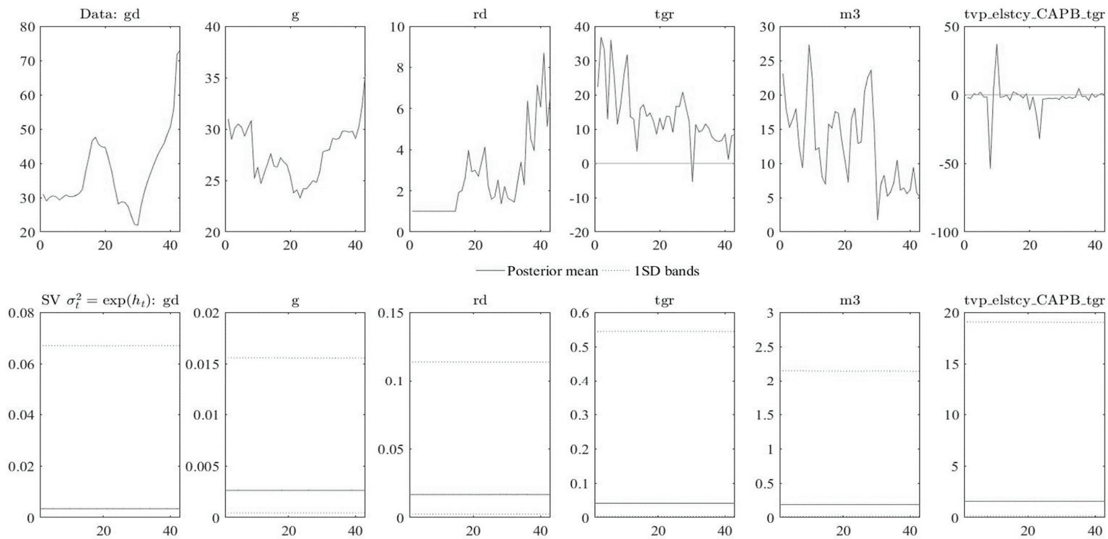

Figure A3. Posterior mean estimates for stochastic volatility of the structural shock for TGR. Where gd_t is domestic government debt, g_t is government expenditure, rd_t is the government debt service payment, tgr_t is government revenue, $m3_t$ is the money supply, and $CAPB\_tgr_t$ is the cyclically adjusted primary balance for government revenue. Composed by the authors.

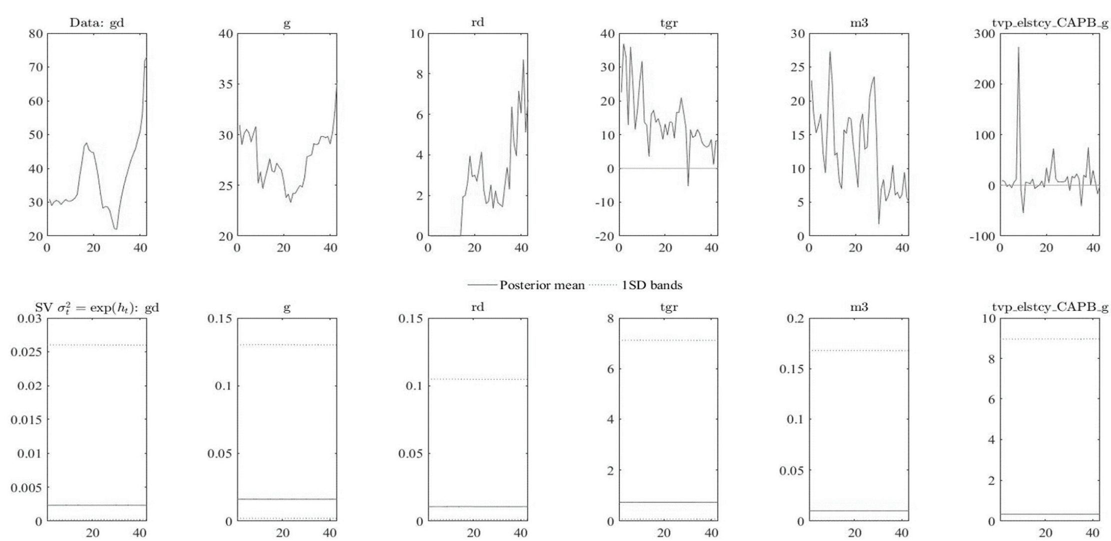

Figure A4. Posterior mean estimates for stochastic volatility of the structural shock for G. Where gd_t is domestic government debt, g_t is government expenditure, rd_t is the government debt service payment, tgr_t is government revenue, $m3_t$ is the money supply, and $CAPB\_g_t$ is the cyclically adjusted primary balance for government expenditure. Composed by the authors.

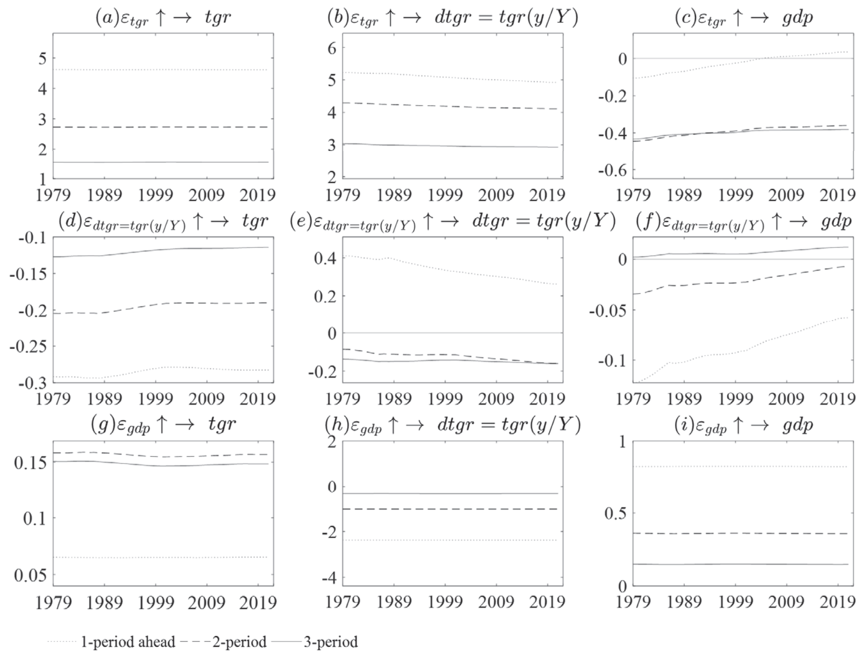

Figure A5. Graph (**a**–**i**) is the time-varying elasticity of government revenue. Where tgr is the total government revenue $tgr = g(y/Y)$ is the g total government revenue times the proportion of potation gross domestic product and gdp is the gross domestic product per person. Composed by the authors.

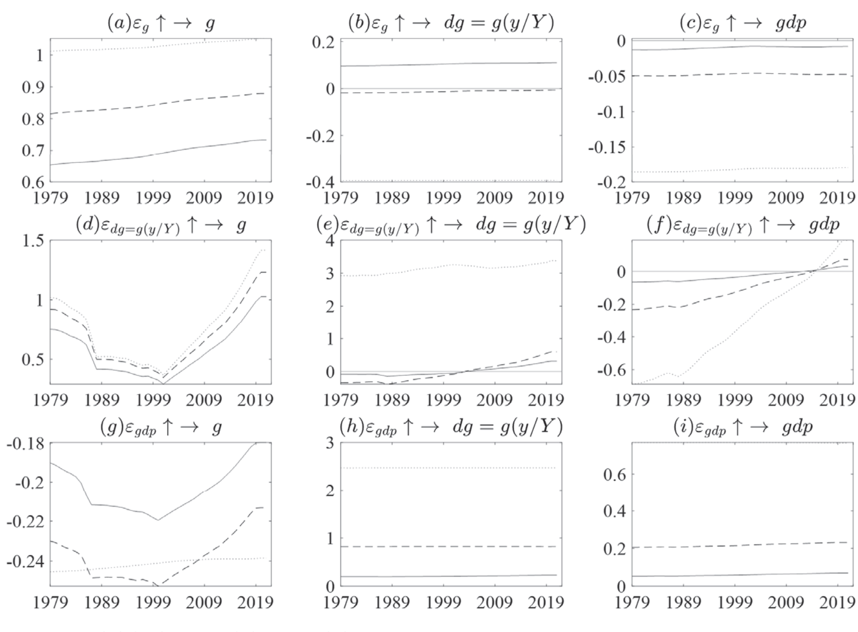

Figure A6. Graph (**a**–**i**) is the time-varying elasticity of government expenditure. Where g is the government expenditure $dg = g(y/Y)$ is the government expenditure times the proportion of potation gross domestic product and gdp is the gross domestic product per person. Composed by the authors.

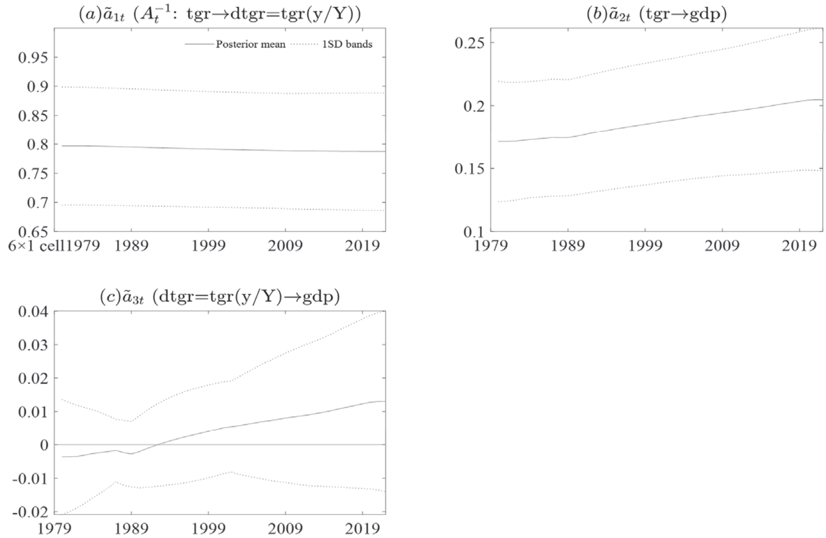

Figure A7. Graph (**a**–**c**) is the posterior draws for each data series for government revenue. Estimation results of $\bar{a}_{1,t}$ on the TVP regression model for the simulated data. True value (solid line), posterior mean (bold) and 95% credible intervals (dashed). The True models are Markov-switching coefficient and stochastic volatility. The TVP regression model with time-varying coefficient and stochastic volatility is fitted. Where tgr is the total government revenue $tgr = g(y/Y)$ is the g total government revenue times the proportion of potation gross domestic product and gdp is the gross domestic product per person. Composed by the authors.

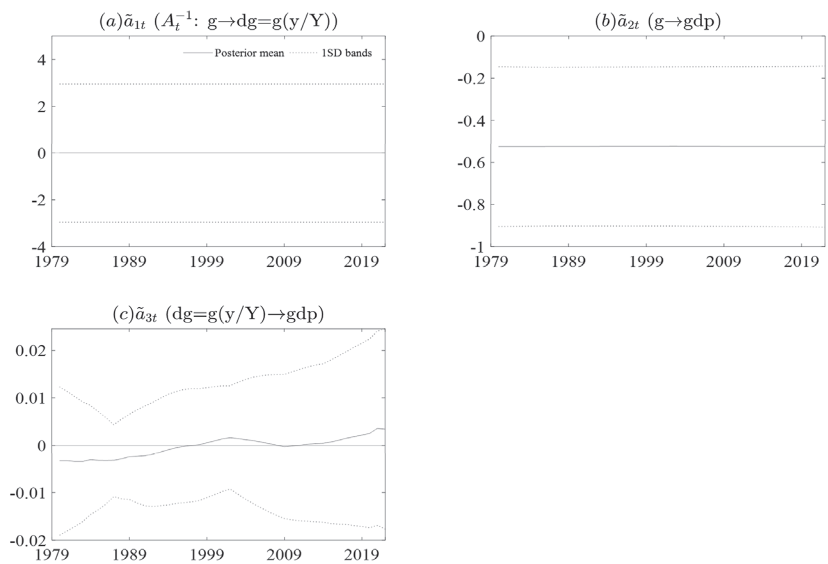

Figure A8. Graph (**a**–**c**) is the posterior draws for each data series for government expenditure. Estimation results of $\bar{a}_{1,t}$ on the TVP regression model for the simulated data. True value (solid line), posterior mean (bold) and 95% credible intervals (dashed). The True models are Markov-switching coefficient and stochastic volatility. The TVP regression model with time-varying coefficient and stochastic volatility is fitted. Where g is the government expenditure $dg = g(y/Y)$ is the government expenditure times the proportion of potation gross domestic product and gdp is the gross domestic product per person. Composed by the authors.

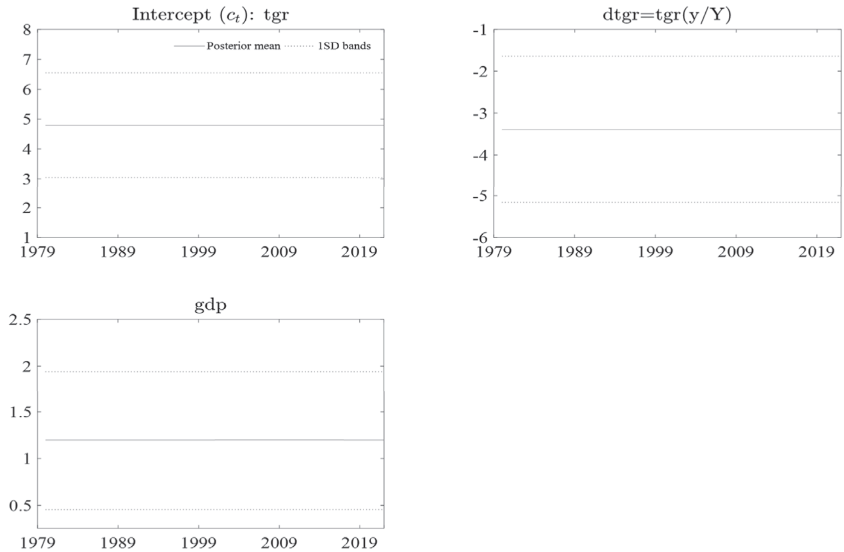

Figure A9. Graph is the evolution sequence of structural information for government revenue. Where tgr is the total government revenue $tgr = g(y/Y)$ is the g total government revenue times the proportion of potation gross domestic product and gdp is the gross domestic product per person. Composed by the authors.

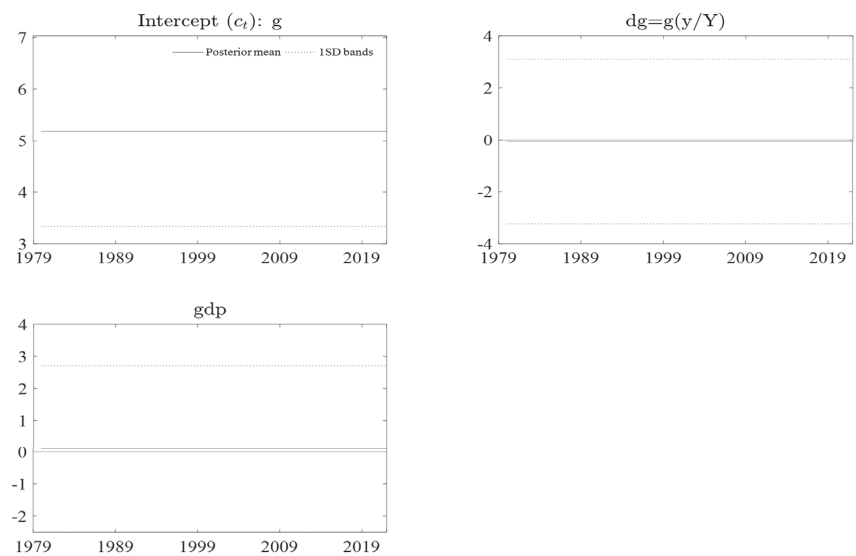

Figure A10. Graph is the evolution sequence of structural information for government expenditure. Where g is the government expenditure $dg = g(y/Y)$ is the government expenditure times the proportion of potation gross domestic product and gdp is the gross domestic product per person. Composed by the authors.

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Article

A Scientometric Review of Grain Storage Technology in the Past 15 Years (2007–2022) Based on Knowledge Graph and Visualization

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Abstract: Food storage helps to ensure the food consumption needs of non-agricultural populations and to respond to major natural disasters or other emergencies, and the application of food storage technology can reduce post-harvest food losses. However, there are still obvious shortcomings in coping with large grain losses. Therefore, quantitative analysis of the research hotspots and evolutionary trends of grain storage technology is important to help the development of grain storage technology. This article uses the Web of Science database from 2007 to 2022 as a data sample with the help of CiteSpace software to analyze the basic situation, research hotspots, and evolutionary trends to draw a series of relevant knowledge maps. Visual analysis revealed that the number of publications had grown rapidly since 2015. First, the *Journal of Stored Products Research*, *Journal of Economic Entomology*, and *Journal of Agricultural and Food Chemistry*, with citation frequencies of 929, 536, and 453, should be focused on in order to keep up with the latest research developments in this field. The United States, China, and Brazil occupy dominant positions in relation to grain storage technology studies in general. Purdue University, Kansas State University, and Agricultural Research Institute ranked the top three in terms of the number and centrality of publications. In terms of research hotspots, the centrality of temperature, insects, carbon dioxide, and quality were 0.16, 0.09, 0.08, and 0.08. It shows that the field of grain storage technology in recent years has focused on grain storage temperature, pest control, and grain storage quality research. From the perspective of the evolution trend, the life cycle of emergent words lasts for several years, after which the strength of emergent words slowly decreases and is replaced by new emergent words. Mortality was the first keyword to appear and remained from 2007 to 2011, indicating that research on fumigants and their toxicity, as well as pest mortality under air fumigation and chemical fumigation conditions, became more popular during this period. In recent years, new terms have emerged that had never been used before, such as "grain quality" (2019–2022) and "stability" (2020–2022). We can find that people pursue food quality more with the improvement of people's living standards. In this context, future research should seek more efficient, safe, economical, and environmentally friendly methods of grain storage and continuously improve the level of scientific grain storage.

Keywords: postharvest losses; food security; grain storage; CiteSpace; visualization

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1. Introduction

Food is the basic means of living for the survival and development of human society and is an important material to stabilize the market and ensure the livelihood of the nation [1]. Food security is an important guarantee for world peace and development, as well as an important foundation for building a community of human destiny, and all countries in the world give top priority to the issue of food security [2]. However, global food security is facing serious challenges. In recent years, adverse factors affecting world food security have increased [3]. The interplay of economic recession and food trade supply chain disruption is caused by international conflicts and extreme weather [4]. COVID-19 has exacerbated instability and uncertainty in the global food supply system [5]. The new crown outbreak in late 2019 not only poses a formidable challenge to global health security but also puts global food security in jeopardy [6]. Food insecurity is primarily related to food waste and food loss; food waste is the reduction in the quantity or quality of food due to the decisions and actions of food service providers and consumers [7]. Food losses include the harvested crop throughout the entire food supply chain. Losses can be broadly classified as weight loss, quality loss, nutritional loss, seed viability loss, and commercial loss [8]. Grain is a living organism with hygroscopic and respiratory characteristics. Grain respiration during the storage chain causes loss of nutritional value, metabolites, and physiological parameters (germination and vitality) of food products, while the development of fungal and insect pests inside the grain pile directly accelerates the process of grain deterioration [9]. Appropriate measures are needed to maintain the quality of grains and reduce grain losses [10]. Solutions to the global food crisis and improvements in the food security situation can be achieved by increasing food production and preventing losses in the food supply chain [11]. So far, most scientific research efforts have been aimed at increasing agricultural crop yields, but reducing post-harvest losses may be a sustainable solution for increasing food availability, reducing pressure on natural resources, eliminating hunger, and improving farmers' livelihoods, especially in developing countries [12–14].

The current literature that systematically summarizes the current status of grain storage technology research is mostly a qualitative summary and collation analysis. Manandhar et al. [15] evaluated different post-harvest grain storage practices of farmers in developing countries around the world and different post-harvest losses associated with the grain supply chain, based on which a rational grain storage structure was proposed and used to effectively reduce post-harvest grain storage losses. Hussain et al. [16] reviewed the recent research progress in the application of classical and non-destructive techniques to evaluate the safety and quality of cereals and their products. The advantages and limitations of these technologies are presented, and future trends and challenges are elucidated. Paul et al. [17] reviewed the current status of established post-harvest pest control methods and emerging pest control technologies and discussed the role model and potential of these technologies in developing a green approach for effective control of storage pests at all stages. Moirangthem et al. [18] reviewed the latest applications of ionizing radiation, modified atmosphere, and dielectric heating in grain storage pest control. Reading review articles in the field of grain storage technology reveals that although a large number of papers and research literature have been published in different journals by scholars in the field of grain storage technology. However, there are very few systematic analyses using new bibliometric tools or visual analysis tools (e.g., CiteSpace). There is also less review literature that combines quantitative visualization methods to analyze the current state of research and future research trends in the field.

It is necessary to conduct a systematic analysis of existing research results to gain a deeper understanding of the current status and future trends of grain storage technology research. Based on this, this paper conducted basic situation analysis, research hotspot analysis, basic knowledge identification, and evolution trend analysis using CiteSpace software and Web of Science database from 2007 to 2022 related literature in the field of grain storage technology as data samples. The purpose of the work was to show the evolution path of grain storage technology research by drawing a series of related knowledge maps. It provides a reference for further theoretical research and practical exploration of grain storage technology.

2. Data Collection and Research Methods

2.1. Data Collection

The research object of this paper is the literature related to the field of grain storage technology, and the data source is the Web of Science (WOS) database. Web of Science is the world's largest comprehensive academic information resource covering the largest number of disciplines, with over 9000 peer-reviewed, high-quality journals (covering 178 disciplines) in the natural sciences, engineering, biomedicine, and other research fields [19]. The rich and powerful search function of the Web of Science makes it easy to quickly find valuable scientific information and obtain a comprehensive understanding of research information on a particular subject or topic. Users can search across all databases subscribed to the platform at the same time or select one of them for a single search [20]. The Impact Factor (IF) introduced by Web of Science has become a common international journal evaluation index, which is not only a measure of the usefulness and display of the journal but also an important indicator of the academic level of the journal and even the quality of the paper [21]. CiteSpace is based on the WOS data format, and data downloaded from a non-WOS database must be converted to the WOS data format. A subject search was selected to cover the research status in the field of grain storage technology as comprehensively as possible, and the literature data spanning about 15 years from January 2007 to May 2022 were collected with a cut-off time of 31 May 2022. The search topics were "Grain Storage Technology, Low-Temperature Storage, Controlled Atmosphere Storage, Grain Storage Technology AND Ventilation, Refrigeration, Atmosphere, Carbon Dioxide, Nitrogen, Gas, Temperature, Humidity, Insect, hermetic, detection, inspect, granary". A total of 1645 literature data were collected.

2.2. Research Methods

Knowledge mapping combines co-citation analysis theory and pathfinding network algorithms by integrating modern bibliometrics and information science. Present the development history, frontier areas, and research hotspots of this research topic in the form of a visual map [19]. It is difficult to sort out and judge the literature in a certain research field as a whole in the traditional literature analysis method. The traditional literature analysis method belongs to qualitative analysis, which is by sorting out the main contents of the literature, and it is difficult to grasp the research status comprehensively and accurately from a large amount of data. It depends on the size of the researcher's reading volume and summarizing ability, which has a certain subjectivity [22]. The quantitative analysis represented by knowledge mapping has begun to be widely used in review research with the rise and popularity of Internet technology, which reveals the dynamic development pattern of the knowledge domain through data mining, information processing, knowledge measurement, graphic drawing, and provides practical and valuable references for disciplinary research [23]. At present, the main tools for mapping knowledge in academia are CiteSpace, SPSS, Ucinet, VOSviewer, etc., among which CiteSpace software is the most commonly used tool. The main function of CiteSpace software is to present and analyze the evolutionary trends and knowledge association status of disciplinary frontiers through visualization functions such as keyword cooperation, institutional distribution, author collaboration, and literature coupling [24]. The information visualization tool used in this paper is CiteSpace software, version CiteSpace 6.1.R1 (64-bit). CiteSpace is a scientific bibliometric visualization and analysis software developed by Prof. Chaomei Chen of Drexel University, based on the Java environment platform, which shows the research field through the size of nodes, network connectivity, and other elements CiteSpace is a scientific bibliometric visualization and analysis software based on Java environment platform [25]. Centrality is a measure of the importance of a node in a network by which the importance of the literature is discovered and measured, according to CiteSpace author Dr. Chen [26]. Given this, this paper uses CiteSpace software as a visualization tool for the study to draw a series of relevant knowledge maps and analyze the research overview and research dynamics in the field of grain storage technology.

The process of conducting the review in this paper is divided into three steps: in the first step, the current state of research in the field is analyzed based on the number of publications in the literature. The authors and institutions are analyzed using CiteSpace, and the main research in the field is analyzed by studying representative literature. The second step consists of an analysis of analyzing the research hotspots, frontiers, and trends in the field. CiteSpace is used to perform co-word analysis and cluster analysis on the literature and then study representative literature based on the results to derive research hotspots, frontiers, and trends. In the third step, future research directions are proposed by synthesizing the results of the analysis.

3. Results

3.1. Trend Analysis of Literature Publication

The annual number of publications and the annual cumulative number of publications for grain storage technology research in the Web of Science database was plotted, as shown in Figure 1.

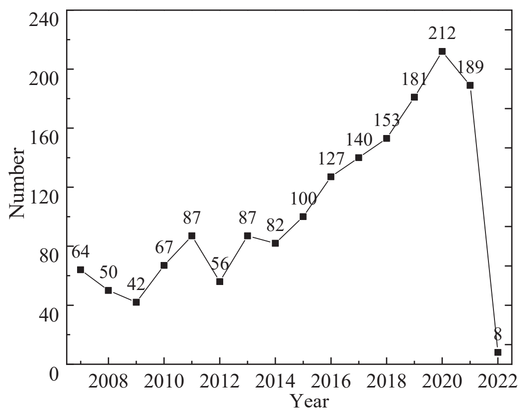

Figure 1. The number of articles published from 2007 to 2022.

The trend of publications on the Web of Science from 2007 to 2015 is relatively stable. The increasing trend is slow, with an annual average of about 60 publications, although the cumulative number of publications has increased each year. It belongs to the budding stage of research discussion and accumulation, and it has not yet formed a more complete disciplinary form. The increase in the number of publications accelerated from 2016, reaching 153 in 2019 and peaking at 212 in 2020. This indicates that more and more people are engaged in research on grain storage technology, the heat of research on grain storage technology is increasing, and scholars are paying more attention to it. The decline in the number of published papers by 2021 may be related to the emergence of emerging fields. It may take some time for the research to produce results as technology evolves and scholars begin to combine research with smart technologies. The 2022 article is not representative of the whole year because it was only retrieved in May.

3.2. Analysis of Journal Co-Citation Network

Journal co-citation analysis is performed on journals in which cited articles appear (Cited Journal), and the co-citation network of journals can be plotted by CiteSpace. The value of "Year Per Slice" is set to 1, a time partition of 1 year is used, and the node type is set to Cited Journal, which finally generates a knowledge graph of grain storage technology research co-cited journals, as shown in Figure 2. Table 1 shows the top 15 cited journals.

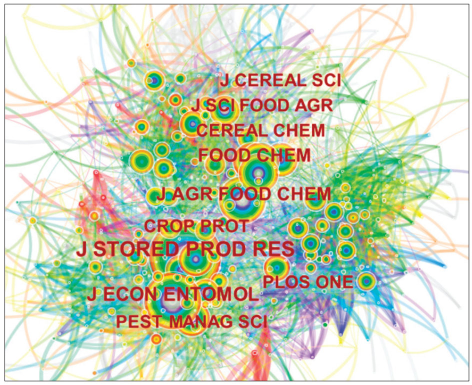

Figure 2. Journal co-citation network.

Table 1. Journals information table of the top 15 cited frequency.

Ranker	Cited Frequency	Centrality	Journal
1	929	0.01	*Journal of Stored Products Research*
2	536	0.01	*Journal of Economic Entomology*
3	453	0.03	*Journal of Agricultural and Food Chemistry*
4	349	0.03	*Food Chemistry*
5	318	0.02	*Crop Protection*
6	311	0.03	*Cereal Chemistry*
7	288	0.02	*Journal of The Science of Food and Agriculture*
8	256	0.02	*Pest Management Science*
9	249	0.06	*Journal of Cereal Science*
10	247	0.04	*PloS One*
11	239	0.04	*Annual Review of Entomology*
12	218	0.05	*Journal of Food Science*
13	201	0.04	*Food Engineering Reviews*
14	182	0.01	*Food Control*
15	174	0.02	*International Journal of Food Microbiology*

Figure 2 shows the results of the co-citation analysis of journals published in the literature related to grain storage technology. At the same time, the level of influence of each journal publication can be visualized by analyzing the citation frequency and centrality of journals [23]. To comprehensively reflect the distribution pattern of co-cited source journals, the top 10 journals in terms of citation frequency and their centrality were summarized by querying the relevant information in the background of the atlas. The top three journals with the most nodes, as seen in Figure 2, are Storage Products Research, Economic Entomology, and Agricultural and Food Chemistry, with citation frequencies of 929, 536, and 453, respectively. It shows that these three journals ranked top in citation frequency which are important windows to explore the research progress and development trend in this field. Centrality is a measure of the importance of nodes in the network by which the importance of journals is found and measured [27]. *Journal of Cereal Science*, *PloS One*, and *Journal of Agricultural and Food Chemistry* are the top three journals in terms of centrality. It can be found that there is no positive correlation between citation frequency and centrality by comparing journal frequency with centrality ranking, which means that even a high citation frequency does not necessarily indicate that the journal is influential. The *Journal of Agricultural and Food Chemistry* is the most cited and centered journal. This indicates that it has the greatest utility in the overall network of cited journals and is the top journal in the discipline of agricultural and forestry sciences. The *Journal of Cereal Science* and the *Journal of Food Science* is not among the top journals in terms of citation frequency, but their centrality ranks first and second among all journals, and their importance and authority in research on grain storage technology cannot be overstated. The *Journal of Cereal Science* was established in 1983 to provide an international forum for the publication of high-level original research papers on the functional and nutritional quality of cereals and the relationship of their products to the grains used. The *Journal of Food Science*, published in 1961, covers all aspects of food science.

The journal co-citation analysis shows the research journals that cite journals related to grain storage technology in international studies. It indicates that the research results of these journals are recognized and adopted in international studies, and the results can guide researchers to quickly find suitable journals for publishing papers related to grain storage technology.

3.3. Analysis of Author Cooperation Network

The analysis of posting authors and their collaborative networks can identify the main research teams in a research field, present the collaborative relationships between different researchers, and clarify the core figures in the field [27]. Based on the CiteSpace visualization tool, the network cooperation analysis was performed by clicking the "Author" function in CiteSpace, and the lines between the nodes represented the cooperation status among the cited authors in the same literature. The collaborative network knowledge graph of authors posting in the field of grain storage technology is shown in Figure 3, with the number of co-occurring nodes being 565, the number of connections being 653, and the network density being 0.011. The top 20 authors posting according to the final algorithm of CiteSpace are listed in Table 2.

Figure 3. Author cooperation network map.

Table 2. Author information table of the top 20 published articles.

Anker	Count	Centrality	Author	Anker	Count	Centrality	Author
1	40	0.05	Baributsa D	11	16	0.05	Baoua IB
2	33	0.02	Murdock LL	12	15	0.00	Du SS
3	27	0.00	Arthur FH	13	15	0.01	Opit GP
4	23	0.00	Jayas DS	14	15	0.01	Stejskal V
5	23	0.02	Liu ZL	15	14	0.00	Coradi PC
6	20	0.00	White NDG	16	14	0.01	Daglish GJ
7	19	0.00	Athanassiou CG	17	14	0.00	Hubert J
8	18	0.01	Mvumi BM	18	13	0.00	Amadou L
9	17	0.01	Elias MC	19	13	0.01	De Oliveira M
10	17	0.01	Maier DE	20	13	0.01	Liu QZ

Consistent with observations in other research areas, a small group of prolific authors has contributed considerably to research publications on grain storage technology. The most productive author in grain storage technology research is Baributsa from Purdue University, with research interests in Pest Management, Agricultural Entomology, Storage Entomology, and Grain storage. Murdock, also from Purdue University, has the same research interests as Baributsa, followed by Arthur from Agricultural Research Service United States. He interconnects Ecology, Warehouse, Biopesticide, Physical control, and Relative humidity in the investigation of issues within PEST analysis. His Pesticide study incorporates themes from Pest control, Chemical control, and Integrated pest management. Authors with a high volume of publications are not necessarily highly centric-scholars. They are the leading scholars who have had a fundamental impact on the development and evolution of grain storage technology when the nodes have high school cardinality [28]. Their work deserves more attention because it may change the direction of grain storage technology research. In terms of the influence of scholars, Liu and Baoua have fewer publications but higher centrality. The strength of representative scholars and core research teams in the field of grain storage technology can be determined by analyzing the collaborative networks of the authors. Authors who published a large number of articles showed clear network characteristics, with Baributsa and Murdock forming the largest core collaborative network. This indicates that these core authors have established a high-yield author research team in the field of grain storage technology, which has initially taken shape. It can be noted that the density of graphical linkages is particularly high, which proves that the research on grain storage technology has initially matured and formed a good scale of clustering and made more contributions to the development of grain storage technology. The fragmented scholars should cooperate and communicate more with other scholars to work together for the long-term development of the field of grain storage technology.

3.4. Analysis of Country Cooperation Network

Based on the CiteSpace visualization tool, that node type selects the Country node and runs the software to obtain the country (region) cooperation map. The cooperation network knowledge map of research literature issuing authors in the field of grain storage technology is shown in Figure 4, where the number of nodes is 565, the number of connections is 653, and the network density is 0.011. The number of issuing in the top 20 countries is listed in Table 3 according to the final algorithm of CiteSpace.

Figure 4. Country cooperation network map.

Table 3. Information table of the top 20 major research countries with the published article.

Anker	Count	Centrality	Country	Anker	Count	Centrality	Country
1	354	0.17	USA	11	39	0.03	ITALA
2	243	0.10	CHINA	12	38	0.03	KENYA
3	173	0.08	BRAZIL	13	36	0.00	MEXICO
4	126	0.11	CANADA	14	35	0.02	ARGENTINA
5	78	0.06	AUSTRALIA	15	34	0.04	NIGERIA
6	69	0.07	INDIA	16	34	0.05	GREECE
7	59	0.02	PAKISTAN	17	31	0.07	SPAIN
8	54	0.3	ENGLAND	18	27	0.04	JAPAN
9	42	0.02	KOREA	19	26	0.00	POLAND
10	42	0.04	GERMANY	20	25	0.00	EGYPT

The three countries with the largest nodes are the United States, China, and Brazil, with 354, 243, and 173 publications, respectively. It is relatively one-sided to judge the development degree of grain storage technology in each country only from the number of published. Therefore, it can be found that the United States is the most influential country in the field of grain storage technology by comparing Figure 4 and Table 3. The U.S. leads other countries in both frequencies of publication and centrality and is the most active country in conducting research. It shows that the United States has the closest cooperation and exchange with other countries and plays an important role in international cooperative research. China and Brazil rank second and third, respectively, in terms of the number of publications but are slightly behind the UK in terms of centrality. China and Brazil still need to strengthen the links and cooperation with other countries to improve the relevant technology and enhance international influence to promote the further development of grain storage technology. The low number of published articles but high centrality rankings in the UK and Spain indicate that these two countries are also among the world leaders in the field of grain storage technology and still have room for development.

3.5. Analysis of Institutional Cooperation Network

The network cooperation analysis of institutes and institutions can be performed by clicking on the "Institution" function in CiteSpace. The collaborative network knowledge graph of research institutions in the field of grain storage technology is shown in Figure 5, with the number of cooperation nodes of 128 research papers between 2014 and 2021 being 1743 and the number of links at 3476, 1743 and 3476. n in top-n is set to 60 (meaning that the 60 most frequently cited documents are extracted in each time slice. The top 20 major research institutions with published articles according to the final algorithm of CiteSpace are listed in Table 4.

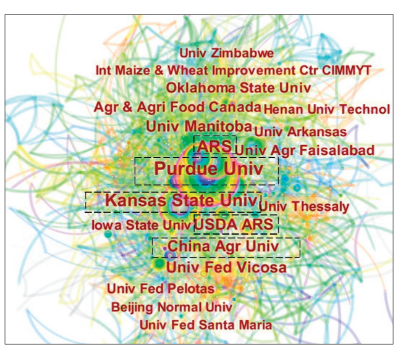

Figure 5. Institutional cooperation network map.

Table 4. Information table of the top 20 major research institutions with published articles.

Anker	Count	Centrality	Institution
1	86	0.23	Purdue University
2	55	0.17	Kansas State University
3	51	0.14	Agricultural Research Institute
4	41	0.08	USDA Agricultural Research Service
5	39	0.05	China Agricultural University
6	36	0.08	Federal University of Vicosa
7	36	0.06	University of Manitoba
8	29	0.08	Contact Agriculture and Agri-Food Canada
9	27	0.12	University of Agriculture Faisalabad
10	26	0.02	Oklahoma State University
11	22	0.02	University of Thessaly
12	22	0.00	University of Arkansas
13	22	0.09	Iowa State University
14	21	0.07	Univ Fed Pelotas Univ Fed Pelotas
15	20	0.03	University of Zimbabwe
16	20	0.08	International Maize and Wheat Improvement Center CIMMYT
17	20	0.01	Beijing Normal University
18	19	0.01	Federal University of Santa Maria
19	18	0.04	Henan University of Science and Technology
20	17	0.01	Chinese Academy of Agricultural Sciences

From Figure 5, it can be seen that a mature cooperation network has been formed among international research institutions. The number of connected lines shows that international research institutions on grain storage technology have close co-citation relationships and considerable prospects for subsequent development. The top five institutions in terms of the number of publications were Purdue University (86), Kansas State University (55), Agricultural Research Institute (51), USDA Agricultural Research Service (41), and China Agricultural University (39 times), while the top five institutions in terms of centrality were Purdue University (0.23), Kansas State University (0.17), Agricultural Research Institute (0.14), University of Agriculture Faisalabad (0.12), and Iowa State University (0.09). Among them, Purdue University, Kansas State University, and Agricultural Research Institute ranked the top three in terms of the number and centrality of publications. It proves that these three institutions have a high influence in the field of grain storage technology and have strongly promoted the development of grain storage technology research. It can also be seen from Figure 5 that the largest inter-team collaborative network was formed with Baributsa as the leader, and the network consisted of 86 writers, including Murdock from Purdue university and Njoroge from the University of Florida. The research team led by Baributsa from Purdue university has become a stalwart in the field of grain storage technology. Cooperation between universities, enterprises, research institutes, and other research institutions can better enable researchers to understand real-life needs, inspire research and form new research directions. Therefore, universities should strengthen cooperation and exchange with enterprises and research institutes in future research and work together for the long-term development in the field of grain storage technology.

3.6. Analysis of Hot Research Topics

CiteSpace's cooperation analysis of keywords and nomenclature in the literature provides access to the hotspots of grain storage technology research [27]. The keyword cooperation analysis was performed by selecting the "Keyword" function item to obtain a cooperation map of high-frequency keywords and terms, as shown in Figure 6, containing 491 nodes and 3811 connections. The circles in Figure 6 represent keywords and Table 5 lists the keywords with a cooccurrence frequency greater than 20 times.

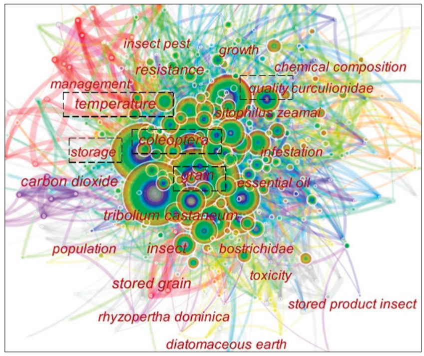

Figure 6. Keyword cooperation network map.

Table 5. Information table of the top 20 keywords.

Ranker	Count	Centrality	Keyword
1	196	0.10	grain
2	191	0.07	storage
3	166	0.16	temperature
4	166	0.07	coleoptera
5	128	0.08	quality
6	119	0.04	wheat
7	108	0.04	tribolium castaneum
8	84	0.05	essential oil
9	80	0.04	sitophilus zeamai
10	76	0.06	resistance
11	69	0.04	rhyzopertha dominica
12	68	0.06	growth
13	66	0.08	carbon dioxide
14	65	0.04	maize
15	64	0.02	toxicity
16	64	0.02	hermetic storage
17	61	0.09	insect
18	59	0.01	sitophilus oryzae
19	59	0.05	protein
20	55	0.02	pest

The cooperation frequency of grain and storage in the keywords as the retrieved subject terms are 196 and 191, respectively, which rank first and second in the cooperation frequency of keywords. The centrality of temperature, insect, carbon dioxide, and quality were 0.16, 0.09, 0.08, and 0.08, respectively, ranking in the top four of centrality. It can be inferred that the research on grain storage technology is mainly focused on the control of grain storage temperature and humidity, pest control, and grain quality. The keywords related to grain storage pests have high citation frequency. Finally, the following three major research hotspots in grain storage technology are derived by analyzing the frequency and centrality of each key subdivision in the chart:

1. Temperature: In the grain storage ecosystem, the temperature of the grain pile rises abnormally due to the concentration of heat, or the phenomenon that the temperature of the grain should rise instead of falling is called grain pile fever. It will further develop into mildew and eventually affect the use value and edible value [29]. Grain heat is mainly the result of respiration and heat accumulation by organisms in the grain pile. Reed et al. [30] studied the response of storage molds to different initial moisture contents of maize stored at 25.1 °C and its effect on respiration rate and nutrient composition. Aldred et al. [31] investigated the effect of three essential oils

and antioxidants on the control of growth and ochratoxin production by Penicillium wolframite and Aspergillus accidentally under different moisture and temperature conditions. Preventing grain storage heat needs to do a good job of insulation and moisture, improving storage conditions, timely ventilation, and airtight. Doing a good job of predicting and forecasting grain fever, early detection of problems, and timely treatment is also an important job to prevent losses due to grain storage fever [29]. In addition to simple indicators of anomalous changes in grain temperature and moisture [32], it is possible to predict the heat in grain storage by measuring the evolution of microbial taxa in grain storage [33]. Of course, it also needs to be equipped with appropriate equipment and trained inspectors. For the treatment of fever, different measures should be taken according to the cause of the fever. The most fundamental measure is to dry treatment if the grain heat and mold growth are caused by wet grain, such as drying, drying or mechanical ventilation, water, and temperature reduction.

2. Insect: The respiration of the stored grain pests will change the moisture and temperature of the grain pile, which will affect the grain security, cause weight loss and seriously decrease the quality. The excreta and carcasses of stored grain pests can contaminate food, leading to substandard health indicators and affecting human health [33]. Gas-conditioned grain storage is the world's most recognized green, safe, and effective grain storage pest control technology, unlike the traditional drug fumigation to kill insects, which is filled with a high concentration of carbon dioxide or nitrogen gas in a well-sealed silo to destroy the living environment of insects and mold. This results in the death of pests and reduces the respiration of grain to improve grain quality and safe storage [34]. In addition, a portion of scholars has studied low-risk, less contaminated fumigant insecticides. Hertlein et al. [35] concluded that carbendazim is effective in controlling important pests associated with grain storage, as well as insect strains that have developed resistance to other grain protectants and have low toxicity to mammals. Safe storage and protection of grain also include the use of plant-based fumigants as a green control technique. Several scholars have studied the repellent effect and fumigant activity of herbs and essential oils against storage pests [36–38]. A theoretical basis for the development and application of plant fumigants in the integrated management of food pests. More research is needed in the future to develop formulations to improve their efficacy and stability and reduce their cost. Further experiments are needed to ensure that the consumption of fumigated grain does not negatively affect humans and other animals. There are also biological and physical control methods. Temperature management is one of the best biological control methods, which involves ventilating and cooling the grain to inhibit the growth of insect populations, as well as using thermally forced air distributed in food processing facilities to thermally kill insects. Nanopreparations also have great potential in developing alternative pest control methods. Rajkumar et al. [39] showed that polymeric chitosan nanoparticles could improve the insecticidal activity of essential oils by controlling the effective release of essential oils to storage product pests. Physical control methods have the characteristics of safety and are not easy to produce physiological resistance, which can effectively prevent and control grain storage pests and achieve the purpose of safe grain storage. Inert powders have all had a long history of use as grain storage protectants, and recent studies have shown that diatomaceous earth is considered the best class of natural powder insecticides available. The inert powder has a long history as a protective agent for stored grain. Recent studies have shown that diatomite is considered to be the best among natural powder insecticides [40]. Erturk et al. [34] studied the insecticidal activity of a new diatomaceous earth wettable powder against rice weevil. It was also tested for its effectiveness against adult Streptococcus Ricinus under laboratory conditions. Sealed storage has been of interest as a physical method to control post-harvest pests, and there is a growing body of research on the use of sealed containers to control stored

pests. Njoroge et al. [41] used O_2 sensors, acoustic sensors, and visual observation to further measure the effect of confined storage on pest activity and mortality. Abass et al. [42] tested seven maize storage methods based on the Central Corridor maize growing system in Tanzania and compared them with the traditional polypropylene bag storage method. The results showed good results for the insecticidal treatment of maize using the traditional Tanzanian method of storage in polypropylene bags. Chemical pesticides should be avoided for public health as well as health reasons. Therefore, closed storage without pesticides is preferred, but storage materials need to be made affordable to farmers. It is also important to ensure that farmers handle and manage these technologies properly. Grains must be properly dried before storage, and re-infestation during the intermittent opening of sealed containers should be prevented as much as possible.

3. Quality: The results showed good results in the insecticide treatment of maize using the traditional Tanzanian method of storage in polypropylene bags [43]. Post-harvest grain will continue to respire during storage and produce microorganisms, such as mold, that can be harmful to the quality of stored grain. Temperature, air humidity, and time are the main factors causing changes in the grain storage process. High temperatures and humidity can lead to deterioration in grain storage quality and production losses. Qu et al. [44] investigated the effect of microwave heating of wheat seeds on flour gluten, flour quality, pasting properties, and baking (buns and cookies) properties. The experimental results showed that microwave treatment could inactivate LA and LOX and prolong the storage period. Keskin et al. [45] evaluated the effect of wheat sample storage and granaries L. infestation on the process characteristics of wheat samples, and the results showed that the physical, chemical, and physicochemical properties of wheat and flour were affected by wheat and flour mold. Mutungi et al. [46] conducted on-farm experiments to investigate the effects of smallholder farmers' maize harvesting and handling practices on the quality of products before and during storage at two different agricultural sites. A rapid method to identify and measure stored grain quality is needed that can help reduce stored grain quality losses and establish appropriate storage conditions to verify how storage technology affects the rate of quality deterioration. Near-infrared spectroscopy (NIRS) is an efficient technique for the chemical characterization and screening of agricultural crops. Belzoni et al. [47] explored the potential of near-infrared spectroscopy (NIRS) as a process analytical technology for the evaluation of soybean quality under different storage conditions. Pohndorf et al. [48] used kinetic models and Arrhenius' law to verify the oxidative stability of soybeans under different storage conditions. The study also provided technical support for controlling temperature and relative humidity during soybean storage in hot and humid regions. A large number of studies have shown that gas conditioning and low-temperature storage as a green grain storage technology can effectively solve the problem of residual harmful substances in stored grain and slow down the aging of stored grain, and effectively inhibit grain quality deterioration. However, the ultimate purpose of the storage is circulation. Therefore, the quality change of paddy after the storage is directly related to the economic efficiency of grain enterprises, and the research on controlling the quality change of paddy after unsealing is also extremely important.

3.7. Analysis of Frontiers Trending

In this paper, the Kleinberg burst detection algorithm was used to detect burst words in the literature space and identify several terms that represent the frontiers of research [27]. The node type was set to "Keyword" and "Timezone", and the top 30 emergent words were arranged in ascending order of their emergence time together with the keyword time zone map, as shown in Figure 7. Year in the figure represents the year of the first occurrence, Strength represents the burst intensity, and Begin and End represent the years of beginning and ending within the burst period.

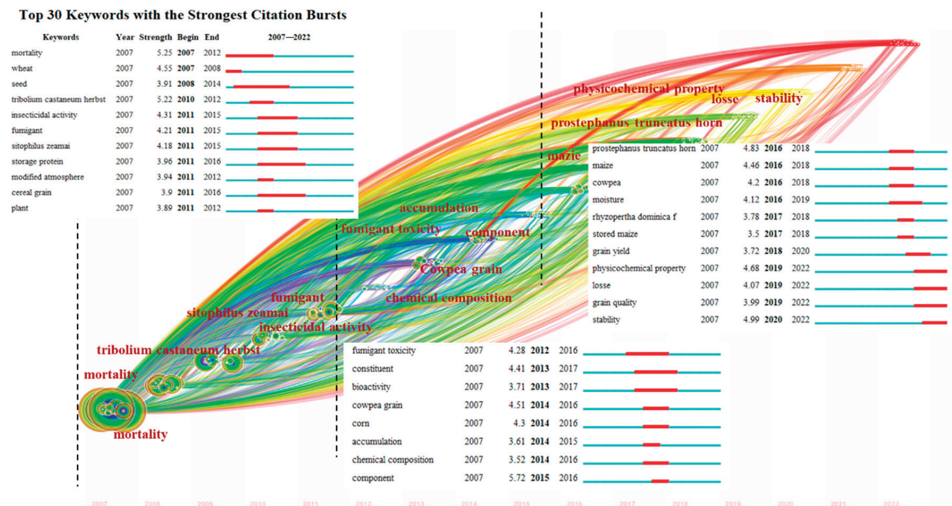

Figure 7. Top 30 burst keywords detection.

As shown in the figure, the life cycle of emergent words lasts for several years, after which the strength of emergent words slowly decreases and is replaced by new emergent words. In this way, it is possible to obtain a quick overview of the overall leap and transition process of hot topics in the field of grain storage technology. Mortality was the first keyword that started to emerge and was maintained from 2007 until 2011, during which mortality (2007–2012), tribolium castaneum herbst (2010–2012), insecticidal activity (2011–2015), fumigant (2011–2015), and modified atmosphere (2011–2012) all had high emergence intensity. This was closely followed by storage protein (2011–2016), sitophilus zeamai (2011–2015), wheat (2007–2008), and seed (2008–2014). It shows that studies on fumigants and their toxicity, as well as studies on pest mortality under chemical fumigation conditions, were more popular during this period. Overall, the current study is relatively homogeneous. Fewer emergent words appeared in 2012–2015, which were fumigant toxicity (2012–2016), constituent (2013–2017), bioactivity (2013–2017), cowpea grain (2014–2016), corn (2014–2016), accumulation (2014–2015), chemical composition (2014–2016), and component (2015–2016), with cowpea grain and component being more prominent and becoming the main research in this phase. In addition, fumigation and chemical pest control still showed research fervor. The years 2016–2020, on the other hand, showed a large number of emergent words, with stability (2020–2022), prostephanus truncatus horn (2016–2018), physicochemical property (2019–2022) with the highest centrality of 4.99, 4.83, and 4.68 respectively. There are also emergent words, such as grain quality (2019–2022) and stability (2020–2022), that have never appeared in the past. It is not difficult to find that the research frontiers of grain storage technology research in recent years are fumigant toxicity, physicochemical property, and grain quality. People are seeking foods with improved flavor while limiting the use of additives as people's living standards improve [49]. Weight loss, quality loss, nutrient loss, and seed vigor loss have become new research hotspots. In this context, achieving high-quality and safe food and identifying appropriate processing and sterilization technologies have also become key issues. Several food processing techniques have been explored and implemented with the ultimate goal of maintaining the safety, freshness, and nutritional attributes of the food. It indicates that the research related to grain storage technology will be carried out around it in multiple aspects and dimensions for quite some time in the future. Protecting food from loss is the greatest principle of food storage and the goal of maximizing the benefits to all and society. Currently, the protection of stored grain has been introduced and is gradually becoming intelligent [32]. It can achieve low temperature, low oxygen, and low energy consumption green management of the grain in stock to achieve loss reduction, consumption reduction, and freshness preservation with the Internet of Things + intelligent grain storage technology [50]. Food damage can even be reduced to near zero if the technology is mature and scientific storage and management practices are used [51].

4. Discussion

The summary of the above results found that the relevant scholars have conducted more in-depth research on grain storage technology and achieved certain scientific results. Further reading of the relevant literature summarizing the important nodes involved in the operation of the software revealed that the following technologies are mainly used to prevent grain storage losses: grain storage pest control technology, low-temperature storage technology, and airtight and air-conditioned grain storage technology. The quality of the grain before storage is also an important factor in determining whether it can be stored safely in the long term. Therefore, the grain can be treated with UV-C, microwave, magnetic field, and other physical methods before storage [52].

Further analysis revealed that pest control is a key aspect of grain storage to ensure grain quality, as losses during grain storage are mainly caused by pests [18,53]. At present, there are three main methods of grain storage pest control: biological, physical, and chemical. Physical control techniques for grain storage pests include high-temperature and low-temperature insecticides, air conditioning (high CO_2 or low O_2) insecticides, radiation, inert powder, drying, etc. The high-temperature insecticide has the advantages of short treatment time and good effect, but it is only suitable for the insecticidal treatment of a small amount of food, such as farmers [54]. Low-temperature freezing to kill insects is due to the poor cold tolerance of grain storage pests [55]. Mechanical ventilation can be used to reduce the temperature in practice and do a good job in the warehouse insulation transformation, so the cryogenic freezing insecticide and cryogenic storage technology have an organic combination. The control of grain storage pests through drying technology includes two aspects, one is synchronized with high-temperature insecticide technology [56], and the other is by reducing moisture [57]. The growth and development of grain storage pests are inhibited under the ecological conditions of dry grain piles. However, the control of stored grain pests may cause the weight loss of stored grain along with water loss of stored grain, which will bring huge economic losses to the grain storage enterprises [54]. Radiological control is the direct killing of pests or making them sterile and unable to reproduce by treating grains with high-energy radiation using radioisotopes or electron gas pedals [58]. The history of using inert powder as a grain storage protectant is very long. There are four basic types of inert powder used as grain storage protectants: first, clay, sand, and dust; second, synthetic silica-oxygen gel; third, non-oxidized silica-like powder; and fourth, diatomaceous earth [59]. Among them, diatomaceous earth may have a good prospect as a grain storage protective agent. The main advantage is that it has very low toxicity to higher animals, and diatomaceous earth is produced in more than 30 countries around the world [60]. In the past 10 years, relevant scholars focused on natural enemies of pests, entomopathogenic microorganisms, insect growth regulators, research and application of insect pheromones, and other aspects. The United States and other developed countries attach great importance to the research and development of biological insecticides or pest control agents, and many products are already on the market [61]. The application of monitoring traps will greatly improve the safety of grain storage if high concentrations of natural pheromones are extracted or efficient pheromone analogs of grain storage pests are synthesized based on controlled production costs for pheromone control of grain storage pests [62]. Chinese medicinal plants are rich in sources and species, and many of them have insecticidal activities. It is feasible to study the insecticidal effects of herbal plants and their extracts and use them to develop grain storage-related agents [63]. With the in-depth research and application of relevant advanced results, the innovation in biological control of grain storage pests focuses on the research of large-scale cultivation and release techniques of natural enemies of pests [64]. The essence of pest management is to take full advantage of environmental and natural factors to control pests. Biological and physical methods are considered first, and chemical methods should be used only when control fails. Chemical control methods consist of the use of insecticides to control pests in grain storage. The advantages are rapid and thorough insecticidal effects and low treatment costs. The disadvantages are contamination of the grain and the toxicity of the insecticide to both humans and animals [65]. It is still the most cost-effective means of killing insects despite the many disadvantages of chemical control methods.

Low-temperature food storage technology will receive more and more attention as mankind faces serious challenges to survival and the environment [66]. Several countries have applied low-temperature grain storage technology, which has greatly reduced the amount and use of grain storage chemicals. So far, the main way to achieve low temperature is still the grain cooler and other mechanical refrigeration, ventilation, underground low temperature, and solar adsorption refrigeration [67]. Among them, mechanical ventilation is the most commonly used low-temperature grain storage technology, which can effectively reduce grain temperature, eliminate condensation, reduce grain storage moisture, reduce moisture gradient, adjust the quality and increase humidity, and eliminate odor from grain piles [68]. It is commonly used in Australia, the United States, Canada, and other developed countries, where most farm vertical silos are equipped with mechanical ventilation facilities. From the perspective of international research and development dynamics, the focus of technological innovation in the coming period is to research and develop automatic control systems for grain storage ventilation and cooling with artificial intelligence [67]. The main purpose of air conditioning grain storage technology is to kill pests by changing the concentration of O_2, N_2, and CO_2 in the air [69]. Although the cost of fumigation is higher than the general fumigation technology, it can effectively maintain the grain quality without any pollution of the stored grain and does not affect human health [70]. The key to its technological innovation is the development of economic and practical airtight technology and airtight materials for grain silos, which can effectively improve the airtightness of grain silos and reduce the cost of grain storage while significantly reducing the cost of silo construction [71]. As a mature green grain storage technology, air conditioning and airtight grain storage can effectively maintain grain quality, effectively replace chemical supplies, and have no pollution to grain storage [72].

In summary, relevant scholars have conducted more in-depth research on grain storage technology and achieved certain scientific results. The research conclusions and recommendations made through the analysis of knowledge mapping are as follows. From the research profile, more and more people are engaged in grain storage technology research, and the heat of grain storage technology research is increasing. Fragmented scholars should cooperate and communicate more with other scholars to work together for the long-term development of the field of grain storage technology. In terms of research hotspots, the field of grain storage technology in recent years has focused on grain storage temperature, pest control, and grain storage quality. How to implement temperature-controlled grain storage technology in different bin types, grain storage ecological zones, and different grain varieties are the focus of researchers. The use of appropriate control techniques is important to maintain grain quality and quantity because grain storage pests cause significant grain losses each year. China is rich in sources and species of medicinal plants, and with the in-depth research and application of relevant advanced achievements. Various special active substances can be extracted and synthesized by using high technology and precision instruments in the future and used in combination with various existing means such as gas conditioning and fumigation. From the evolutionary trend, intelligent insecticidal instruments such as IoT insecticidal lamps are gradually coming to the fore. Pest data should be systematically collected and used for pest management decisions with the deepening of research on storage grain pest control and new tools for studying insect population sampling and the application of these data in computer-aided decision-making. Combining grain storage technology with IoT technologies, wireless transmission technologies, and big data analytics to maximize their advantages also deserves further study. In summary, relevant scholars have conducted more in-depth research on grain storage technology and achieved certain scientific results.

5. Summary

This paper uses CiteSpace to conduct quantitative and qualitative research in the field of science in a visual manner to improve knowledge and understanding of the research field of grain storage technology. The quantitative visualization and qualitative analysis were conducted using the Web of Science database from 2007 to 2022 as the data sample. It provides a valuable reference for a better and faster understanding of the basic overview and research progress in the field of grain storage technology research. It helps scholars broaden their research horizons, identify future research directions, and provide references for future research of related scholars. Currently, grain storage technology has introduced high-tech equipment and is gradually becoming intelligent. It is possible to reduce food damage to even close to zero using scientific storage and management practices. The future should seek more "efficient, safe, economic, health, green, environmental protection", new methods of grain storage, and new ways to continuously improve the level of scientific grain storage and improve social and economic benefits. Scholars should try more interdisciplinary collaborative research in subsequent research work to further advance the development of grain storage technology research. However, this study has some limitations. Although a relatively comprehensive literature database has been established, the choice of the search strategy and manual screening limited the collection of literature, and the data set not included in this study resulted in a small sample of missing data, which would affect the precision of the scientometric and thematic analysis to some extent. Based on these limitations, a more in-depth content interpretation and analysis are recommended for future studies.

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sustainability

Article

The Role of Live-Streaming E-Commerce on Consumers' Purchasing Intention regarding Green Agricultural Products

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Abstract: Live-streaming e-commerce has boosted the marketing vitality and possibilities of green agricultural products. However, academic research on this emerging marketing method remains insufficient. To fill this literature gap, this paper examines whether live-streaming e-commerce has gained consumers' trust and strengthened their intention to purchase green agricultural products. On the basis of a literature review, in this paper, we establish an evaluation system for live-streaming e-commerce which includes information quality, system quality, service quality, telepresence, and social presence and assumes that high-quality live-streaming e-commerce will increase consumers' green trust and, thus, strengthen green purchase intention. Altogether, 726 valid questionnaires were collected, and structural equation modeling (SEM) and stepwise regression were used to analyze the data. The results demonstrate that the five aforementioned dimensions of live-streaming e-commerce quality that were used as criteria positively impact green trust. The findings provide suggestions for green-product companies on how to improve their live-streaming quality to enhance consumers' purchase intention to realize economic and social value.

Keywords: green agricultural products; live-streaming e-commerce; green trust; green purchase intention

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1. Introduction

Sustainable development is the actual need and inevitable choice of human future development, and food safety is related to the life and death of human society. Green agricultural products, which are environmentally friendly, recyclable, and high-quality [1,2], not only follow the principle of sustainable human development, but also avoid the problem of food insecurity. By vigorously developing green agricultural products, one can promote the coordination of human society, economy, and ecology, and lay a solid foundation for sustainable development. In order to achieve sustainable development and ensure food safety, the Chinese government proposed that "quality promotes agriculture, and greenness promotes agriculture" in the "No. 1 Central Document". However, the market share of green agricultural products in China accounts for only 1% to 1.5% of the entire food market [3]. For consumers, in addition to price factors, insufficient understanding of green agricultural products and inconvenient purchase channels are the reasons for the low market share [4,5]. There is still a large consumer market to be tapped in China for green agricultural products.

Selling green agricultural products through live-streaming e-commerce is an emerging marketing method. According to the SOR framework [6], in the e-commerce environment, consumers are influenced by external stimuli and make purchases through their own internal evaluations. Existing research shows that consumers' purchase intentions of green agricultural products are usually based on trust [7–9]. How to use the emerging marketing method of live-streaming e-commerce as an external stimulus to generate trust and purchase intention among consumers is a problem worthy of research and exploration. This is also the core research question of this study.

Before the era of e-commerce, the factors that affected purchase intention regarding green agricultural products could be summarized as product factors (e.g., price, brand image, etc.), consumers' personal factors (e.g., habits, knowledge, income, etc.), and social-situation factors (e.g., social norms, etc.) [10,11]. With the rise and generalization of e-commerce, e-commerce quality has emerged as another decisive factor influencing consumers' decisions to make green purchases [12–14]. Based on the D&M information systems (IS) model proposed by Delone and McLean [15], it has been demonstrated that the information, system, and service quality (the updated IS success model) of e-commerce influences green purchases. High-quality information, systems, and services make consumers trust in e-commerce [16–19] and generate purchase intentions [7–9]. As a new form of e-commerce, although studies have pointed out that live-streaming e-commerce is characterized by virtual presence, including telepresence and social presence [8,20], there is still a lack of research on its impact on the purchase of green agricultural products.

This research will fill this academic gap and build on the extant research to explore how consumers can trust and purchase green agricultural products in the context of live-streaming e-commerce. This research adds telepresence and social presence from live-streaming e-commerce on the basis of an updated IS success model and theoretically defines the quality-evaluation framework of live-streaming e-commerce; we then propose that live-streaming e-commerce quality (LSECQ) affects green trust and, by extension, green purchase intention.

Based on the updated IS success model, this research takes information quality, system quality, service quality, telepresence, and social presence as the evaluation dimensions of live e-commerce quality in combination with the characteristics of live-streaming e-commerce. Based on the SOR framework, the five aspects of live-streaming e-commerce quality are used as external stimuli (S), namely, independent variables; green trust is used as organism assessments (O), namely, mediating variables; and green purchase intention is used as the response (R), the dependent variable of the research model. A survey was conducted from July 2020 to August 2020 among 726 volunteers. Structural equation modeling (SEM) and stepwise regression were used to analyze the collected data. The empirical analysis results reveal the factors that affect consumers' green consumption intention in live-streaming e-commerce, and we put forward targeted suggestions which can provide a theoretical basis for researchers and practitioners.

The rest of this paper is organized as follows. Section 2 presents a literature review related to this study; based on the extant research, hypotheses are constructed. Section 3 introduces the research methodology used in the present study, including how the variables are measured and the data collected. In Section 4, the empirical results are presented. Finally, conclusions are given in Section 5.

2. Literature Review and Hypotheses

There are many potential factors affecting consumers' purchase behavior, including personal factors such as personal habits, lifestyle, and environmental knowledge [10,21], as well as situational factors such as price, social norms, and marketing messages [10]. For consumers' online purchase behavior, many researchers use the stimulus–organism–response (SOR) framework. The SOR framework was built by Mehrabian and Russell [6] and is often used to explain the relationship between the external stimuli received by the people (S) and inner organism assessments (O) and their responses (R). Based on SOR, Gil and Jacob [22] examined the relationships between green perceived quality, green satisfaction, green trust, and green purchase intention. Similarly, Ahmed, W. and Zhang, Q. [23] studied the relationship between e-commerce service quality and consumers' green psychology, including green trust and consumers' green purchasing behavior. In these studies, green trust is seen as inner assessments of consumers under external stimuli acting as a mediating factor to influence their purchase intention.

This research focuses on the role of live-streaming e-commerce in consumers' purchase intention toward green agricultural products. Based on the SOR framework, green trust will act as an intermediary inner assessment factor (O) to influence the effect of live-streaming e-commerce (S) on purchase intention (R).

2.1. Green Trust and Live-Streaming E-Commerce Quality

In the e-commerce context, trust refers to an optimistic attitude and expectation concerning the goodwill and ability of trading partners or platforms to fulfill their promised obligations [24,25]. Green trust attributes this positive attitude and expectation to capabilities and reliability in terms of environmental performance [26,27]. On this basis, in this study, we define green trust in the live-streaming e-commerce context as live-streaming viewers' optimism and positive expectations concerning the platform and sellers' capabilities related to the environmental reliability of the products and services that they provide. Green trust usually arises from the consumers' perceived quality and value before and during the purchase process [22,28,29]. Referring to the existing literature, green trust depends on the quality of live-streaming e-commerce.

The information quality, system quality, and service quality constitute the updated IS success model to measure e-commerce quality [30–34]. High-quality information content and design help convince online consumers that a website is trustworthy [35,36], thereby creating trust in the products sold on the website. In addition, the operating system's stability and operability are also important in the network environment. If the system is running well and is flexible and easy to operate, this will increase the user's confidence and trust [37]. For live-streaming e-commerce, service quality mainly refers to timely response to consumers' needs, which could earn trust by resolving disputes and ambiguity effectively [38].

H1. *Green trust is positively related to live-streaming e-commerce's information quality.*

H2. *Green trust is positively related to live-streaming e-commerce's system quality.*

H3. *Green trust is positively related to live-streaming e-commerce's service quality.*

As an emerging form of e-commerce, live-streaming e-commerce has its own uniqueness, but research on how the quality of its uniqueness affects consumers' trust is still rare. The main different feature of live-steaming e-commerce compared to traditional e-commerce is the virtual presence brought by live streaming. Virtual presence is used to describe the subjective feelings of being immersed in a virtual world similar to offline consumption scenarios [8,20,39]. Compared with other products, virtual presence through live-streaming e-commerce with green agricultural products is more obvious because the live streaming usually occurs in the farmland or production bases of agricultural products, providing immersive experiences and interaction for audiences [40,41]. Furthermore, virtual presence includes social presence and telepresence [39,42,43]. Through live-streaming e-commerce with agricultural products, consumers feel the warmth and kindness of the streamer's enthusiastic explanations, defined as social presence [44]. Simultaneously, live streaming in farmland can make consumers feel as if they are physically present in the middle of farmland, a phenomenon called telepresence [45,46].

Live-streaming e-commerce's virtual-presence features are also crucial in generating green trust among consumers [8,47]. The live streaming of agricultural products allows viewers to witness the picking, digging, and processing of agricultural products through a computer screen to understand production methods. The resulting telepresence and social presence allow consumers to immerse themselves in a virtual world that resembles an offline consumption setting [8,20], thereby reducing consumers' uncertainty and psychological distance between themselves and merchants, which enhances consumer trust [46,48–50]. Accordingly, in this research, we propose the following hypotheses:

H4. *Green trust is positively related to live-streaming e-commerce's social presence.*

H5. *Green trust is positively related to live-streaming e-commerce's telepresence.*

In summary, this research advocates adding social presence and telepresence to the dimensions of live-streaming e-commerce quality evaluation, combined with information quality, system quality, and service quality in the updated IS success model, to jointly determine how the quality of live streaming affects the generation of consumer trust in green agricultural products.

2.2. Green Trust and Green Purchase Intention

Green purchase intention has evolved from common purchase intention, adding the internal motivation of consumers for environmental protection [51]. Trust is seen as an economically meaningful social relationship [52] and it plays an important role in the decision-making process for purchasing green products [53]. A lack of trust and confidence in green claims and characteristics attributed to products is a significant barrier to the purchase of green products [10]. Many existing studies have proved that trust influences purchase behavior regarding green products. Yin et al. [54] indicated that Chinese consumers' intent to purchase green foods is affected by the degree of trust in green food. Lam et al. [28] pointed out the positive impact of green trust on green purchase intention and proposed that green trust mediates consumers' green perceived value and green purchase behavior. Gil and Jacob [22] put green trust into the SOR framework and indicated the mediation effect of green trust between green perceived quality and purchase intention. Chen et al. [55] empirically proved that consumers' trust plays an important role in their willingness to purchase green-labeled food products.

The current study suggests that green trust positively affects consumers' purchase of green products. Thus, the following hypothesis is proposed:

H6. *Green purchase intention in live-streaming e-commerce is related positively to consumers' green trust.*

2.3. Research Model

On the basis of the theoretical exploration presented above, we propose that LSECQ affects green trust. LSECQ includes information quality, system quality, service quality, telepresence, and social presence. Green trust can also lead to green purchase intention. The research model is presented in Figure 1 below.

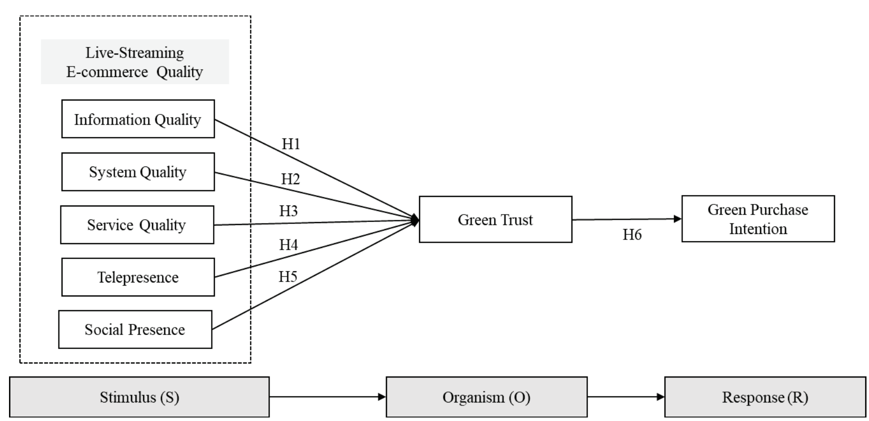

Figure 1. Research model.

3. Methodology

3.1. Measurements of Variables

An online questionnaire survey was distributed to collect data and test the research model. The questionnaire's content and measurement items were originally developed based on a literature review, then modified by marketing experts to fit this study's purposes. The survey questionnaire investigated respondents' demographic characteristics, such as age, gender, income, knowledge of green agricultural products, and purchase experiences with green agricultural products. The questionnaire's main measurement items are provided in Table 1.

Table 1. Measurement items.

Abbr.		Measurement Item	References
Live-Streaming E-Commerce Quality (LSECQ)			
Information Quality (InQ)	InQ1	In the green agricultural product live stream, the details about green agricultural products are correct.	[34,39,47,56–58]
	InQ2	In the green agricultural product live stream, the details about green agricultural products can be trusted.	
	InQ3	In the green agricultural product live stream, there are no errors in details about green agricultural products.	
	InQ4	In the green agricultural product live stream, the source of green agricultural product content is dependable.	
	InQ5	In the green agricultural product live stream, the streamer who displays the green agricultural product details is credible.	
System Quality (SyQ)	SyQ1	Anyone who is interested in the live room can enter the live room.	
	SyQ2	Even if many people enter the live room at the same time, there will be no delays or errors.	
	SyQ3	The audience can enter the live-streaming room that they are interested in at any time without time or place limitations.	
	SyQ4	After entering the live room, the audience can carry out any operation they are interested in without any inconvenience.	
	SyQ5	The live-streaming e-commerce platform allows audiences to watch video and hear sound with no stuck phenomenon.	
Service Quality (SeQ)	SeQ1	The streamer's response time to audience questions is acceptable.	
	SeQ2	The streamer is very happy to communicate with me.	
	SeQ3	The streamer can provide relevant information on my inquiry in a timely manner.	
	SeQ4	The streamer's response is closely related to my problems and requests.	
	SeQ5	The anchors can answer my questions and requests in time.	
Telepresence (TP)	TP1	While watching the green agricultural product live stream, I was totally immersed in the world that the live stream created.	
	TP2	While watching the green agricultural product live stream, it seems that I have really seen the products.	
	TP3	The production environment for green agricultural products that I watched through live streaming felt like an immersive experience.	
	TP4	The details on the green agricultural products on the live stream felt very real to me.	
	TP5	The green agricultural product live stream created a new world for me, and the world suddenly disappeared when the live stream ended.	

Table 1. *Cont.*

Abbr.		Measurement Item	References
Social Presence (SP)	SP1	While watching the green agricultural product live stream, I was totally immersed in the world that the live stream created.	
	SP2	While watching the green agricultural product live stream, it seems as if I really have seen the products.	
	SP3	The production environment for the green agricultural products that I watched through live streaming felt like an immersive experience.	
	SP4	While watching the green agricultural product live stream, there was a sense of personness in the live room.	
	SP5	While watching the green agricultural product live stream, communication with the streamer made me feel at ease.	
		Green Trust (GT)	
GT1		I trust the sellers of green agricultural products through live streaming.	[59–61]
GT2		I believe that the green agricultural products provided in the live stream are produced to high standards.	
GT3		The green agricultural products presented during the live stream will fulfill their commitments and guarantee environmental safety.	
GT4		The eco-friendly reputation of the green agricultural products presented during the live stream is commonly trustworthy.	
GT5		While watching the green agricultural product live stream, I felt that the environmental performance was generally dependable.	
		Green Purchase Intention (GPI)	
GPI1		I will consider purchasing green agricultural products through live streaming.	[62]
GPI2		Purchasing green agricultural products through live streaming has many advantages.	
GPI3		I think it is a good choice to purchase green agricultural products through live streaming.	
GPI4		Along with other options, I will give priority to purchasing green agricultural products through live streaming.	
GPI5		I will advise my friends and acquaintances to purchase green agricultural products through live streaming.	

3.2. Data Collection and the Sample

The survey started on 10 July 2020 and ended on 20 August 2020. Altogether, 800 volunteers were recruited to take the questionnaire survey, and they were invited to join our WeChat (China's largest social networking app) chatting groups. First, volunteers were required to watch live streams of green agricultural product sales through the network links, which were mainly from Taobao.com live and Douyin.com. After watching the live streams, they were asked to answer the online questionnaire. Altogether, 726, or 90.75%, answered the questionnaires, and these answers went through a series of statistical analyses using SPSS 24.0 and AMOS 23.0.

Structural equation modeling (SEM) using AMOS 23.0 was used as the statistical tool to examine the measurement and structural model. Because we used a complex model with a mediating variable in this study, SEM was more suitable. SEM can account appropriately for the correlations between dependent variables, whereas considering the independent variables as independent in systems of regression equations may result in overstatement of the unique effect of each one [63]. In this approach, the model fit algorithms, correlated regression coefficients, and correlated residuals are generated as standard output. A critically important assumption in the use of this method is that the data are multivariate and normally distributed. Therefore, the Skewness and Kurtosis test for normality was employed to determine the distribution of each variable. Accordingly, Skewness values were between -1.307 and -0.341 and Kurtosis values were between -0.978 and 0.687; these are both well within the acceptable threshold of ± 2, so that it can be concluded that the data are normally distributed [64].

Among the sample from which data were collected, 91% were under 40 years old, 42% were male, and 58% were female. The respondents' demographic characteristics are presented in Table 2 below.

Table 2. Respondents' characteristics.

Characteristics		Frequency	Percentage
Age	18–25 years old	182	25.1
	26–35 years old	236	32.5
	36–45 years old	242	33.3
	Older than 45 years old	66	9.1
Gender	Male	305	42.0
	Female	421	58.0
Income	Less than RMB 2000 per month	58	8.0
	RMB 2000–5000 per month	189	26.0
	RMB 5000–10,000 per month	261	36.0
	RMB 10,000–15,000 per month	175	24.1
	More than RMB 15,000 per month	43	5.9
Knowledge of green agricultural products	None	37	5.1
	Not much	153	21.1
	General	232	32.0
	Know well	240	33.1
	Know very well	64	8.8
Access to green agricultural products	Internet media	346	60.1
	Recommended by relatives and friends	256	44.4
	Store promotion recommendation	298	51.7
	TV, newspapers, and other media	289	50.2
Purchase times via live-streaming e-commerce	0–2 times	65	9.0
	3–5 times	225	31.0
	6–10 times	218	30.0
	11–20 times	131	18.0
	Over 20 times	87	12.0
Do you have experience shopping online for green agricultural products?	No	428	59.0
	Yes	298	41.0
Do you have experience shopping online for green agricultural products via live-streaming e-commerce?	No	630	86.8
	Yes	96	13.2

4. Results

4.1. Measurement Model

To check for common method bias, we conducted Harman's one-factor test using the guidelines from Podsakoff et al. [65]. The results from an exploratory factor analysis (EFA) indicated that the first factor explained 24.2% of the variance; this is less than 40%, suggesting that common method bias overall was not a serious problem in the current study. According to Nunnally [66], Cronbach's α values should be greater than 0.7 to verify reliability. As shown in Table 3, the reliability values in this study, gauged using SPSS24.0, all exceeded 0.8, indicating good internal consistency. The validity analysis found that the Kaiser–Meyer–Olkin (KMO) value was 0.918, which exceeds the standard of 0.8 [67]. Therefore, this study is suitable for factor analysis.

Table 3. Construct reliability and validity.

Construct	Item	Factor Loading	CR	Cronbach's Alpha	AVE
Information Quality (InQ)	InQ1 InQ2 InQ3 InQ4 InQ5	0.766 0.828 0.770 0.754 0.890	0.901	0.899	0.645
System Quality (SyQ)	SyQ1 SyQ2 SyQ3 SyQ4 SyQ5	0.779 0.739 0.711 0.763 0.788	0.870	0.869	0.572
Service Quality (SeQ)	SeQ1 SeQ2 SeQ3 SeQ4 SeQ5	0.728 0.769 0.784 0.832 0.782	0.886	0.884	0.608
Telepresence (TP)	TP1 TP2 TP3 TP4 TP5	0.863 0.815 0.639 0.848 0.761	0.891	0.887	0.623
Social Presence (SP)	SP1 SP2 SP3 SP4 SP5	0.738 0.830 0.696 0.724 0.741	0.863	0.861	0.558
Green Trust (GT)	GT1 GT2 GT3 GT4 GT5	0.764 0.859 0.749 0.831 0.787	0.898	0.896	0.639
Green Purchase Intention (GPI)	GPI1 GPI2 GPI3 GPI4 GPI5	0.859 0.740 0.698 0.790 0.757	0.879	0.877	0.594

CR, composite reliability; AVE, average variance extracted.

The convergence validity was measured by confirmatory factor analysis (CFA) using the factor loading, combined reliability (CR), and average variance extracted (AVE) methods. According to Fornell and Larcker [68], each dimension's factor loading should be greater than the threshold value of 0.5, the structural reliability (CR) of each dimension should be greater than the threshold value of 0.7, and the average variance extracted (AVE) values should be greater than the threshold of 0.5. All data in this study met or exceeded these criteria, thereby indicating structural convergence and validity.

Pearson's correlation coefficient was used to determine discriminant validity. As indicated in the correlation coefficient matrix in Table 4, the square root of the AVE for each dimension was greater than each dimension's correlation coefficient. Therefore, all dimensions of this study are fully discriminant, thereby indicating good discriminant validity.

Table 4. Correlations between constructs.

	1	2	3	4	5	6	7	8	9
1. InQ	0.803								
2. SyQ	0.350	0.756							
3. SeQ	0.368	0.357	0.780						
4. TP	0.239	0.407	0.377	0.789					
5. SP	0.276	0.418	0.414	0.339	0.747				
6. GT	0.575	0.544	0.507	0.411	0.475	0.799			
7. GPI	0.317	0.309	0.307	0.267	0.299	0.553	0.771		
8. EC	0.096	0.106	0.090	0.067	0.156	0.228	0.265	0.738	
9. HC	0.031	0.112	0.071	0.026	0.073	0.207	0.202	0.378	0.716

4.2. Structural Model

In this study, we used AMOS for SEM analysis to verify Hypotheses 1–6. The results of the research model's goodness-of-fit (GFI) indicators show that the overall GFI is acceptable (x^2 = 966.491, df = 544, p = 0.000, GFI = 0.935, AGFI = 0.925, NFI = 0.936, IFI = 0.971, TLI = 0.968, CFI = 0.971, RMSEA = 0.033), as indicated in Table 5.

Table 5. Test of model fit.

	$\chi2$	df	$\chi2$/df	SRMR	GFI	AGFI	NFI	IFI	TLI	CFI	RMSEA
Suggested			1~3	<0.05	>0.9	>0.9	>0.9	>0.9	>0.9	>0.9	<0.08
Actual	966.491	544	1.777	0.037	0.935	0.925	0.936	0.971	0.968	0.971	0.033

Table 6 depicts the full path diagram of the SEM and the results. According to Hair et al. [69], a coefficient of determination value (R^2) above 0.2 is viewed as relatively high and acceptable [69]. In this study, the R^2 values for green trust and green purchase intention were 0.551 and 0.310, respectively, indicating that the SEM results are acceptable.

Table 6. Structural model results (hypothesis testing).

Hypothesis	Causal Path			Estimate	SE	CR	p	Path Coefficient	R^2	Results
H1	InQ	→	GT	0.316	0.033	9.488	***	0.351		Supported
H2	SyQ	→	GT	0.228	0.037	6.177	***	0.342		Supported
H3	SeQ	→	GT	0.166	0.034	4.814	***	0.184	0.551	Supported
H4	TP	→	GT	0.090	0.030	2.963	**	0.105		Supported
H5	SP	→	GT	0.160	0.036	4.445	***	0.168		Supported
H6	GT	→	GPI	0.674	0.050	13.537	***	0.557	0.310	Supported

Significance levels: *** $p < 0.001$; ** $p < 0.01$.

The structural model analysis results indicate that all path coefficients are statistically significant. Information quality (InQ, path coefficient = 0.351, $p < 0.001$), system quality (SyQ, path coefficient = 0.342, $p < 0.001$), service quality (SeQ, path coefficient = 0.184, $p < 0.001$), telepresence (TP, path coefficient = 0.105, $p < 0.001$), and social presence (SP, path coefficient = 0.168, $p < 0.001$) all exerted a significant positive effect on green trust (GT). Accordingly, the results support H1–H5. In addition, green trust (GT, path coefficient = 0.557, $p < 0.001$) exerted a significant positive effect on purchase intention (GPI), thereby supporting H6.

5. Conclusions and Implications

5.1. Empirical Findings and Discussion

For this paper, we collected raw data by conducting a structured survey of live-streaming e-commerce users from China, and we analyzed the collected data via structural equation modeling. The empirical results prove that the research model proposed in this study based on the SOR framework is reliable and all the hypotheses were supported. That is, the quality of live-broadcast e-commerce (S) stimulates consumers to generate green trust (O) and then generate green agricultural product purchase intention (R).

Based on the updated IS model, this paper highlights the characteristics of live-broadcast e-commerce, plus telepresence and social presence, to build a quality evaluation system for live-streaming e-commerce. The empirical results prove that the information quality, system quality, and service quality of e-commerce in the updated IS success model [30] positively affect consumers' generation of green trust. This is consistent with most studies focusing on the role of traditional e-commerce [31,34,36,37]. More importantly, the role of telepresence and social presence, as unique aspects of live-streaming e-commerce, was also proved by the empirical results. Consumers feel as if they are in the farmland or orchard through live-streaming e-commerce, which makes the attributes of green agricultural products more vivid and clear. Through the streamer's explanation, consumers can feel warmth and enthusiasm. These virtual presence features of live streaming are crucial in simulating consumers' trust in green agricultural products. Although scholars have demonstrated the role of telepresence [45,46] or social presence [44,47] in live-streaming e-commerce, we combined them with information quality, system quality, and service quality to build an evaluation system for the quality of live-streaming e-commerce, and we empirically proved the positive effect of green trust.

The empirical results also show that green trust is significantly positively correlated with green purchase intention, which is consistent with the findings of Nuttavuthisit and Thogersen [70]. Consumers' understanding of green products is still narrow and superficial. When consumers have to make choices, if there is a lack of trust in the green products sold, their willingness to purchase green products will be reduced. Through live-streaming e-commerce, consumers can have a more in-depth and vivid understanding of the advantages of green agricultural products; this can stimulate their green trust, which can promote consumers' purchase intention [71].

5.2. Implications and Limitations

This paper defines the evaluation dimension of live-streaming e-commerce quality, which has not received enough research attention. The empirical results demonstrate that improvements in live-streaming e-commerce quality will promote the formation of green trust, thus affecting green purchase intention. This indicates that when employing live-streaming marketing, green agricultural product enterprises should pay special attention to information, system, and service quality, as well as telepresence and social presence. The authenticity and accuracy of live-streaming e-commerce information, the system's stability, and timely service and response are all related to live-streaming quality. Therefore, the streamer should try to understand green agricultural products as much as possible, publicize the green agricultural products' characteristics, and display the products vividly to strengthen consumers' awareness of green agricultural products.

In addition, telepresence mainly generates an "immersive" feeling for consumers, which requires that the live streaming of green agricultural products be as close as possible to the origin or original ecological environment to improve the sense of telepresence. Social presence is achieved mainly through various methods to stimulate consumers' enthusiasm so that they participate in the interaction of live streaming. These also require a high degree of cooperation between the streamer, the live-streaming platform, and the green agricultural product enterprises involved. Through live streaming, consumers can not only find spiritual satisfaction but also truly feel the green agricultural products' environmental and health value.

On the other hand, multi-party participants should strive to guide green purchases in live broadcasts to form normal, benign, and multi-frequency consumption. A responsibility mechanism must be established, strict control of green agricultural products' quality must be carried out in accordance with the government's industry standards, and a clear punishment system must be implemented for producers and operators who use live-streaming platforms for "false marketing" and "false propaganda".

This study has some limitations. First, we studied the formation of green purchase intention in live-streaming e-commerce. In reality, a gap exists between purchase intention and purchase behavior. Second, green consumption behavior is a complex process of psychological and behavioral interaction affected by multiple factors, such as the green products' price and quality. However, due to limitations in models and variables, this paper does not cover these factors.

The following research directions could be pursued in the future. First, green consumption behavior generated by live-streaming e-commerce could be compared with green consumption behavior originating in traditional marketing channels to find a more effective way to promote green-related purchasing. Second, green products' related variables can be placed into the empirical analytical model for further exploration.

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Effects of Different Wastewater Irrigation on Soil Properties and Vegetable Productivity in the North China Plain

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Abstract: The interest in reusing wastewater for irrigation is being popularized in most countries. The objective of this study was to evaluate the effects of different wastewater and nitrogen fertilizer on soil fertility and plant quality, as well as to identify the optimal irrigation mode in the North China Plain. A total of nine treatments, including control (groundwater, no fertilizer), piggery wastewater, reclaimed water, and saline water, combined with nitrogen fertilizer (300 kg/ha and 200 kg/ha), were conducted in a greenhouse in 2019 (Xinxiang, Henan Province). Soil pH, electrical conductivity, organic matter, heavy metals contents, and cucumber yield and quality were analyzed. The results showed that: (1) compared with the underground water (control), soil pH value with a decrement of 0.21 units in piggery wastewater (PW), and 0.24 units in saline water treatments (SW). Soil electrical conductivity (EC) value significantly increased by 5.8~20.9% in PW and SW treatments, while there was no significant difference in EC in reclaimed water. The highest EC (770 μS/cm) was recorded in SW treatment. (2) No dramatic difference on the concentrations of soil lead (Pb) and cadmium (Cd) in the PW, RW, and SW treatments, compared with the control, but soil organic matter, copper (Cu), and zinc (Zn) concentrations in wastewater treatments were increased by 2.1~43.4%, 24.4~27.0%, and 14.9~21.9%, respectively. (3) There were no significant differences in cucumber yield and quality in RW treatment, while there was a slight decrease by 1.4% in yield in the SW treatment. The highest cucumber yield was observed in PWH treatment, with an increment of 17.5%. In addition, the contents of Vitamin C, soluble sugar, and protein were also improved by PW treatment. In this study, PW treatment showed the strongest ability to promote cucumber yield and quality, thus indicating that piggery wastewater irrigation with 300 kg/ha nitrogen would be the optimal practice in this region. Long-term study is necessary to monitor potential risk of heavy metals on the quality of soil and plant.

Keywords: unconventional water resources; nitrogen level; soil heavy metals; vegetable productivity; North China Plain

1. Introduction

The shortage of freshwater is a common problem in most regions of the world; it is estimated that the water shortage will reach 1.3×10 m^3 by 2030 in China [1,2]. Extensive use of irrigation, environmental pollution, and decreasing water resources have threatened the sustainable development of agriculture; alternative sources of water should be considered to maintain the further development [3]. Reusing wastewater is considered to an environmentally disposal practice that helps to prevent wasting the limited resources and minimize the environmental pollution (i.e., direct disposal of wastewater into surface or groundwater) [4]. In addition, studies have shown that wastewater irrigation can enhance soil fertility and crop productivity [5]. However, this practice may cause environmental problems if not appropriately treated and managed [6–8].

To a certain extent, wastewater includes aquaculture wastewater, urban sewage, and saline water, etc. [1]. As an alternative resource, the safe utilization of wastewater has received significant attention, and much literature has been reported frequently [9–14]. It has been reported that reclaimed water significantly increased tomato yields, soluble sugar, and titratable acidity content of the fruit, due to its high levels of nitrogen, organic matter, and other available nutrients [15]. Xu et al. [16] showed that reclaimed water irrigation significantly improved the growth and yield of pakchoi, but had no significant effect on its quality. Within a certain range, saline water irrigation can improve water use efficiency and plant growth, without a dramatic decline in yield [17].

Cucumber (*Cucumis sativus* L.), due to its high controllability and economic benefits, is widely cultivated in several countries, especially China [18]. How to make this cultivation has a greater economic return and higher yield than open-field cultivation does, which becomes the most critical issue for local farmers and drive farmers to overuse water and fertilizers to achieve higher vegetable yields [18]. Clearly, scientific irrigation combined with fertilizer application for plant–soil is necessary to investigate. The interest in reusing wastewater of irrigation is an attractive option of disposal; because of its characteristics, it provides a direct or indirect influence, regarding the relationship between soil and plants. Although the wastewater irrigation is extensively popularized by many countries as an important measure to alleviate scarcity of water resource and reduce fertilizer application, it might aggravate soil salinity, nutritional disorder, poor soil structure, and toxic stress to crop growth [19–23]. Therefore, the management of wastewater irrigation should consider the characteristics of the crop and soil, nature of water source, climate, and other factors. Most of the studies mainly focuses on the effects of single irrigation water quality, irrigation norms, and irrigation patterns [24–27], and there is a lack of systematic research on the effects of different wastewater irrigation on the water–soil–plant in North China Plain. Therefore, considering the regional importance and the uncertain influenced by wastewater irrigation in cultivated land fertility and crop productivity, the objectives of our experiment were to: (1) clarify the effects of different wastewater and N application on soil physicochemical properties, cucumber yield, and quality in North China Plain; (2) obtain the optimal irrigation mode of cultivated land; and (3) provide scientific support for optimizing the reuse of wastewater irrigation in this region.

2. Materials and Methods

2.1. Experimental Site

The experiment was carried out in a greenhouse in April–July of 2019 at the Agricultural Water and Soil Environmental Field Science Research Station, Chinese Academy of Agricultural Sciences (Xinxiang City, Henan Province, 35°19′ N, 113°53′ E). The meteorological data of 60-year was obtained from Xinxiang Weather Station. The experimental site has a warm temperate continental monsoon climate, with annual average temperature was 14.1 °C, annual average precipitation was 588.8 mm, frost-free period was 210 d, and sunshine duration was 2398.8 h. The soil type is tidal soil, and the physical and chemical properties of 0–20 cm soil layer are as follows: soil bulk density: 1.35 g/cm^3, pH value: 8.57, organic matter content: 7.3 g/kg, field capacity: 20.5%, available nitrogen: 0.78 mg/kg, available phosphorus: 18.5 mg/kg, and available potassium: 102.6 mg/kg.

2.2. Description of Experiment

Cucumber cultivar "CASS-106" (*Cucumis sativus L.*) seedlings was provided by the experimental station. A randomized block design (4 × 2) with three replications, and nine treatments in this experiment (total of twenty-nine plots), including control (groundwater, no fertilizer), unconventional wastewater (piggery, reclaim water and saline water), and two nitrogen applications (high: 300 kg/ha and low: 200 kg/ha); the details of experimental design are shown in Table 1.

Table 1. Experimental design in this study.

Treatments	Water Quality	Nitrogen Fertilization (kg/ha)
Control (CK)	Groundwater	0
CKWH	Groundwater	300
CKWL	Groundwater	200
PWH	Piggery wastewater	300
PWL	Piggery wastewater	200
RWH	Reclaimed water	300
RWL	Reclaimed water	200
SWH	Saline water	300
SWL	Saline water	200

Note: control (CK): groundwater; PW: piggery wastewater; RW: reclaimed water; SW: saline water; H: 300 kg/ha nitrogen application; L: 200 kg/ha nitrogen application.

Each plot area was about 6 m^2 (1 m × 6 m), protective rows were set in each treatment block. Following the local conventional fertilizer application, chicken manure 30 t/ha (organic matter ≥ 45%) was applied before cucumber seedlings were transplanted (2 April). The amount of fertilizer was P_2O_5 78 kg/ha, K_2O 51 kg/ha. Throughout the cucumber growth period, irrigation occurred once every 3–5 days, and the total irrigation amount for the experiment was 2100 m^3/ha. Groundwater was pumped from the nearby wells; piggery wastewater was taken from the biogas project in Xinxiang city, Henan Province. Reclaimed water was obtained from the Luotuowan domestic sewage treatment plant in Xinxiang City. Saline water was prepared with sea salt at a concentration of 4 g/L in the laboratory. The water quality of wastewater was judged by using the water quality standard for farmland irrigation (GB5084 2005), as shown in Table 2.

Table 2. The quality of four water source in experiment.

Water Quality	pH	EC μS/cm	TN mg/L	TP mg/L	K^+ mg/L	COD mg/L	NH_4^+ μg/L	NO_3^- μg/L
GW(Control)	8.51	178	0.98	0.51	8.3	0.4	1.56	2.88
PW	7.45	1020	167.8	17.53	58.1	1036	869.32	35.64
RW	8.38	593	11.9	1.12	10.1	4.0	25.36	8.78
SW	7.30	4320	3.21	0.47	22.5	0.5	1.69	3.08

Note: EC: electrical conductivity; TN: total nitrogen; TP: total phosphorus; COD: chemical oxygen demand; GW: groundwater; PW: piggery wastewater; RW: reclaimed water; SW: saline water.

2.3. Sampling and Measurements

2.3.1. Soil Sample

After vegetable harvesting, soil samples were collected as the five-point mixing method. After air-dried naturally, the samples were ground and passed through a 2 mm sieve.

Soil pH was measured by using potentiometric method with soil and water extract at a ratio of 1:2.5 (*w*/*v*) (PHS-3E pH meter, Shanghai Electronic Scientific Instrument Co., Ltd., Shanghai, China). Soil electrical conductivity (EC) was measured in a 1:5 soil and water extract (*w*/*v*) by using portable conductivity meter measurement (DDB-303A, Shanghai Electronic Scientific Instrument Co., Ltd., Shanghai, China.) Soil bulk density was measured by cutting ring method described by Lu [28]. Soil organic matter was determined by using potassium dichromate external heating method [28]. Soil heavy metals were measured by using microwave digestion-atomic absorption spectrophotometry (AA7000F, Shimadzu, Kyoto, Japan).

2.3.2. Cucumber Sample

Mature cucumbers were harvested from plants in each plot and weighed; cucumber count was converted to number per hectare, and cucumber weight was converted to kilogram per hectare to standardize yield measurements.

To estimate the quality of cucumber, four fruits per plot were sampled and washed in deionized water to determine vegetable quality.

Fruit soluble sugar content was measured by anthrone sulfuric acid colorimetry, according to the method of Lu [28]. Vitamin C content was analyzed by using 2,6-dichlorophenol titration, following the method of Wu et al. [29]. Titratable acidity was determined using sodium hydroxide titration [30]. The protein content was determined by the Kjeldahl nitrogen determination method [30]. The content of nitrate was determined by the phenol sulfonic acid method, according to the procedures described by Li et al. [30].

2.4. Data Analysis

Data was calculated by Microsoft excel 2016. Statistical analyses were conducted via the two-way analyses of variance (ANOVA), and the least significant difference (LSD) test for significance using the SPSS 26.0 software (IBM Crop.). Origin 2018 software was used for graphical presentation of results.

3. Results

3.1. Effects of Irrigation with Different Water Quality on Soil Physical and Chemical Properties

3.1.1. Soil pH after Irrigating

Effect of irrigation with different wastewater on soil pH value at 0–40 cm layer, as shown in Table 3. Within 0–20 cm soil layer, soil pH decreased by 0.08 units in PWH and 0.21 units in PWL treatment, compared with the control, but with no significant difference between them. A similar decreasing trend was observed in SW, with 0.24 units in SWH and 0.22 units in SWL treatment. The soil pH values in RW treatment were higher than that in the control, with increment of 0.09 in RWH and 0.11 units in RWL treatment. Except for RW treatment, other treatments decreased by 0.08–0.13 units, compared with the control, in the 20–40 cm layer. The highest pH value of 8.58 was recorded in RWL treatment, followed by 8.56 in RWH treatment (Table 3). The ANOVA showed that the interaction between nitrogen application and water quality had no significant effect on soil pH (Table 3).

Table 3. Changes in soil pH under different irrigation treatments.

Treatments	0–20 cm	20–40 cm
Control (CK)	8.47 ± 0.06a	8.40 ± 0.09ab
CKWH	8.42 ± 0.18a	8.32 ± 0.15b
CKWL	8.46 ± 0.14a	8.40 ± 0.07ab
PWH	8.39 ± 0.32a	8.27 ± 0.30b
PWL	8.26 ± 0.21a	8.32 ± 0.01b
RWH	8.56 ± 0.19a	8.55 ± 0.03a
RWL	8.58 ± 0.23a	8.43 ± 0.09ab
SWH	8.23 ± 0.05a	8.35 ± 0.03ab
SWL	8.25 ± 0.03a	8.35 ± 0.04ab
Water quality (WQ)	NS	NS
Nitrogen application (N)	NS	NS
WQ × N	NS	NS

Note: control (CK): groundwater; PW: piggery wastewater; RW: reclaimed water; SW: saline water; H: 300 kg/ha nitrogen application; L: 200 kg/ha nitrogen application. Different letters indicate a significant level of 5% between the different treatments. NS: no significant difference.

3.1.2. Soil Electrical Conductivity after Irrigating

Results on the effects of different water quality irrigation on soil electrical conductivity (EC) were presented in Figure 1. Compared with the control, the EC values significantly increased by 5.8~20.9% in PW and SW treatments ($p < 0.05$), and there was a dramatic difference in EC variability between the two nitrogen levels of the PW treatments ($p < 0.05$). However, the EC of RW treatment had no significant change, compared with the control (Figure 1). The highest increment was observed in the SWL treatment (770 µS/cm), followed by the SWH treatment (760 µS/cm), which increased by 20.9% and 19.3%, respectively. Moreover, a marked difference was observed in water quality among the unconventional irrigation, as shown in Table 4.

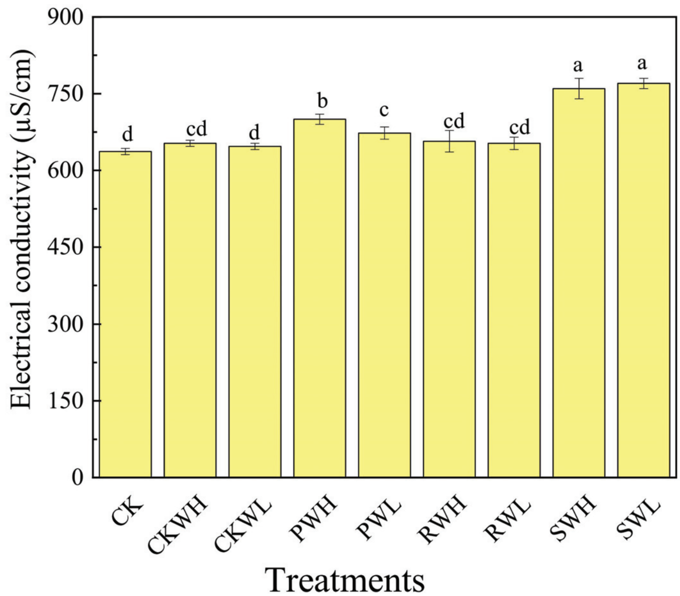

Figure 1. Effects of different irrigation treatments on soil electrical conductivity. Note: control (CK): groundwater; PW: piggery wastewater; RW: reclaimed water; SW: saline water; H: 300 kg/ha nitrogen application; L: 200 kg/ha nitrogen application. Different letters indicate a significant level of 5% between the different treatments.

Table 4. ANOVA analysis for effects of different irrigation treatments on soil EC.

Soil EC	
Water quality (WQ)	**
Nitrogen application (N)	NS
WQ × N	NS

Note: ** means $p < 0.01$; NS: no significant difference.

3.1.3. Soil Organic Matter after Irrigating

Compared to that in the control, a highly significant difference in soil organic matter change was observed in different wastewater irrigation, as shown in Figure 2. Except for the RWH treatment, the soil organic matter content of other treatments was significantly higher than that of the control, but there was no significant difference between nitrogen levels. In the 0–20 cm soil layer, organic matter content of PW treatment was significantly higher than that of the control, with increment of 2.1~43.4% ($p < 0.05$). The highest organic matter content was recorded in PWH treatment, with the value of 19.36 g/kg (Figure 2). In this study, there was significant difference in soil organic matter between water quality and nitrogen application, and the same behavior was found in their interaction (Table 5).

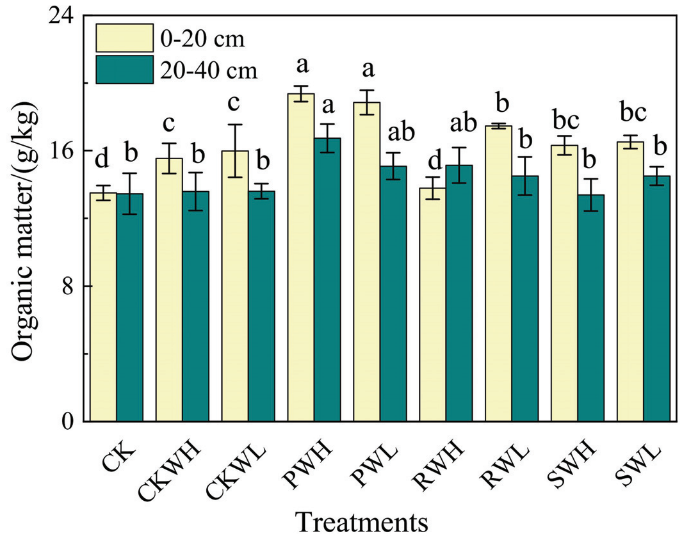

Figure 2. Effects of different irrigation treatments on soil organic matter. Note: control (CK): groundwater; PW: piggery wastewater; RW: reclaimed water; SW: saline water; H: 300 kg/ha nitrogen application; L: 200 kg/ha nitrogen application. Different letters indicate a significant level of 5% between the different treatments.

Table 5. ANOVA analysis for effects of different irrigation treatments on soil organic matter.

SOM	0–20 cm	20–40 cm
Water quality (WQ)	**	**
Nitrogen application (N)	*	NS
WQ × N	**	NS

Note: * means $p < 0.05$; ** means $p < 0.01$; NS: no significant difference.

The treatment effect for soil organic matter was not pronounced or significant, except for the PWH treatment in the 20–40 cm soil layer. Meanwhile, our results demonstrated that the interaction between nitrogen application and water quality had no dramatic difference in organic matter variability, but a highly significant difference in organic matter change was observed with different water quality for irrigation ($p < 0.01$, Table 5).

3.1.4. Soil Heavy Metal after Irrigating

As shown in Table 6, the concentrations of soil heavy metals under different wastewater irrigation were significant different. Soil total copper (Cu) concentration of eight treatments was significantly higher than that of the control, with the highest increment of 27% in PWH treatment, followed by PWL treatment (26.8%). A similar increasing trend was also detected, and the treatment effect was dramatic in total zinc (Zn) concentration modification. The concentration of Zn increased by 21.9%, 21.3%, 17.7%, and 17.2% for PWH, PWL, SWL, and SWH treatments, respectively, compared with the control ($p < 0.05$, Table 6). The highest Zn content was obtained in PWH treatment, with the value of 25.07 mg/kg. The ANOVA indicated that only the quality of wastewater had significant effects on soil Cu and Zn concentrations.

Table 6. Effects of different irrigation treatments on the concentration of soil heavy metals.

Treatments	Cu (mg/kg)	Zn (mg/kg)	Pb (mg/kg)	Cd (mg/kg)
Control (CK)	18.00 ± 0.25c	20.57 ± 0.61d	9.12 ± 0.27a	0.19 ± 0.01abc
CKWH	21.80 ± 0.5b	23.98 ± 0.31c	9.07 ± 0.12a	0.18 ± 0.01c
CKWL	21.77 ± 0.12b	23.99 ± 0.41c	9.09 ± 0.26a	0.19 ± 0.02abc
PWH	22.86 ± 0.44a	25.07 ± 1.05a	9.25 ± 0.25a	0.20 ± 0.01a
PWL	22.83 ± 0.53a	24.95 ± 0.33ab	9.21 ± 0.11a	0.19 ± 0.01ab
RWH	22.4 ± 0.36ab	23.83 ± 0.17c	8.94 ± 0.13a	0.18 ± 0.01bc
RWL	22.38 ± 0.77ab	23.64 ± 0.42c	9.18 ± 0.08a	0.20 ± 0.01ab
SWH	22.55 ± 0.51ab	24.10 ± 0.23c	9.13 ± 0.17a	0.20 ± 0.01ab
SWL	22.51 ± 0.29ab	24.21 ± 0.33abc	9.25 ± 0.08a	0.19 ± 0.01abc
Water quality (WQ)	*	**	NS	NS
Nitrogen application (N)	NS	NS	NS	NS
c	NS	NS	NS	NS

Note: control (CK): groundwater; PW: piggery wastewater; RW: reclaimed water; SW: saline water; H: 300 kg/ha nitrogen application; L: 200 kg/ha nitrogen application. Different letters indicate a significant level of 5% between the different treatments. * means $p < 0.05$; ** means $p < 0.01$; NS: no significant difference.

The results regarding the concentrations of lead (Pb) and cadmium (Cd) indicated that there was no significant difference in the three unconventional water treatments, compared with the control. Similarly, the results showed that the interaction between nitrogen application and water irrigation had no significant difference on soil Pb and Cd concentration (Table 6).

3.2. Cucumber Yield and Quality under Different Water Quality Irrigation

3.2.1. Cucumber Yield

Results on the effect of irrigation treatments on single fruit weight and yield are presented in Table 7. Data on single fruit weight indicated that no significant differences in SW treatments compared with the control. However, irrigating plant with wastewater, resulted in a percentage increase in single fruit weight in PWH, PWL, RWH, and RWL treatments (23.5%, 17.9%, 8.7%, and 9.2%, respectively), compared with the control. The highest increment occurred under PWH treatment, followed by PWL treatment (Table 7). Based on our results, it was concluded that the interaction between water quality and nitrogen application had no significant difference on single fruit weight.

Table 7. Effects of different irrigation treatments on weight per fruit and cucumber yield.

Treatments	Single Fruit Weight (g)	Yield (kg/ha)
Control (CK)	148.42 ± 2.84d	88,613.87 ± 681.07e
CKWH	163.93 ± 5.8b	91,469.93 ± 303.26c
CKWL	164.29 ± 5.04b	90,234.93 ± 685.96d
PWH	183.28 ± 4.64a	104,157.83 ± 1154.73a
PWL	174.97 ± 4.64a	101,371.67 ± 394.61b
RWH	161.40 ± 4.97bc	88,960.07 ± 112.34e
RWL	162.11 ± 5bc	88,077.00 ± 535.61ef
SWH	152.75 ± 3.52cd	87,425.03 ± 728.32f
SWL	150.66 ± 3.37d	87,401.73 ± 361.16f
Water quality (WQ)	**	**
Nitrogen application (N)	NS	**
WQ × N	NS	**

Note: control (CK): groundwater; PW: piggery wastewater; RW: reclaimed water; SW: saline water; H: 300 kg/ha nitrogen application; L: 200 kg/ha nitrogen application. Different letters indicate a significant level of 5% between the different treatments. ** means $p < 0.01$; NS: no significant difference.

Moreover, a marked difference in cucumber yield was recorded in PW treatment, which increased by 17.5% and 14.4%, respectively, compared to that of the control. Interestingly, the yield was significantly different between the two-level nitrogen application, indicating that the cucumber yield increased with increasing nitrogen application. However, data on the yield of cucumber indicated a slight decrease of 1.4% and 1.3%, respectively, in the SWL and SWH treatments, compared with the control. Additionally, there was no significant difference in cucumber yield under RW treatment. Treatments with wastewater irrigation significantly enhanced cucumber yield, compared with the control, and PWH treatment showed the most pronounced promoting effect. The ANOVA suggested that the interaction between water irrigation and nitrogen application had significant difference in the yield of cucumber ($p < 0.05$, Table 7).

3.2.2. Cucumber Quality

The effects of different wastewater treatments on the quality indexes of cucumber are demonstrated in Table 8. Data regarding the content of vitamin C, soluble sugar, and nitrate in cucumber showed no significant changes in the RW and SW treatments, compared with the control. The highest content of titratable acidity (1.49 g/kg) was observed in the SW treatment, with a percentage increase of 18.2% ($p < 0.05$).

Table 8. Effects of different irrigation treatments on the quality of cucumber.

Treatments	Vitamin C mg/kg	Soluble Sugar %	Titratable Acidity g/kg	Nitrate mg/kg	Protein mg/kg
Control (CK)	106.96 ± 5.23bc	3.48 ± 0.17bc	1.26 ± 0.06c	33.67 ± 0.29ab	90.14 ± 3.67c
CKWH	100.05 ± 10.75c	3.79 ± 0.16ab	1.36 ± 0.05bc	33.33 ± 0.58ab	96.61 ± 8.59c
CKWL	108.55 ± 17.22c	3.76 ± 0.26ab	1.26 ± 0.1c	33.33 ± 0.29ab	102.9 ± 5.16bc
PWH	153.18 ± 16.45a	3.95 ± 0.01a	1.39 ± 0.05ab	33.67 ± 0.29ab	128.49 ± 15.36a
PWL	151.01 ± 0.32a	3.83 ± 0.07ab	1.41 ± 0.04ab	34.00 ± 0.5ab	109.1 ± 4.06bc
RWH	120.99 ± 4.85b	3.54 ± 0.21bc	1.42 ± 0.05ab	33.83 ± 1.26ab	119.98 ± 12.43ab
RWL	120.31 ± 7.69b	3.42 ± 0.36bc	1.35 ± 0.09bc	34.00 ± 1.32ab	91.7 ± 17.68c
SWH	116.67 ± 0.58bc	3.55 ± 0.1bc	1.49 ± 0.03a	34.5 ± 1ab	95.5 ± 10.04c
SWL	116.33 ± 4.16bc	3.54 ± 0.23bc	1.49 ± 0.07a	32.67 ± 0.76b	100.5 ± 6.06bc
Water quality (WQ)	**	*	**	NS	*
Nitrogen application (N)	NS	NS	NS	NS	NS
WQ × N	NS	NS	NS	NS	*

Note: control (CK): groundwater; PW: piggery wastewater; RW: reclaimed water; SW: saline water; H: 300 kg/ha nitrogen application; L: 200 kg/ha nitrogen application. Different letters indicate a significant level of 5% between the different treatments. * means $p < 0.05$; ** means $p < 0.01$; NS: no significant difference.

The contents of vitamin C, soluble sugar, and protein in PWH treatment were significantly higher than that of the control, which increased by 43.2%, 13.4%, and 42.5%, respectively ($p < 0.05$). Results showed that quality of cucumber was significantly influenced by different wastewater irrigation, except for nitrate content. However, the interaction between water quality and nitrogen application only had a significant difference in protein content ($p < 0.05$, Table 8).

3.3. Correlation Analysis between Soil Properties and Yield and Quality of Cucumber

Cucumber yields were positively correlated with OM, Vc, SS, protein, and soil total Zn concentration, but negatively correlated with soil pH value. Soil EC had a significant positive correlation with TA and soil total Cu concentration. There were dramatically positive correlations between the OM and Vc, SS, Cu, Zn, Pn, and Cd concentrations. The Vc content of cucumber had significantly positive correlations with protein, Cu, Zn, and Cd concentrations, while the nitrate content of vegetable had no significant correlation with the tested indexes in our experiment (Table 9).

Table 9. Correlation analysis between soil properties, cucumber yield, and quality.

Index	EC	pH	OM	Vc	SS	TA	Nitrate	Protein	Cu	Zn	Pb	Cd	Yield
EC	1												
pH	0.316	1											
OM	0.293	−0.257	1										
Vc	0.161	−0.259	0.704 **	1									
SS	−0.109	−0.364	0.415 *	0.313	1								
TA	0.669 **	0.269	0.154	0.172	0.031	1							
nitrate	−0.083	0.212	−0.016	0.207	−0.101	0.203	1						
protein	0.026	−0.091	0.335	0.594 **	0.302	0.287	0.043	1					
Cu	0.427 *	0.054	0.607 **	0.428 *	0.198	0.513 **	0.123	0.436 *	1				
Zn	0.355	−0.057	0.686 **	0.518 **	0.433 *	0.416 *	−0.022	0.476 *	0.862 **	1			
Pb	0.301	−0.234	0.491 **	0.281	0.027	0.115	−0.075	0.084	0.121	0.026	1		
Cd	0.227	−0.056	0.560 **	0.627 **	0.099	0.144	0.189	0.247	0.161	0.245	0.27	1	
yield	−0.084	−0.525 **	0.697 **	0.794 **	0.624 **	−0.007	0.065	0.585 **	0.307	0.495 **	0.257	0.319	1

Note: EC: electrical conductivity; OM: organic matter; Vc: vitamin C; SS: soluble sugar; TA: titratable acidity; * means $p < 0.05$; ** means $p < 0.01$.

4. Discussions

4.1. Irrigation with Different Wastewater on Soil Properties

It is necessary to investigate the reuse of inferior water–soil–plant relationship because the maintenance of soil health and plant fertility is conducive to the rational construction of sustainable development [31]. Soil pH is an important attribute of saline-alkali, and directly reflect soil nutrient availability and crop growth [17,32]. Liu et al. [33] showed that livestock wastewater irrigation slightly decreased the soil pH, compared with the freshwater. Yang et al. [34] reported that the soil pH in saline water was slightly lower than that of the control. These results were consistent with the findings of this study, i.e., that piggery wastewater and saline water irrigation reduced the soil pH value, as compared with the control. The decrease may be related to the high organic or inorganic nitrogen in piggery wastewater, which promotes an intense nitrification reaction and releases a certain number of protons in the process [17,33]. This slight changes in soil pH could be attributed to the release of exchangeable cations during soil organic matter mineralization process [32,35].

Soil EC is an important indicator for judging soil acidification and secondary salinization [36,37]. The results of this study showed that soil EC was not significantly influenced by reclaimed water irrigation, which was consistent with Wang et al. [5]. However, Liu et al. [38] reported that EC value was greater than 16% in reclaimed water irrigation. A general increase in EC was noted in piggery wastewater irrigation in this study, this result was supported by the findings of Kiziloglu et al. [32], who found that cauliflower and red cabbage having high EC of the wastewater with the slaughterhouse effluent. The discrepancy in EC may be related to the nature of water sources, irrigation frequency, and irrigation amount. The previous study [5,17] showed that EC increased dramatically under saline water irrigation, which was also supported by our result, showed that the highest EC value was obtained in saline water treatment, increased by 20.9% than that of the control. The results in this experiment showed that organic matter significantly increased by 2.1~43.4% in unconventional water irrigation in the 0–20 cm soil layer, and the highest value was observed in piggery water treatment. The same results were obtained in a study by Lu et al. [39], who indicated that biogas slurry irrigation significantly increased the organic matter of rhizosphere soils. The results of this study suggest that piggery wastewater irrigation could be favorable to improve soil structure and aeration [40].

Although many studies have been conducted to examine the impacts of wastewater irrigation on soil heavy metals (such as Cd, Cu, Ni, Zn, Cr, Pb, etc.), there is no consensus on them [32,40,41]. In this study, there were no significant differences regarding the concentrations of the soil's total Pb and Cd under wastewater irrigation, while there were dramatically increased Cu and Zn concentrations. Similar results were supported by the findings of Liu et al. [33], who reported that reclaimed water and piggery wastewater significantly increased Cu and Zn content, with no marked changes in Pb and Cd concentrations in the North China Plain. Huang et al. [41,42] also found that piggery wastewater irrigation caused a notable increase in Cu and Zn contents. The possible reason for this phenomenon may be related to the high Cu and Zn concentrations in the treatments. Though higher concentrations of Cu and Zn were observed in wastewater irrigation, the concentrations of them still within the permissible limits of the Soil Pollution Risk Control Standard for Soil Environmental Quality and Agricultural Land [43].

4.2. Irrigation with Different Water Quality on Cucumber Yield and Quality

Health soil physicochemical properties and nutritional status can produce crop yield and quality [32,44–46]. In the present study, the single fruit weight of cucumber under piggery wastewater and reclaimed water irrigation was significantly increased by 8.7~23.5%. Wu et al. [47] found that cucumber yield in reclaimed water treatment was 24% higher than that of freshwater, while there was no significant change in our study. The study also showed that a higher cucumber yield was observed in piggery wastewater treatment than in the control, which increased by 17.5% and 14.4%, respectively, indicating that yield increased with the increasing nitrogen application in the tested area. In addition, piggery wastewater treatment had the highest value of cucumber yield in this experiment, as a result of the complex factors in the soil. Our results were consistent with the findings of Kiziloglu et al. [32], who found that wastewater irrigation positively affected cauliflower and cabbage yield. Piggery wastewater has an abundance of mineral elements and organic matter, and these characteristics of biogas slurry may enhance crop yield [40,48]. Furthermore, the correlation analysis showed that cucumber yield was significantly correlated with soil organic matter (Table 9), thus indicating that organic matter plays a positive role in increasing vegetable yield. This study found piggery wastewater led to a slight increase in the contents of Vc, soluble sugar, and protein, compared with the control, but there was only significant difference in the protein content in reclaimed water treatment.

Saline water irrigation has been reported to play a negative role in plant growth and crop yield with high salinity [49,50]. In this study, no significant change was recorded in single fruit weight in saline water treatment, but cucumber yield was 1.4% lower than that of the control. The result was consistent with Huang et al. [23], who found that saline water irrigation reduced melon yield in northwest China. Mugwanya et al. [21] also reported that cucumber growth and yield was significantly decreased by saline water irrigation. The reason for a slight decrease in yield may be due to the highest value of soil EC (770 μS/cm), which was observed in saline water treatment, and high salt concentration may cause the disturbance of several physicochemical and physiological attributes, including soil bulk density, water uptake, nutritional disorder, and photosynthetic capacity, etc. [51–54]. This study only found that the content of titratable acidity was significantly influenced by saline water treatment. Unconventional water irrigation was still limited by various objective or subjective factors, such as the nature of water, irrigation amount and frequency, soil texture, crop, and other uncertainties [55–57]. Therefore, it is necessary to conduct in-depth research on promoting the advantages of unconventional water. The above-mentioned results indicated that piggery wastewater had the most positive effect on vegetable yield and quality in this study.

5. Conclusions

Three unconventional water irrigation types affect the soil properties, cucumber yield, and quality, apparently differently, in this study. Therefore, the characteristics of wastewater, soil, and crops should be considered in managing wastewater irrigation. Compared with groundwater irrigation, piggery wastewater and saline water irrigation decreased the soil pH but significantly increased the soil EC; the highest soil EC was observed in saline water. The results of wastewater irrigation indicated no significant changes in soil Pb and Cd concentrations, but remarkably increased in soil organic matter, Cu, and Zn concentrations, but the concentrations of Cu and Zn were far lower than the standard limit, indicating that short-term irrigation would not cause the accumulation of heavy metals pollution in soil.

Saline water irrigation resulted in a percentage decrease in cucumber yield. Piggery wastewater irrigation not only significantly improved the yield of cucumber, but also increased the content of Vc, soluble sugar, and protein. In this study, piggery wastewater was superior to all the other irrigation and had the highest cucumber yield. Considering the economic and environmental benefits, piggery wastewater irrigation combined with 300 kg/ha nitrogen was the optimal mode for this region. Further experimental research is needed.

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Profiles of Food Insecurity: Similarities and Differences across Selected CEE Countries

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Abstract: Food security (FS) is influenced by primarily financial but also sociodemographic factors. Identification of correlates of food insecurity (FI) is a crucial issue in the context of achieving sustainable development goals. The aims of the study were: (1) to recognize FI in the selected Central and Eastern European (CEE) countries, (2) to examine common socioeconomic and demographic characteristics for FI. The analysis used the set of eight-item FI indicators adopted by the Food and Agriculture Organization, applying the Gallup World Poll survey data from 2017 to 2019. Multinomial logistic regressions were used to examine FI at mild and moderate or severe levels compared with FS. Differences in the profiles of FI were observed in analyzed countries: Poland, Lithuania and Slovakia. Lithuanians experienced the lowest FS, and Slovaks the highest. The FI status was associated with education, gender, age, household composition and income. It was found that the impact of these factors was not the same in the examined countries. Differences in profiles of FI in CEE countries indicate the need to analyze the problem individually for each country. Identifying groups particularly vulnerable to FI may allow appropriate targeting of instruments counteracting FI and adapt them to people with different characteristics.

Keywords: food insecurity; profiles; sustainable development goals; multinomial logistic regression models; relative-risk ratio; CEE countries; Poland; Lithuania; Slovakia; socioeconomic and demographic characteristics

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1. Introduction

Ending global hunger and all forms of malnutrition is the most pressing global challenge [1]. Although current per capita global food production is estimated at 2796 kcal per individual per day, which is more than the minimum dietary energy requirement for adults [2], the global hunger rate is about one in ten people. Furthermore, since 2015, the global hunger rate has been on the rise. The problem is not only undernutrition caused by chronic insufficient supply of energy, but also malnutrition caused by insufficient supply of vitamins and minerals (micronutrient deficiencies) and overweight and obesity. Global estimates suggest that at current trajectories, all of these forms of malnutrition will increase globally from one in three persons in 2017 to one in two persons by 2030 [1]. It seems that it is not an insufficient global food production, but rather its inadequate distribution and utilization, that contributes to the problem of hunger and food insecurity. Thus, the need for urgent global remedial action has been included in the 2030 Agenda for Sustainable Development, adopted by all United Nations member states in 2015. The Sustainable Development Goal (SDG) No. 2 "Zero hunger" aims to end hunger and food insecurity, improve nutrition and promote sustainable agriculture by 2030 [3–5]. It is worth noting that hunger and food insecurity are related, but are not synonymous. Food security (FS) exists when an individual has regular physical, social and economic access to sufficient, safe and nutritious food which meets his/her dietary requirements and food preferences for an active and healthy life [6]. On the contrary, food insecurity (FI) occurs when individual people and/or relatives in a household alter their food consumption or preferences because of a lack of physical or economic resources [7,8].

Food insecurity is a well-recognized cause of undernutrition and stunting [9]. While every human should be food secure, ensuring an adequate amount of nutritious food is especially important for women of childbearing age and children [3]. Insufficient intake of energy and/or nutrients, and consequently malnutrition, in these vulnerable groups has a large impact on the health condition of the entire population. Overall, malnutrition alters the immune system and increases vulnerability to infections in affected individuals at every stage of life [10]. In recent decades, FI has also been linked with obesity in high-income countries [11]. It is worth emphasizing that overweight and obesity as forms of malnutrition are recognized risk factors for severe course of COVID-19 at the individual level, also in young adults with no underlying conditions [12,13].

Although on a global scale, factors affecting FS include those controlling food production, i.e., climate change, the poor performance of the agriculture sector and poverty [6,14]; the FS status of an individual or a household is influenced by primarily financial but also sociodemographic factors and others (e.g., gender, time, employment skills, housing status, health condition, food skills or capabilities, health insurance status, social support, past economic hardship, aliment availability) [15–18]. However, these factors may have a different share in ensuring FS depending on the population/country/region.

1.1. Food Insecurity Assessment

Achieving the Sustainable Development Goals to a large extent depends on monitoring and follow-up processes [19–21]. Several markers and methods for assessing FI have been proposed so far to identify the problem and monitor progress in eradicating hunger and malnutrition, as well as to set goals for policy action at a national and international level. Although no generally accepted official measurement of FI in the world has been accepted [22], the Food Insecurity Experience Scale (FIES) was selected for monitoring Target 2.1 of the United Nations′ 2030 Agenda for Sustainable Development [3]. The FIES survey includes eight questions examining the individual respondent's experiences or the experiences of the respondent's household as a whole. These questions focus on the food-related behaviors and experiences reported by respondents and associated with increasing difficulties in accessing food due to resource constraints. The FIES is based on a well-grounded concept of the experience of FI composed of the following domains: 1. worry/anxiety; 2. changes in food quality; 3. changes in food quantity [23,24]. On the basis of the FIES scale, the risk of FI might be identified in individuals and communities in comparable way across different groups. Based on the FIES score (the number of positive answers to questions), the severity of FI can be access: ranging from zero (FS status) to eight (all symptoms of FI). The FIES score when analyzed in conjunction with the respondent and household characteristics can deepen the understanding of the risk factors and consequences of FI at an individual and household level [25,26].

1.2. Context for the Research

Nowadays, a growing body of literature on FI can be observed. There are a number of research papers on FI from a global perspective [25,27–31], as well as studies analyzing the situation in a group of countries [32–34] or a single country [26,35–39].

In the scientific literature, much attention has been allocated to FI in the less-developed countries of South Asia, Sub-Saharan Africa and Latin America [40–44]. Research on FI in developed countries has also begun to develop as the problem has been noticed and analyzed [22,45–49].

Research on FI in developing countries emphasizes the special role of agriculture in improving food availability and achieving food security [50]. The question arises whether, in global terms, agriculture will keep up with the increased demand for food, reported with an increase in the population or migration [51]. At the same time, differences in the agricultural production potential that occur in individual countries are pointed out [50,52,53].

In the literature, various attempts in measuring FI can be found [31,45,54–56]. Thus, different indicators are used in FI studies across the world. Notwithstanding, regardless of indicators analyzed, most research shows that FI is strongly negatively associated with income [41,42,57]. However, some temporarily low-income individuals may be able to afford food by drawing down savings or incurring debts. The literature reveals that various individual assets have a significant relationship with FI [58,59]. Specifically, on the one hand, savings enhance the capacity for current consumption, but on the other hand, debts reduce it [59,60].

Most academics across the world indicate the important role of sociodemographic characteristics, such as location of dwelling, gender, age, high educational level and household composition as risk factors of FI [25,28,31,42]. Regarding location of dwelling, on one hand, in low-income economies, individuals living in rural areas seem to be more vulnerable than those living in cities and towns [31,42]. On the other hand, in upper middle-income economies, no significant difference between urban and rural areas regarding FI is found [31]. Analyzing FI in Europe, Grimaccia and Naccarato [61] found that FI in large cities was higher than in a rural location; however, the difference between those living in rural areas and small towns was not statistically significant. Similarly, results regarding gender are unambiguous—they depend on the examined population [25,28,31]. Specifically, Broussard [28] revealed higher mild FI among women that among men in the EU but no significant difference was found regarding moderate and severe FI.

Numerous scholars point out the inverted U-shape relationship between the age and the prevalence of FI, indicating less FI for younger and older individuals than for middle-aged [36,61]. However, this relationship was not confirmed in low-income economies by Smith et al. [31]. Furthermore, research regarding multiracial and multicultural countries revealed the effects of race, ethnicity and religion on FI [40,58,62].

Because some factors influencing FI may be unique to a certain country or region with specific socioeconomic, cultural and geographic settings, then there is a need to investigate the situation in various regions across the world.

1.3. The Picture of Analyzed Countries

The spatial scope of our research covers selected countries of Central and Eastern Europe (CEE): Lithuania (LT), Poland (PL) and Slovakia (SK) (Figure 1, Table 1). To the best of our knowledge, there is a lack of research on FI for these countries.

Table 1. Characteristics of analyzed countries: Lithuania (LT), Poland (PL) and Slovakia (SK).

Indicator	LT	PL	SK
Population density *	44.6	123.6	112.0
Gini *	35.4	28.5	22.8
Real GDP growth rate (% average per year in 2014–2019)	3.3	4.1	3.2
GDP per capita in PPS *	83	73	70

Source: own elaboration based on Eurostat, 2021 [63]; * data for year 2019.

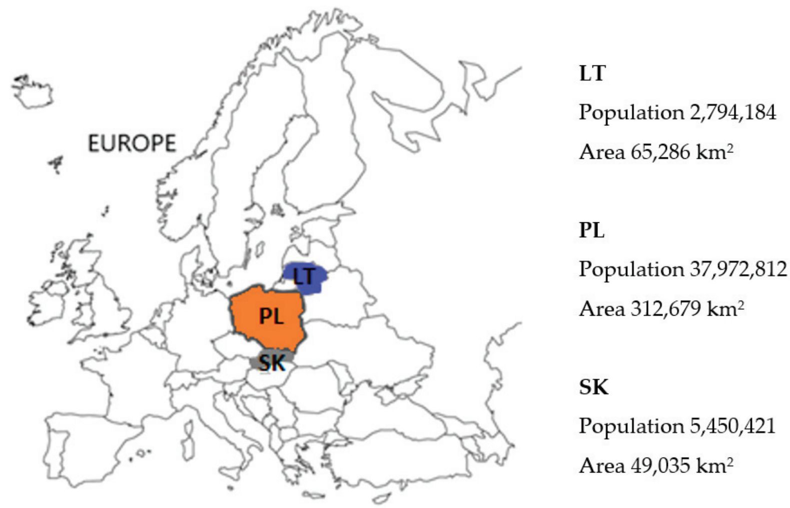

Figure 1. The study area and localization of analyzed CEE countries: Lithuania (LT), Poland (PL) and Slovakia (SK)—data for year 2019. Source: own elaboration based on Eurostat, 2021 [63].

Poland is the largest among the surveyed countries in terms of population; it also has the highest population density. The analyzed countries are located in close proximity: they constitute an area characterized by many cultural and political similarities related not only to the model of their socioeconomic development. Lithuania, Poland and Slovakia have common historical roots. Poland and Lithuania were part of the same country for many centuries; the same situation applies to Slovakia, which along with a large part of Poland belonged to the Austro-Hungarian Empire. Nowadays, these countries follow a similar path of economic transformation and integration with the European Union (EU), to which they have belonged since year 2004. They have managed to move from a centrally planned economy to a fully market economy, now with strong economic ties to major EU countries and the world economy. After the Second World War, Poland and Slovakia were satellites of the USSR, while Lithuania until 1990 was one of its republics. However, despite the indicated similarities, the CEE countries cannot be perceived as a fully homogeneous group [64]. There are clear differences in the level and dynamics of social and economic development, as well as internal differences in this respect.

According to the data for 2019, Lithuania showed one of the highest levels of income inequality among EU countries [63]. The Gini index of disposable income of households was 35.4, which makes Lithuania the second country (after Bulgaria) with the highest income inequalities in the EU. In turn, Slovakia is the country with the most even distribution of income in the European Union (with Gini coefficients at 22.8). In Poland, the indicator was 28.5, which is slightly less than the EU average.

The studied countries are also characterized by different dynamics of the economic development. In the years 2014–2019, the average annual GDP growth was the highest in Poland and amounted to 4.1%, whereas Slovakia and Lithuania had similar dynamics of development [63]. It is worth noting that Poland is the only country outside the eurozone; Slovakia has been in the eurozone since 2009, and Lithuania since 2015, respectively. To sum up, the presented data show that despite the similar geographic location and historical and cultural connections of all analyzed countries, there are differences in the shaping of various macroeconomic factors. This made us decide to analyze the issue of FI separately and create profiles for each country.

1.4. The Purpose and Scope of the Study

Our research is territorially oriented at selected CEE countries, i.e., Poland and its neighbors: Lithuania and Slovakia. The Czech Republic was excluded at the preliminary stage of the study due to the lack of availability of complete statistical data describing FS. Analyzed countries, as mentioned before, joined the EU in 2004, and are characterized by similar development conditions, but on the other hand, there are significant socioeconomic differences between them. The research area selected in this way allows to display the FI profiles. In the CEE countries, there is a lack of regular and methodologically consistent measurement of FI. Therefore, there is a need for investigations about the prevalence of FI and how it may be changing across countries. Combating FI and its associated consequences requires an understanding of the profiles of food-insecure individuals. Thus, our goal was to identify national profiles of food insecurity in countries under question.

The focus was on profiles of FI indicating whether people belong to the food secure category or the mild, moderate or severely food insecure categories. Multinomial regression models were estimated that aimed to explain the likelihood of belonging to each of the FI profiles.

The investigation of the socioeconomic and demographic factors affecting FI could help with the development of social policies to minimize the prevalence of FI in a given country. Thus, it is highly important to identify people being exposed to various forms of FI. In other words, vulnerable groups should be recognized.

We aim to answer the question: who are the food insecure in the CEE countries? Moreover, we want to examine which socioeconomic and demographic characteristics are common to the countries concerned, and which are not.

2. Materials and Methods

2.1. Food Insecurity Measurement Methods

The study uses Gallup World Pool (GWP) data for 2017–2019. Each country's sample size was about 1000 individuals, representative of the resident population aged 15 and older. More specifically, in 2014–2018 the sample size in each country was 1000, and in 2019—1080. The survey questions referring to various FI experiences are based on the Food Insecurity Experience Scale (FIES). The survey questions are presented in Table 2.

Table 2. Questions in the FIES.

No.	During the Last 12 Months, Was There a Time When, because of Lack of Money or Other Resources:	Short Reference
(Q1)	You were worried you would not have enough food to eat	WORRIED
(Q2)	You were unable to eat healthy and nutritious food	HEALTHY
(Q3)	You ate only a few kinds of foods	FEWFOODS
(Q4)	You had to skip a meal	SKIPPED
(Q5)	You ate less than you thought you should	ATELESS
(Q6)	You ran out of food	RANOUT
(Q7)	You were hungry but did not eat	HUNGRY
(Q8)	You went without eating for a whole day	WHLDAY

Source: FAO, 2021 [65].

The questions were asked to a nationally representative sample through face-to-face interviews. Respondents could answer either "Yes" or "No". FI experiences can be ranked in terms of severity from mild to severe (see Figure 2) [66]. In other words, the more food insecure a person is, the more likely she or he will report having suffered from the worst experience.

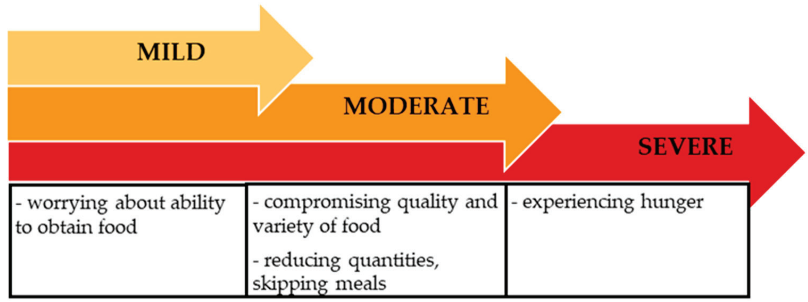

Figure 2. The range of severity of food insecurity. Source: [65,66].

The responses to the FIES questions are aggregated to produce raw scores ranging from 0 to 8. On this basis, FI is usually classified into 4 categories [67,68]:

1. food secure with raw scores of 0;
2. mild FI with raw scores of 1–3;
3. moderate FI with raw scores of 4–6;
4. severe FI with raw scores of 7–8.

However, as in the analyzed CEE countries the prevalence of severe FI is negligible (approx. 1% of the population), in our study we consider 3 categories:

1. food secure with raw scores of 0 (FS);
2. mild FI with raw scores of 1–3 (MFI);
3. moderate or severe FI with raw scores of 4–8 (SFI).

Apart from FIES data, the Gallup World Poll database includes data relating to demographic and socioeconomic characteristics of individuals. Thus, the study examines the impact of various characteristics on FI.

The set of potential correlates includes: educational level, gender, age, location of dwelling, the income quintile group and household composition. Moreover, the influence of social capital is examined. This is done by using a binary variable which equals one if the individuals feel they can count on their family and/or friends in times of need.

The educational level was categorized as elementary (elementary or lower), secondary and tertiary (high or higher). The place of residence was classified as either city or suburbs, town, rural area or farm based on the current address of participants. The household composition included number of adults and number of children under 15.

2.2. Methods

In the first stage of statistical analysis, the associations between FI and categorical socioeconomic and demographic variables were assessed by using the chi-squared test. Moreover, Cramer's V measure was used to estimate the strength of these associations.

In the second stage of statistical analysis, multinomial logistic regressions were used to examine FI at mild and moderate or severe FI levels relative to food security. Despite that the analyzed dependent variable describing FI is ordered and could be investigated by ordinal logistic regression, we applied multinomial logistic regression instead. We chose this approach because:

1. It does not impose the strong assumption of proportional odds (as ordinal logistic regression does);
2. It provides the interpretation of results in terms of relative-risk ratios;
3. Our goal is to investigate separate effects of socioeconomic and demographic characteristics on different levels of FI (i.e., mild and moderate or severe FI).

Multinomial logistic regression model assumes m equations for the m outcomes. Usually, it is assumed that the outcomes are coded using the set {1, 2,..., m} and that the outcome of one is used as the base reference group. Thus, the probability of the response for the *i*th observation is equal to the *j*th outcome and can be expressed as [69]:

$$p_{ij} = P(y_i = j) = \left\{ \begin{array}{l} \frac{1}{1+\sum_{r=2}^{m} \exp(\boldsymbol{x}_i \boldsymbol{\beta}_r)}, \text{ if } j = 1 \\ \frac{\exp(\boldsymbol{x}_i \boldsymbol{\beta}_j)}{1+\sum_{r=2}^{m} \exp(\boldsymbol{x}_i \boldsymbol{\beta}_r)}, \text{ if } j > 1 \end{array} \right\} \tag{1}$$

where $\boldsymbol{x}_i$ is the row vector of observed values of the independent variables for the ith observation, $i = 1, 2, \ldots, n$,

n is the number of observations,

$\boldsymbol{\beta}_j$ is the coefficient vector for outcome j, $j = 2, \ldots, m$.

The unknown parameters in each vector $\boldsymbol{\beta}_j$ are typically jointly estimated using the maximum likelihood method [70,71]. However, their interpretation is hard because of nonlinearity in formula expressing probabilities in multinomial logit model. Therefore, the estimated coefficients are often transformed to relative-risk ratios (RRR), where the relative risk refers to the probability for each outcome of the dependent variable relative to the probability of the reference outcome ($j = 1$):

$$\frac{p_{ij}}{p_{i1}} = \frac{P(y_i = j)}{P(y_i = 1)} = \exp\left(\boldsymbol{x}_i \boldsymbol{\beta}_j\right) \tag{2}$$

The relative-risk ratio for multinomial logit can be defined as [69]:

$$RRR_{jk} = \frac{P(y_i = j|x_k + 1)/P(y_i = 1|x_k + 1)}{P(y_i = j|x_k)/P(y_i = 1|x_k)} = \exp\left(\beta_{jk}\right), j = 2, \ldots, m,\ k = 1,\ 2, \ldots, K, \tag{3}$$

where β_{jk} is a parameter for the kth independent variable (x_k) corresponding to jth outcome (category),

K is the number of independent variables included in model.

The RRR is independent of the particular values of covariates. A positive parameter β_{jk} for an explanatory variable (x_k) implies an increased relative risk of observing an observation in category (outcome) j rather than category 1 as x_k rises by one unit, holding other covariates constant; a negative parameter β_{jk} implies that the chance of being in the reference category (outcome) is higher relative to the jth category as x_k increases by one unit.

In particular, if an independent variable (x_k) is a binary variable, then

$$RRR_{jk} = \frac{P(y_i = j|x_k = 1)/P(y_i = 1|x_k = 1)}{P(y_i = j|x_k = 0)/P(y_i = 1|x_k = 0)} = \exp\left(\beta_{jk}\right) \tag{4}$$

As noted in the last section, in our research we consider three categories ($m = 3$) and reference outcome is food security ($j = 1$). We conducted all statistical analyses using the STATA program (StataCorp LP, College Station, TX, USA). The GWP post-stratification national sampling weights have been applied to the survey data.

3. Results

A comparison between examined countries in terms of answers to individual FIES questions is presented in Figure 3. These eight questions (see Table 2) focus on respondents′ behaviors and experiences related to the increasing difficulty in accessing food as a result of resource constraints. A positive answer to specific questions enables the classification of the FI intensity. The percentage of people who answered positively to all FIES questions was the highest in Lithuania. However, this difference was particularly evident in respect to questions No. Q1–Q3 and Q5. Comparing the situation of Poland and Slovakia, it can be noticed that in Poland, relatively more people than in Slovakia responded positively to questions No. Q1–Q3, while in Slovakia, there was a higher percentage of respondents answering positively to questions relating to moderate or severe FI (No. Q4–Q8).

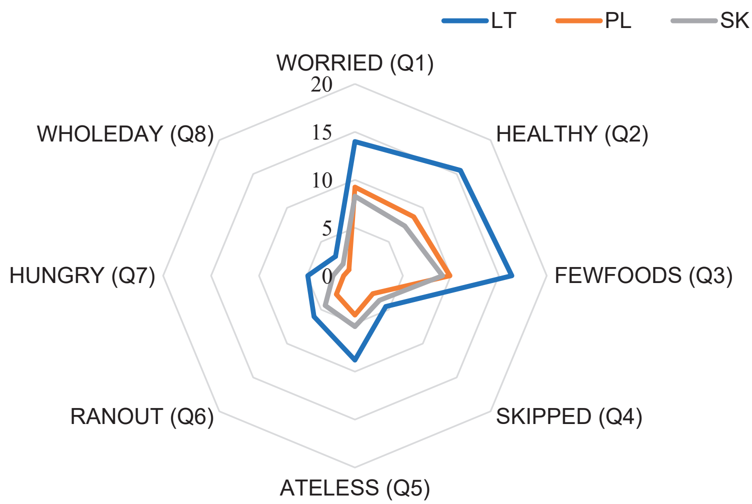

Figure 3. Percentage of positive responses to individual FIES questions (Table 2) in analyzed countries: Lithuania (LT), Poland (PL) and Slovakia (SK).

More condensed information on the prevalence of FS, mild FI and moderate or severe FI is presented in Figure 4.

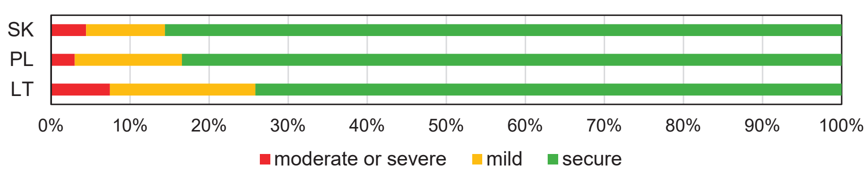

Figure 4. The prevalence of food insecurity in Lithuania (LT), Poland (PL) and Slovakia (SK) in 2017–2019.

Figure 4 shows that the lowest FS was experienced by Lithuanians, while the share of people with both mild and moderate or severe FI was the highest compared with other examined countries. The lowest percentage of people with moderate or severe FI was observed in Poland, while the lowest percentage of individuals with mild FI was identified in Slovakia.

More detailed information on the significance of differences between countries is presented in Figure 5. The prevalence of FS ranged between 72% in Lithuania and 84% in Slovakia. As all the confidence intervals for Lithuania do not overlap with ranges for Poland and Slovakia, this means that in Lithuania, the food security situation is different than in Poland and Slovakia (at all FI levels). On the other hand, when comparing Poland and Slovakia, no statistically significant differences were found in the proportions of food-secure and moderate or severe FI. Only for mild FI, the higher proportion for Poland compared to Slovakia was observed.

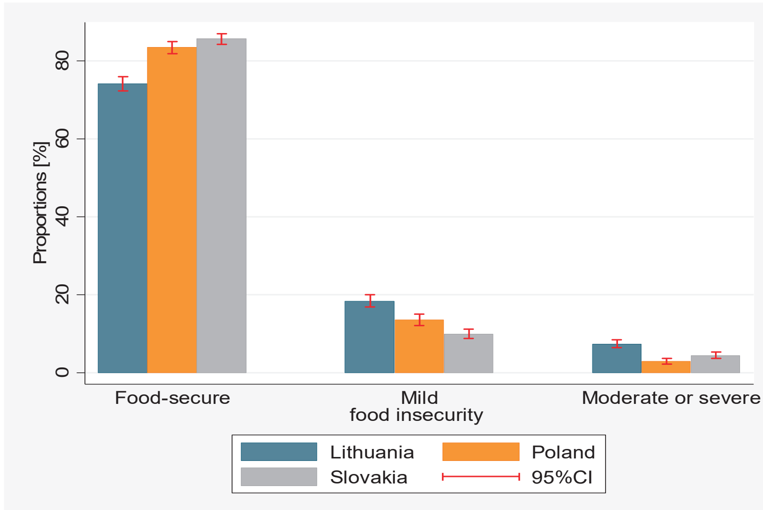

Figure 5. Confidence intervals associated with the specific FI category in 2017–2019.

Statistical analysis enables more detailed insight on the association between FI and individual characteristics. Therefore, in the subsequent stage, bivariate analyses were performed, including the chi-squared test (Table 3).

Table 3. The relationship between food insecurity and individual characteristics.

Variables	Lithuania		Poland		Slovakia	
	χ2 Statistics *	**Cramer's V**	**χ2 Statistics ***	**Cramer's V**	**χ2 Statistics ***	**Cramer's V**
Gender	**9.35**	0.06	**6.68**	0.05	**7.16**	0.05
Number of adults in household	**136.77**	0.15	**72.75**	0.11	**73.32**	0.11
Number of children in household	**80.78**	0.11	**44.93**	0.09	**59.16**	0.10
Education	**52.63**	0.09	**79.44**	0.11	**56.28**	0.10
Location of dwelling	**33.18**	0.07	5.67	0.03	**13.58**	0.05
Social capital	**69.38**	0.15	**45.90**	0.12	**145.35**	0.22
Income quintile	**316.42**	0.23	**157.29**	0.16	**265.49**	0.21
Age	**70.88**	0.11	**42.83**	0.08	**28.12**	0.07
Years	2.80	0.02	**68.35**	0.11	**13.84**	0.05

* Note: numbers marked in bold indicate results that are significant at a 0.05 level.

Significant differences were noted between FI and the majority of the examined variables, namely: gender, household composition, education, social capital, income and age. Nonetheless, for place of residence, no significant difference was noted in Poland. Cramer's V measure revealed that among categorical variables, social capital and income showed the strongest association with FI. Contrarily, the weakest relationship referred to gender and location of dwelling.

In the next stage of our study, the multinomial logistic regression model was used to examine differences in individual characteristics in countries under question. Results of multinomial logistic regression analyses are presented in Table 4. Two comparisons are shown between FI categories. The first set of coefficients predict mild FI (MFI) versus FS, the second set of coefficients compares moderate or severe food insecurity (SFI) to food security. The description of the results focuses on comparisons between mild food insecurity and food-secure individuals and between moderate or severe food insecurity and food-secure individuals. These comparisons examine whether: (1) mildly food-insecure individuals are different to food-secure individuals; (2) moderate or severely food-insecure individuals are different to food-secure individuals. Table 4 summarizes the results of the multinomial logistic regression of individuals' socioeconomic and demographic characteristics and shows the relative risk ratios (RRR).

Table 4. Relative risk ratios from multinomial logistic regression.

Variable	Mild FI vs. FS						Moderate or Severe FI vs. FS					
	LT		PL		SK		LT		PL		SK	
	RRR	SE	RRR	SE	RRR	SE	RRR	SE	RRR	SE	RRR	SE
Women	**1.26**	0.15	**1.44**	0.19	1.25	0.16	1.30	0.24	1.50	0.42	1.06	0.21
Number of adults in household	**0.72**	0.04	0.90	0.07	**0.76**	0.05	**0.72**	0.08	**0.62**	0.10	**0.65**	0.07
Number of children in household	**1.28**	0.09	**0.82**	0.08	**0.79**	0.08	**1.40**	0.12	0.73	0.14	0.91	0.10
Social capital	0.79	0.13	**0.50**	0.08	**0.40**	0.07	**0.35**	0.07	**0.32**	0.09	**0.17**	0.04
Age (ref. Age below 35)												
Age 35–44	1.40	0.25	1.10	0.23	**1.63**	0.34	1.53	0.42	1.19	0.56	1.08	0.36
Age 45–54	1.30	0.25	1.38	0.29	1.63	0.29	**1.95**	0.54	1.44	0.64	1.46	0.49
Age 55–64	**1.67**	0.33	**1.69**	0.35	**1.52**	0.33	1.49	0.47	1.17	0.55	1.33	0.44
Age 65–74	1.21	0.25	1.53	0.37	1.33	0.30	**2.08**	0.65	0.97	0.46	1.55	0.52
Age 75 +	**1.69**	0.39	0.92	0.37	1.16	0.33	**2.79**	0.94	0.60	0.40	1.41	0.56
Education (ref. Secondary)												
Tertiary	**0.59**	0.10	**0.53**	0.10	0.92	0.18	**0.57**	0.15	**0.26**	0.14	**0.41**	0.18
Elementary	1.47	0.32	1.21	0.28	1.11	0.21	1.63	0.51	**2.29**	0.84	**2.12**	0.53
Location of dwelling (ref. Cities or suburbs)												
Towns	**0.52**	0.07	1.02	0.15	0.97	0.14	**0.34**	0.07	0.63	0.18	**0.51**	0.11
Rural areas	0.72	0.13	0.82	0.17	1.06	0.19	**0.44**	0.13	**0.29**	0.16	0.67	0.18
Income quintile group (ref. Fifth quintile group)												
First quintile group	**4.90**	1.06	**5.71**	1.46	**10.05**	2.50	**13.20**	5.03	**51.94**	27.66	**20.71**	8.07
Second quintile group	**4.50**	0.91	**2.74**	0.68	**4.06**	0.96	**4.31**	1.65	**7.90**	4.64	**4.30**	1.71
Third quintile group	**2.38**	0.50	**2.89**	0.67	**3.08**	0.72	**2.72**	1.12	**4.40**	2.69	1.64	0.70
Fourth quintile group	**1.59**	0.32	**2.38**	0.55	1.37	0.35	1.98	0.81	**7.41**	4.21	1.40	0.62
Years (ref. 2017)												
2018	1.05	0.16	**0.29**	0.05	**1.66**	0.26	1.29	0.31	**0.46**	0.15	**1.91**	0.48
2019	0.87	0.13	**0.38**	0.06	**1.66**	0.26	0.69	0.17	**0.20**	0.08	**2.19**	0.54
Constant	**0.24**	0.07	**0.21**	0.07	**0.09**	0.03	**0.11**	0.05	**0.06**	0.05	**0.10**	0.05

Note: RRR are relative risk ratios, SE-standard errors, numbers marked in bold indicate results that are significant at a 0.05 level.

The results shown in Table 4 reveal interesting findings. Firstly, when comparing the results for mild FI regression and moderate or severe FI regression, it can be noticed that some socioeconomic and demographic characteristics significantly influenced one process but not another. For example, in the model for LT and PL, gender was significant in mild FI regression, but at the same time was insignificant in moderate or severe FI regression. Secondly, the set of significant correlates was not the same in all countries under question. In particular, location of dwelling was rather significant in the model for LT, but this finding was not confirmed for PL and SK, especially in mild FI regression.

A detailed interpretation of the impact of various characteristics can be made on the basis of an RRR computed using formula 3. The RRR is interpreted as the effect of a one-unit change in the explanatory variable on the probability of being in the dependent variable outcome (category) under consideration, compared with the reference outcome (category). In our study, on the one hand, an RRR that is less than one indicates that there is a lower likelihood of being insecure than the likelihood of being food secure. On the other hand, an RRR greater than one means that there is a greater likelihood of being insecure than being food secure. For example, considering the gender effect for Lithuania, we found that (see formulas 3–4):

$$RRR_{2.\ Women} = \frac{P(y_i=2|Women=1)\,/\,P(y_i=1|Women=1)}{P(y_i=2|Women=0)\,/\,P(y_i=1|Women=0)} = 1.26 \text{ or equivalently}$$
$$\frac{P(y_i=2|Women=1)}{P(y_i=1|Women=1)} = 1.26\cdot\frac{P(y_i=2|Women=0)}{P(y_i=1|Women=0)}$$

This result means that the relative risk of being mildly FI comparing with being food secure in Lithuania was 1.26 times (i.e., 26%) greater among women than among men when holding other predictors constant. The considered relationship can be also expressed as:

$$\frac{P(y_i = 2|Women = 1)}{P(y_i = 2|Women = 1)} = 1.26\cdot\frac{P(y_i = 1|Women = 0)}{P(y_i = 1|Women = 0)}$$

What can be interpreted is that Lithuanian women compared with Lithuanian men were 26% more likely to be mildly food insecure than food secure.

Thus, on the basis of the model, we may state that the relative risk of being mildly FI rather than being food secure was greater among women that among men: in Lithuania by 26% in Poland by 44%; however, in Slovakia there was no significant difference between gender. This relative risk decreased if the number of adults in household increased by one person: in Lithuania by 28%, in Slovakia by 24%; however, in Poland there was no statistically significant relationship in this regard. At the same time, the mild FI relative risk increased by 28% in Lithuania if the number of children in the household increased by one child, but decreased in Poland and Slovakia by 18% and 21%, respectively. For those individuals that felt they could count on their friends and family in times of need, the relative risk was twice as low in Poland and 60% lower in Slovakia. By contrast, social capital in Lithuania was not a statistically significant factor. Regarding the age, the relative risk was greater for older persons than for those aged below 35; specifically, in all countries for individuals aged 55–64, the risk was greater at about 60%. In the case of education, the relative risk of mild FI in Lithuania and Poland was about twice as low among individuals with tertiary education compared with secondary education; nevertheless, in all three countries there was no statistical difference between those with secondary and elementary education. In Lithuania, the relative risk was about twice as low among individuals living in towns compared with people living in cities or suburbs; however, in Poland and in Slovakia there was no statistically significant relationship in this regard. As expected, the RRR was higher for individuals with lower income; specifically, comparing with the fifth quintile group, the RRR for people from the first quintile group was about five times higher in Lithuania and in Poland and tenfold higher in Slovakia. To sum up, the relative mild FI risk was subject to a downward trend in Poland and growing trend in Slovakia, while none of the significant trend was observed in Lithuania during the 2017–2019 period. Thus, when analyzing mild FI, it was found that, in principle, in relation to each of the examined factors (gender, household composition, social capital, age, education, location of dwelling, income quintile group), there are differences in the analyzed countries.

A similar interpretation for the RRR corresponding to the next FI category was performed. We may notice that the relative risk of being moderately or severely FI rather than being food secure did not differ in terms of gender in all three countries, but decreased if the number of adults in household increased by one person: by 28% in Lithuania, 38% in Poland and 35% in Slovakia. Corresponding RRR increased by 40% in Lithuania if the number of children in the household increased by one child, while in Poland and Slovakia there was a lack of significant relationship in this regard. Additionally, the relative risk was about three times smaller in Lithuania and Poland and more than five times smaller in Slovakia for those individuals that felt they could count on their friends and family in times of need. In the case of age, the RRR was more than twice as high among individuals over the age of 65 compared with individuals aged below 35 in Lithuania; nevertheless, in Poland and in Slovakia there was no significant relationship in this regard. Regarding education, the RRR was lower among individuals with tertiary education compared with secondary education (RRRs: Poland 0.26, Lithuania 0.57 and Slovakia 0.41), and it was about twice as high among individuals with tertiary education among Poles and Slovaks, while in Lithuania, there was no significant relationship between elementary and secondary education. The RRR was about threefold lower among individuals living in towns and 56% lower among villagers compared with people living in cities or suburbs in Lithuania; in Poland, it was 71% lower among villagers, and in Slovakia about twice as low among individuals living in towns compared with people living in cities or suburbs. In all countries, the RRR was higher for individuals with lower income. Summing up, relative risk of being moderately or severely FI showed a downward trend in Poland during 2017–2019, and a growing trend in Slovakia; however, none of this significant trend was observed in Lithuania during the analyzed period.

Based on the above results, it can be concluded that when it comes to moderate or severe FI compared with mild FI, there were more common statistically significant factors for all three countries. Specifically, in all countries, a relevant role of social capital, higher number of adults in household, higher education comparing with secondary education, rising income in decreasing the likelihood of moderate or severe FI were noted. Moreover, no gender differences in all three countries, ceteris paribus, were found.

Based on the results of multinomial logistic regressions estimates, we have designated four exemplary types of individuals (Table 5). Obviously, these sample types do not exhaust all possible values of the explanatory variables included in the models. However, they provide insight into how different FI profiles are for people with different demographic, social and economic characteristics.

Table 5. Types of individuals based on demographic, social and economic characteristics in the year 2019.

Characteristics	Type 1	Type 2	Type 3	Type 4
Gender	Man	Woman	Woman	Man
Number of adults in household	1	1	3	3
Number of children in household	0	0	3	2
Social capital	bad	bad	good	good
Age	55–64	Above 75	45–54	Below 35
Education	Elementary	Elementary	Tertiary	Tertiary
Location of dwelling	Cities or suburbs	Cities or suburbs	Towns	Towns
Income quintile group	First	First	Third	Fifth

The first two types refer to individuals with the worst traits, the third to average and the fourth to rather favorable. It should be noted, however, that the favorable discriminants are not always the same in the analyzed countries, e.g., the number of children. The common unfavorable traits included: no children in the household, one-person household, elementary education, living in cities or suburbs and low income. The determinants predisposing to FS included: presence of three adults and more than one child in the household, tertiary education, living in a town, a higher level of income and age under 54 years.

For these four distinguished types, according to formula (1), we determined the probabilities corresponding to different FI profiles. Based on the estimated probabilities, we developed percentages charts (i.e., probabilities expressed in percentages) (Figure 6).

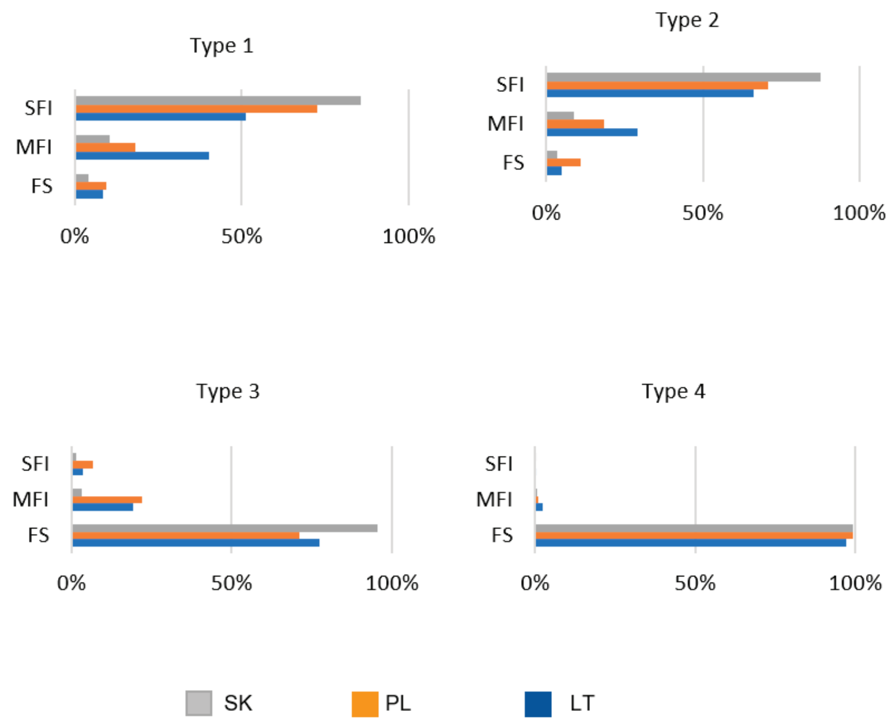

Figure 6. Predicted percentages of individuals in analyzed CEE countries: Slovakia (SK), Poland (PL,) Lithuania (LT) and according to specified FI profiles (SFI—moderate or severe food insecurity; MFI—mild food insecurity; FS—food security).

The predicted probability of experiencing a specific FS situation for all distinguished types, except type 4, varies from country to country, with the highest differences for type 1. For this type, the predicted probability of experiencing moderate or serious FI was the highest for Slovakia and the lowest for Lithuania. On the contrary, the predicted probability of experiencing mild FI in Lithuania was more than 2–2.5 times higher compared with Poland and Slovakia, respectively. On the other hand, the predicted probability of FS for type 1 was approximately two times lower for Slovakia compared with Poland and Lithuania. Similarly to type 1, type 2 also indicated a set of discriminants negatively influencing the FS situation. In this type, we estimated a similar probability pattern of experiencing different FS situations, but the differences between countries were not so marked. The second difference is that Poles with the characteristics defined as type 2 are about twice as likely to experience FS as compared with Lithuanians and Slovaks. For type 3, the probability of FS is the highest for Slovakia, where the predicted probability of moderate and severe FI was extremely rare in this country. For type 4, the probability of moderate and severe FI or mild FI is extremely low ($\leq$1%). Only in the case of Lithuania, 3% of individuals belonging to type 4 can be projected to be mildly food insecure.

4. Discussion

Based on the obtained results, it can be stated that there are differences in the profiles of FI in analyzed CEE countries. The Lithuanians experienced the lowest FS, and the Slovaks the highest. The differences found can be explained to some extent by the differences in the living conditions of the population in the analyzed countries. Lithuania clearly stood out among the countries studied: in the case of many characteristics, the presence of FI was more common in this country. Explaining the worse situation of Lithuania compared with Poland and Slovakia, one should mention differences in the level of material deprivation, on the basis of which Lithuania is classified as one of the countries with a high level, while Poland and Slovakia are among the countries with an average level [63,72]. This can significantly determine FI and explain the identified differences in terms of the FI profile. It is worth adding that the prevalence of FI identified in the surveyed countries corresponds to the variation in the percentage of people at risk of poverty or social exclusion, which in 2018 was by far the highest in Lithuania (28.3%), and lower in Poland (18.9%) and in Slovakia (16.3%). This proves the relationship of FI with the economic situation of the population and shows how complex the conditions for the presence of FI can be. These results are also confirmed by the subjective assessment of life satisfaction, which in Lithuania is described as low by as many as 36% of the population [63]. The average rating of life satisfaction in this country is also relatively low (6.4 points), which is the lowest among the countries surveyed and low compared with the EU average (7.3). Lithuania is also characterized by the lowest percentage of public social spending in GDP [73] and still (despite an increase in recent years) the lowest share of social benefits to households as a percentage of GDP, which may be important for the prevalence of FI.

The reasons for the identified differences between the analyzed countries in the prevalence of individual FI forms may also result from different situation of individuals. The explanation can be seen in the existence of large disparities in disposable income in the surveyed countries or differences in food prices (e.g., the greatest income stratification and disadvantageous income situation of pensioners in Lithuania [74,75], and the best situation in Slovakia, which is the country with the most even income distribution in the European Union. The individual situation with regard to the burdening of household income with fixed charges (e.g., loan repayments, fixed house maintenance fees) may be important, especially for the existence of moderate or severe food security. In the case of mild food security, its prevalence may depend on the type of typically consumed and important food products (e.g., considered as healthy, with a high nutritional value), their availability and prices on domestic markets, which may significantly differ in the analyzed countries due to, e.g., traditions, culture or religion.

In our study, we focused primarily on the analysis of the impact of individual socioeconomic and demographic characteristics on the presence of FI. It turned out that specifically, compared with men, women in Lithuania and Poland have a greater propensity to be classified as mildly food insecure rather than food secure. Our findings are in line with those of Broussard [28], who revealed the gender difference in terms of mild FI in the EU but no significant difference regarding moderate and severe FI. A potential explanation for this may include the specific role of women in the household, who are more often than men responsible for housekeeping and day-to-day food supply decisions. Only the exceptionally difficult situation of the family in terms of FI (moderate or severe) engages all household members, regardless of gender.

Contrary to our expectations, the same importance of children in households in the context of the prevalence of FI was not found in the analyzed countries. It turned out that outside Lithuania, the number of children is not significant for moderate or severe FI. Moreover, in Lithuania, FI, regardless of its severity, increased if the number of children in the household increased. The example of this country shows how important it is to ensure that FS is the national (social) policy in the field of supporting families with children. Lithuania did not have a universal child benefit system until 2018, and the existing tax instruments were, in practice, difficult for parents to use [76]. This was accompanied by a low level of enrollment in the case of young children [77], which could limit the economic activity of parents on the labor market, especially single parents, who are also at the highest risk of poverty in Lithuania [78]. Due to the introduction of a child support system in Lithuania in 2018 (“child money”), an improvement in the income situation of families with children can be expected in the future, which may affect the occurrence of FI.

Our other findings are largely consistent with empirical studies that use GWP FIES data [28,31]. The results of our study revealed that generally FI was greater for older persons than for those aged below 35. As an explanation, it can be indicated that the income of older people grows slower than in other age groups. Additionally, pensions are usually lower than wages and, as shown by the example of Lithuania, pensions grow more slowly as the average wage increases [75,79]. This can make the situation of older people more difficult, as well as their subjective feelings worse. This is also confirmed by the large percentage of households of people over 65 in all surveyed countries (compared with total households) that have difficulties making ends meet [63].

Similar to Miller et al. [80] and Smith et al. [31], our study showed that midlife appears to be a period of increased vulnerability to FI. Specifically, in all countries, for individuals aged 55–64, the relative risk of being mildly FI rather than being food secure was greater at about 60%. The age range of 55–64 is classified as late middle age, in which, as evidence shows, adults experience many changes in their lives (in the social, psychological and biological spheres), which may increase the risk of FI [80]. At this age, the number of social roles increases [80,81]; this is called the sandwich generation, where people take care of both aging parents and children, and often also grandchildren, while combining it with professional work.

In line with Smith et al. [31], we found that the largest increase in the likelihood of experiencing FI was associated with low income, low social capital and low levels of education. This may be due to the fact that better educated people are more aware of the importance of their lifestyle, especially nutrition, for health and well-being. People having access to social support when their resources are constrained experience lower FI. As nutritional needs are elementary, belonging to any of those groups results in help for vulnerable individuals, which reduces the risk of experiencing FI.

An interesting issue in our research is the lack of dependence, apart from Lithuania, between mild FI and the place of residence, which has already been indicated in other studies [36]. In the case of moderate and severe FI, the risk of its occurrence is higher in large cities and suburbs, which is confirmed by the study of Grimaccia and Naccarato [25]. This may be associated with higher costs of living in large cities than in towns or rural areas. Moreover, it should be emphasized that the studied countries are characterized by a different territorial division and a different distribution of urban and rural population, which may explain the obtained results. Summing up, it can be stated that the analyzed socioeconomic and demographic characteristics determined a different degree being exposed to various forms of FI in the studied countries.

When analyzing the FI profiles, it would be worthwhile to take into account the impact of other characteristics, e.g., financial burden on respondents (loans, expenditure on some goods, for example, those which are health-related). Apart from the information on the number of adults and children, it is also worth taking into account the biological type of the household in which the respondent lives (i.e., whether the household consists of parents and children, or if it is a multigeneration unit, etc.). Unfortunately, the GWP lacks detailed information on the above-listed issues.

In conclusion, it should be noted that the obtained results in terms of FI are important in the context of the COVID-19 pandemic. Preliminary research in such countries as Brazil [82], Mexico [67], Ethiopia [83] and the United States [84] revealed that COVID-19 and national lockdowns have had a substantial impact on FI. Unfortunately, data from 2020 are not available to us. However, in order to be able to understand the impact of the pandemic on FI, a reliable baseline for comparison is needed. Thus, in the light of the COVID-19 pandemic, our results contribute by providing a baseline for comparing the experience of pre- and post-pandemic FS in the CEE in further studies. We realize however, that the issue of FI requires constant monitoring, which is a premise for further research in this area.

5. Conclusions

We analyzed profiles of FI using three categories: food security, mild FI, moderate or severe FI. We found that FI rates decreased with increasing severity. Our study revealed the presence of the FI problem in CEE countries and its various forms, which shows that the topic is timely and important in the context of achieving sustainable development. We found differences in terms of profiles of FI in analyzed countries, which shows that it is worth analyzing the situation of FI in a given country separately. The identification of FI profiles can help in achieving the sustainable development goals at the country level. We found that the presence of FI translates into the assessment of satisfaction with the life of the population, which is in line with the hierarchy of human needs and confirms the importance of activities aimed at ensuring FS in the politics of each country. We examined the influence of socioeconomic and demographic correlates using multinomial logistic regression models, with food security as the reference category. Our findings reveal that there are significant distinctions in the relationships between individual characteristics and FI status. Our study explores the individual's FI profiles and provides evidence on the dependence of socioeconomic and demographic characteristics. Responding to the question of who are the food insecure in CEE countries, it was found that FI status was related to education, gender, age, household composition and income. Apart from typical correlates of FI, a remarkable negative effect of social capital on FI was found.

Our results show that the same socioeconomic and demographic discriminants determine the different probability of the occurrence of FI and its different forms in individual countries. Identifying groups particularly vulnerable to FI may allow appropriate targeting of instruments counteracting FI and adapt them to people with different demographic, social and economic characteristics. Awareness of the factors that are associated with FI should help to target those individuals most at the risk of FI, as well as focus policy recommendations.

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Article

Food Insecurity in Central-Eastern Europe: Does Gender Matter?

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Abstract: Food insecurity (FI) remains a challenge not only in less-developed countries but also worldwide. The literature indicates higher rates of FI for women than men in some regions of the world. Thus, the main objective of this cross-sectional study was to assess differences in experiencing FI according to gender in Central-Eastern Europe—a region that has been little researched in terms of FI. The study analyzes individual-level data on FI from the Gallup World Poll (GWP) for the years 2018–2019, obtained under a license from the Food and Agriculture Organization (FAO). Dataset encompasses representative samples of individuals aged 15 and above for each studied country. Apart from bivariate analysis, the ordered logistic regression, the generalized ordered logistic regression and multinomial logistic regression models were used. It was found that women experienced mild FI more often than men. However, gender differences with respect to moderate or severe FI were not confirmed. Moreover, the significant associations of all severity levels of FI with education, employment status, social capital, social network, age, marital status, household composition and income were observed. The research findings can be used to inform policy and to design targeted assistance programs for those in need.

Keywords: Sustainable Development Goals; Europe; socioeconomic and demographic characteristics; ordered logit model; generalized logistic regression; multinomial logistic regression

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1. Introduction

As defined by the Food and Agriculture Organization of the United Nations (FAO), food insecurity (FI) occurs when individuals do not have adequate physical, social or economic access to sufficient, safe and nutritious food satisfying their nutritional requirements and food preferences for an active and healthy life [1]. Food insecurity is a substantial problem worldwide [2,3]. Therefore, the United Nations (UN) among the Sustainable Development Goals (SDGs) pointed out the need to "end hunger, achieve food security and improve nutrition and promote sustainable agriculture" [4]. To monitor Target 2.1 of the UN 2030 Agenda for SDGs, the prevalence of moderate or severe FI in the population, based on the Food Insecurity Experience Scale (FIES), has been used as the SDGs Indicator 2.1.2 [5].

Another of the SDGs integral to all dimensions of inclusive and sustainable development is women's equality and empowerment [6]. This equality should apply to all aspects of life and functioning in society, including especially food security (FS). However, the prevalence of moderate or severe food insecurity worldwide is slightly higher in women compared to men. At a global level, women had about a 13 per cent higher chance of being moderate or severe food insecure than men, and almost 27 per cent higher chance of experiencing severely FI. Two-thirds of countries worldwide reported higher rates of food insecurity for women than men [7]. Even when women have the same level of income, education and live in similar areas as men, their access to food is more difficult. It is worth noting that gender gaps in poverty are the widest in the age of 25–34, which is the period of biological reproduction and childcare responsibilities [8].

A large body of evidence indicates that when women experience poverty, this negatively affects human capital. Poverty is a strong risk factor for FI, almost half of those living in poverty are food insecure [9]. When FS is disrupted, the nutritional value of the diet is initially reduced simultaneously with an increase in the share of energy, mainly from saturated fats and sugar, causing undernourishment and promoting excessive weight gain [10–13]. Evidence indicates that maternal undernutrition is associated with intrauterine growth restriction of fetus, with lifelong consequences for the future child's physical and mental development [14,15]. While obesity in women, especially during pregnancy, contributes to the health risks of their children and this deepens the health inequities across generations [16–18].

Conversely, women's greater access to income and resources, better nutritional status and higher education result in better health and educational outcomes for their children [19–21]. In turn, greater investment in child welfare improves the productivity of the next generation of workers and has a positive effect on economic development [22]. In addition, research shows that women tend to invest as much as 10 times more in their family's well-being, including in children's health, nutrition and education [23–25]. Consequently, when women control the household budget, family members tend to have better nutrition status, and children's survival rates increase [26]. It is worth emphasizing that addressing the dietary needs of adolescent girls, as well as women during pregnancy and lactation has been set as the Target 2.2 of the UN 2030 Agenda for SDGs [5].

Despite women's greater vulnerability to poverty, a low share of social protection policy is gender sensitive. Compared to men, women are more often involved in unpaid care and housework, which in turn limits their access to social protection [27]. Moreover, they are more likely to be working in low-paid sectors that do not offer sufficient social protection measures. When households cannot access adequate amount of food, this bias is likely to be reinforced, with negative consequences for the nutritional status and health of girls and women [28,29].

The FI status of a household or an individual is primarily influenced by economic but also sociodemographic factors and others, e.g., gender, employment skills, time, housing status, health status, food/cooking skills or capabilities, health insurance status, social support, past economic hardship and food accessibility [30,31]. Literature shows that these factors may be different depending on the country and/or region. This research focuses on gender differences in FI, which in context of the SDGs of the UN 2030 is particularly important.

1.1. Food Insecurity Assessment

Achievement of the SDGs largely depends on monitoring and follow-up processes [32,33]. Several methods and indicators are used to estimate FS and monitor its changes worldwide. The Food Insecurity Experience Scale (FIES) is an experience-based metric of food insecurity severity that ensures global comparability [34]. The FIES includes eight questions examining self-reported food-related behaviors and experiences associated with increasing difficulties in gaining access to food due to resource constraints of the individual respondent or of the entire respondent's household (Table 1). It is the official instrument used by the FAO to generate estimates of the prevalence of FI in the context of the SDGs' Target 2.1 monitoring [35].

Table 1. Questions in the FIES.

No.	During the Last 12 Months, Was There a Time When, Because of Lack of Money or Other Resources:	Short Reference
(Q1)	You were worried you would not have enough food to eat	WORRIED
(Q2)	You were unable to eat healthy and nutritious food	HEALTHY
(Q3)	You ate only a few kinds of foods	FEWFOODS
(Q4)	You had to skip a meal	SKIPPED
(Q5)	You ate less than you thought you should	ATELESS
(Q6)	You ran out of food	RANOUT
(Q7)	You were hungry but did not eat	HUNGRY
(Q8)	You went without eating for a whole day	WHLDAY

Own elaboration based on FAO [36].

The FIES is based on a well-established concept of FI experience consisting of three domains: worry/anxiety, changes in food quality and changes in food quantity [35,37]. With the FIES scale the risk of FI might be identified in communities and individuals in comparable manner in different populations. Based on the number of "yes" answers to questions (the FIES score,) the severity of FI can be accessed, ranging the FS status (zero positive answers) to all symptoms of FI (8 positive answers). FI is typically classified into four categories [35,38,39]:

1. Food secure—raw scores of 0;
2. Mild FI—raw scores of 1–3;
3. Moderate FI—raw scores of 4–6;
4. Severe FI—raw scores of 7–8 (see Figure 1).

Figure 1. The severity range of food insecurity. Own elaboration based on FAO [36].

The FIES score analyzed in conjunction with the respondent and household characteristics can broaden the knowledge of FI risk factors and consequences on an individual and household level [40,41].

1.2. Gender in Food Insecurity Research—A Brief Review of the Literature

Most of the studies on FI include gender as one of the explanatory variables [40,42–44]. FI scores for women and men depend, among others, on: (i) country/region of residence and (ii) method of FI measurement.

Smith et al. [42] analyzed the FAO's FIES data from 134 countries from 2014 and showed different results for low-income, lower-middle-income, upper-middle-income and high-income economies. Broussard [45] investigating the FAO's FIES data from 2014 for 146 countries worldwide, presented the results for 11 groups of countries, which showed that significant differences in FI between women and men were not observed in all groups of countries. Similarly, Grimaccia and Naccarato [40], considering the FAO's FIES data for over 100 countries, obtained different conclusions depending on the analyzed group of countries. In particular, it was found that in intermediate, less-developed and in the least-developed countries, women experienced FI more often than men, while in very rich and developed countries, the opposite results were obtained [40].

Another issue is the method of measurement. Studies with the binary variable dominate the literature. Specifically, analyzing data based on responses to eight questions in the FIES about the individual's experience with food insecurity, the authors typically apply a cut-off of one out of eight [46,47], a cut-off of two out of eight [45], a cut-off of four out of eight [42,48] and a cut-off of seven out of eight [42,48].

The literature indicates that results regarding gender are sensitive to the chosen cut-off. For the threshold one out of eight [47], a higher prevalence of FI among Polish women than men has been observed. Similar results for the EU were revealed by Broussard [45] with the threshold two out of eight. However, no statistically significant differences at the 0.05 level were found for moderate and severe FI in the EU. These results were also confirmed in the analysis of FI in 2017–2019 for Poland and Lithuania [49], where a higher mild FI among women than men was found, but no statistical difference referring to moderate or severe FI. Moreover, the choice of the model in the FI analysis is not without significance. The few studies using ordered logit models include Grimaccia and Naccarato [40] and Grimaccia and Naccarato [50]. They demonstrated that women experienced more FI compared to men—both globally and at the European level. In analyses where multinomial models were used, the results depend on whether mild, moderate or severe FI has been considered [49].

In addition to examining gender and FI, many studies also take into account various socioeconomic and demographic characteristics. Some factors influencing FI, such as poor education or low income, are universal in countries around the world [42]. Some of them, however, may be unique to a given country or a group of countries [40,42,49].

The few studies devoted to the relationship between FI and gender in the EU include Broussard [45] and Grimaccia and Naccarato [50]. Similar to Broussard [45] and Grimaccia and Naccarato [50], the study analyzed combined data from many countries belonging to a selected region. This analysis, however, concerned a rarely explored region: Central-Eastern Europe.

1.3. The Central-Eastern Europe Countries

The research focus was on eight post-communist countries of Central-Eastern Europe (CEE) who accessed the European Union (EU) in 2004. This EU enlargement incorporated the Visegrád Four (i.e., Czechia, Hungary, Poland and Slovakia) the Baltic Three (i.e., Estonia, Latvia and Lithuania) and Slovenia. The literature indicates, that despite the worse situation of these countries in 2004 compared to the "old" member states of the EU, the CEE countries have caught up the more advanced EU-15 economies [51,52].

The economies that acceded to the EU in 2004 have all had income levels below the EU average. However, analyzing the country-level FAO data it cannot be unequivocally said that the prevalence of moderate or severe FI in the "new" member states is higher than in the "old" member states of the EU (i.e., the countries that became the EU members before 2004) [53].

Since all these countries belong to the EU, food supplies as well as food quality and safety are subject to the same legal regulations and control systems. It is worth emphasizing that one of the EU's policy objectives is to ensure safe, nutritious, high-quality and affordable food for EU consumers [54]. However, as Hossain et al. [55] observed, food availability is not related to food accessibility, in other words, food supplies have minimal impacts on food security.

1.4. The Purpose and the Scope of the Study

The main goal of the study was to assess the differences in terms of different FI categories between women and men. Because of a very low incidence of severe FI, three categories: (i) food secure (FS), (ii) mild food insecure (MFI) and (iii) moderate or severe food insecure (SFI) were considered. To examine gender differences in food insecurity, bivariate and multivariate methods were applied. Apart from two-way findings (comparing FI and given individual factors), the results of the logistic regression models were presented. Such an approach allowed us to assess the significance of gender influence on FI after controlling typical socioeconomic and demographic characteristics indicated by the FI literature.

In this article statistical methods were used to address the following questions:

1. Are there any differences in experiencing FI according to gender in the CEE?
2. Are differences with respect to gender the same across all categories/severity levels of FI?
3. Are socioeconomic and demographic factors influencing FI with respect to gender the same across the CEE countries?

4. Do the results obtained with the use of different logistic regression models lead to the same conclusions?

Apart from bivariate methods, ordered, generalized ordered and multinomial logistic regression models were used. To the best of our knowledge, such "a bundle of models" has not been applied simultaneously so far in food insecurity analysis.

2. Materials and Methods

2.1. Description of the Dataset

This cross-sectional study uses individual-level data from the Gallup World Poll (GWP) (Global Research: See the World in Data | Gallup), made available by a license from the FAO. The GWP is a worldwide survey conducted annually in over 140 countries, using probability-based, multi-cluster sampling. It provides nationally representative samples of the adult population (aged 15 and above) in each country. More details about the GWP data in the context of FI research can be found in the FAO et al. report [7], Cafiero et al. [34], Ballard et al. [35], Broussard [45], Smith et al. [42] and dedicated website [36].

In this study, the dataset covering eight CEE countries (see Figure 2) was analyzed. Data relating to the situation before the COVID-19 pandemic have been taken into account. Due to the fact that for the Czech Republic and Slovenia the latest available data concerned year 2018, the data from 2018 and 2019 were combined. To be exact, the following data were included: for Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia data from 2018–2019, for the Czech Republic and Slovenia—only from 2018.

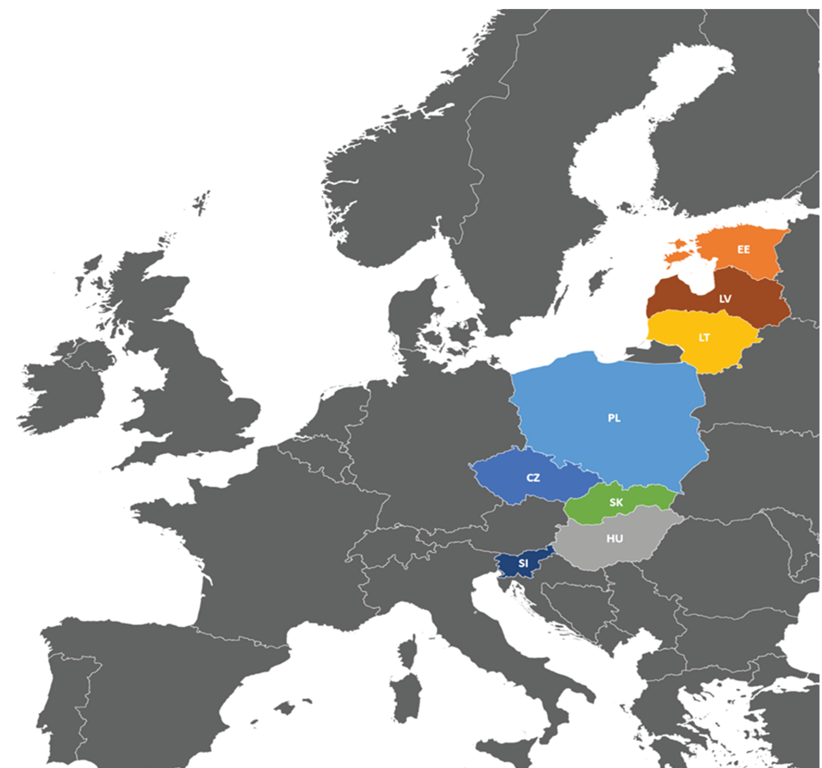

Figure 2. The location of analyzed CEE countries in Europe: Estonia (EE), Latvia (LT), Lithuania (LT), Poland (PL), Czech Republic (CZ), Slovakia (SK), Hungary (HU) and Slovenia (SI).

The sample size for a given year in a country was at least 1000 respondents aged 15 and above. In particular, in 2018 for the Czech Republic, Estonia, Hungary, Lithuania, Poland and Slovakia—1000 people; for Latvia—1021 people; and for Slovenia—2000 people. On the other hand, the 2019 data are samples of 1080 observations in each of the analyzed countries (i.e., Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia).

Assessment of FI in this study is based on the Food Insecurity Experience Scale (FIES) that uses a set of eight questions capturing a range of FI, with yes/no response (see Table 1). Since in the analyzed CEE countries the prevalence of severe FI is negligible (approx. 1.5% of the population), in the study three categories were considered:

1. Food secure with raw scores of 0 (FS);
2. Mild FI with raw scores of 1–3 (MFI);
3. Moderate or severe FI with raw scores of 4–8 (SFI).

Therefore, combined moderate and severe FI, which is of particular importance as it has been included in the SDG Indicator 2.1.2, was considered. Besides the FIES data, the Gallup World Poll database includes data relating to demographic and socioeconomic characteristics of individuals. Thus, the study examined the impact of various characteristics on FI. Apart from gender, the set of potential correlates included: educational level, age, the income quintile group and household composition. Moreover, the social capital and social network characteristics were considered. As in the work by Smith et al. [42], (i) social network is a binary variable that equals one if the respondent is satisfied with his/her ability to make friends, and (ii) social capital is a binary variable that equals one if the respondent feels she/he can count on friends and/or family in need. The household composition taking into account household size and presence in household at least 3 children up to 15 years old were included in the analyses. In the analysis of bivariate association, household size was categorized as a one-person, a two-person, a three-person, a four-person and at least a five-person household. Alternatively, in logistic regression models, logarithm of household size was also considered.

The educational level was categorized as elementary or lower (elementary), secondary and high or higher (tertiary). The age was classified into groups: below 34, 34–54, 55–69 and at least 70. Marital status was categorized as never married, married, living with partner, divorced or separated or widowed. The employment status was classified as fulltime employed for an employer, fulltime self-employed, out of workforce, part-time employee who wants to be fulltime employed and part-time employee who does not want fulltime employment.

2.2. Methods

As a first step, the proportions of the various FI categories for men and women were showed. Then, in this analysis, in order to analyze the strength of the relationship between respondents' characteristics and FIs among women and men, the Cramer's V coefficients were calculated. Finally, a regression model approach enabling the assessment of the significance of gender difference in respect to FI controlling socioeconomic and demographic factors was used.

In this study, logistic regression models to examine correlates of FI were used. As the outcome variable describing FI is ordered, the starting point in this research is ordinal logistic regression assuming (1):

$$P(y \le j|\boldsymbol{x}) = \Lambda(\alpha_j - \boldsymbol{x\beta}),\ j = 1,\ 2,\ \ldots,\ m, \tag{1}$$

where $\boldsymbol{x}$ is the vector of explanatory variables;

α are the threshold parameters;

$\boldsymbol{\beta}$ is the vector of the slope parameters;

$$\Lambda(\alpha_j - \boldsymbol{x\beta}) = \frac{1}{1 + \exp(-(\alpha_j - \boldsymbol{x\beta}))} \tag{2}$$

m is the number of outcomes/categories.

The predicted probabilities belonging to a given category are defined as (3) [56,57]:

$$P(y_i = j|\boldsymbol{x}) = \Lambda(\alpha_j - \boldsymbol{x\beta}) - \Lambda(\alpha_{j-1} - \boldsymbol{x\beta}),\ \ j = 1,\ 2,\ \ldots,\ m, \tag{3}$$

with $\alpha_0 = -\infty$ and $\alpha_m = \infty$.

In the study, three FI categories were considered, i.e., m = 3. Therefore, it is further proceeded as:

$$P(y = 1|\boldsymbol{x}) = \Lambda(\alpha_1 - \boldsymbol{x\beta})$$
$$P(y = 2|\boldsymbol{x}) = \Lambda(\alpha_2 - \boldsymbol{x\beta}) - \Lambda(\alpha_1 - \boldsymbol{x\beta})$$
$$P(y = 3|\boldsymbol{x}) = 1 - \Lambda(\alpha_2 - \boldsymbol{x\beta})$$

The ordinal logistic regression imposes a strong assumption of parallel regression. According to this assumption, the slope parameters should not differ for different categories. This assumption can be verified by the Brant test, the Wolfe–Gould test and the likelihood ratio test [56,58–61].

If the assumption of parallel regression is violated, such models as generalized ordered logit model or multinomial model can be used [57]. The generalized ordered logit model can be written as (4):

$$P(y \leq j|\boldsymbol{x}) = \Lambda(\alpha_j - \boldsymbol{x\beta}_j) \tag{4}$$

or:

$$P(y_i = j|\boldsymbol{x}) = \Lambda(\alpha_j - \boldsymbol{x\beta}_j) - \Lambda(\alpha_{j-1} - \boldsymbol{x\beta}_j),\ \ j = 1,\ 2,\ \ldots,\ m, \tag{5}$$

with $\alpha_0 = -\infty$ and $\alpha_m = \infty$ and Λ described by Formula (2).

Thus, the generalized ordered logit model allows the slope parameters to differ for each category j = 1, 2, . . . , m [56,57]. Therefore, Formula (4) generalizes (1) and Formula (5) generalizes (3).

A multinomial logit model is defined for nominal outcome. However, it is often used for ordinal data [56,62]. The multinomial logit model can be expressed as (6):

$$P(y = j|\boldsymbol{x}) = \frac{\exp\left(\alpha_j + \boldsymbol{x\beta}_{j|b}\right)}{\sum_{r=1}^{m} \exp(\alpha_r + \boldsymbol{x\beta}_{r|b})} \tag{6}$$

where b is the base (reference) category.

In this study, the outcome of one is used as the base category. Therefore, the predicted probabilities are calculated as (7):

$$P(y = j|\boldsymbol{x}) = \begin{cases} \frac{1}{1+\sum_{r=2}^{3} \exp(\alpha_r + \boldsymbol{x\beta}_r)} & \text{for } j = 1 \\ \frac{\exp\left(\alpha_j + \boldsymbol{x\beta}_j\right)}{1+\sum_{r=2}^{3} \exp(\alpha_r + \boldsymbol{x\beta}_r)} & \text{for } j = 2 \text{ or } 3 \end{cases} \tag{7}$$

The parameters of all described models were estimated by maximizing the log-likelihood. Statistical analyzes were performed using the STATA program (StataCorp LP, College Station, TX, USA).

In this research, the analyzed outcome variable has three categories: 1 denotes food security (FS), 2 means mild food insecurity (MFI) and 3 denotes moderate or severe food insecurity (SFI). For deeper investigation of the implication of the violation of parallel regression assumption, all described models were applied.

3. Results

The analytical sample comprised 15,501 individuals (52.88% female) spanning o eight CEE countries for the period of 2018–2019. The following sections present the prevalence of FI status in terms of gender, the associations between FI and the characteristics of respondents and the results of the logistic regression models.

3.1. The Prevalence of Food Insecurity

Table 2 presents the differences of the prevalence of FS status in terms of gender in CEE countries.

Table 2. Gender differences in FS status in CEE countries.

Gender	Percent	Std. Error	95% Confidence Interval	
		Food secure		
Men	81.45	0.54	80.36	82.49
Women	78.07	0.51	77.06	79.05
		Mild food insecure		
Men	13.13	0.48	12.23	14.09
Women	15.31	0.44	14.47	16.19
		Moderate or severe food insecure		
Men	5.42	0.32	4.83	6.07
Women	6.62	0.31	6.03	7.26

Source: Own elaboration.

When analyzing the results presented in Table 2, it can be noticed that men experienced food security more often than women (corresponding 95% confidence intervals do not overlap). However, when considering FI, only significant differences were found with regard to mild FI.

A comparison between women and men in terms of answers to individual FIES questions is presented in Figure 3. These eight questions (see Table 2) focus on the respondents' behaviors and experiences related to the increasing difficulty in accessing food as a result of resource constraints.

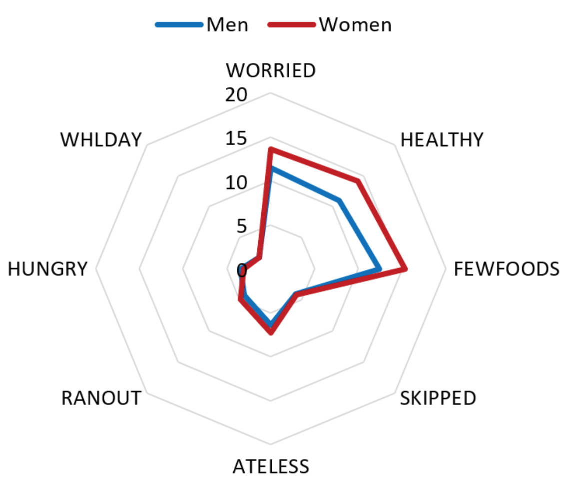

Figure 3. Percentage of positive responses to individual FIES questions (Table 2).

Figure 3 provides a detailed insight into the differences in responses to individual FIES questions.

On the basis of Figure 3, it can be seen that women more often than men answered positively to the questions Q1–Q3. These questions relate to mild FI [63]. However, the differences in the answers to the questions Q4–Q8 are not so pronounced. This means that in terms of experiencing moderate or severe FI, the response rate of women does not differ much from that of men.

3.2. Food Insecurity and Respondent Characteristics—Bivariate Analyses

To assess the association between FI and respondent characteristics, bivariate analyses were performed (Table 3). In this case, three categories of FI were also included.

Table 3. Association of food insecurity with respondent characteristics.

Variable	χ^2 Statistics	Cramer's V
Gender	**34.602**	**0.047**
Age	**57.708**	**0.043**
Household size	**214.411**	**0.083**
At least three children	**95.926**	**0.079**
Marital status	**377.988**	**0.111**
Education	**344.206**	**0.106**
Employment status	**366.382**	**0.109**
Social network	**166.206**	**0.073**
Social capital	**232.379**	**0.123**
Income quintile	**1300**	**0.202**

Note: numbers marked in bold indicate results that are significant at a 0.05 level.

For all variables, significant bivariate associations between FI and socioeconomic and demographic characteristics have been found. These results indicate that income and social capital were the factors with the closest relationship with FI, while the characteristics with a weaker relationship with FI were gender and age. Thus, a relationship between FI and gender was weak, but significant.

To assess the gender differences regarding strength of the dependence, Cramer's V coefficients were calculated separately for men and women (Figure 4 and Table 4).

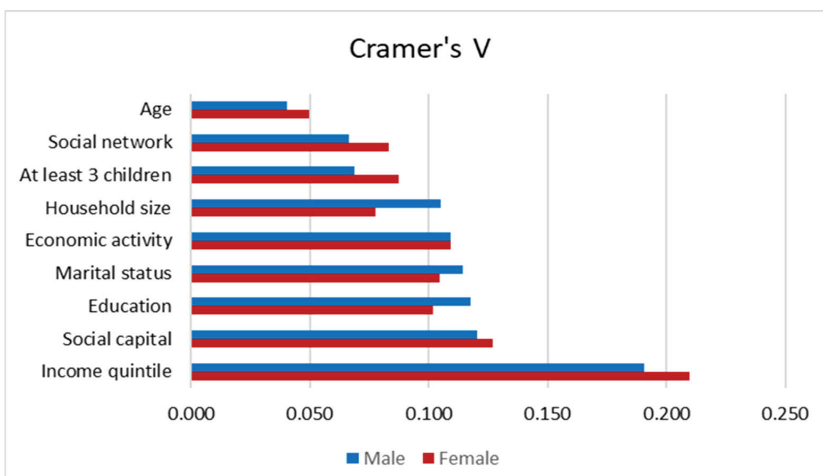

Figure 4. Association between food insecurity and the respondents' characteristics (Cramer's V measures).

On the basis of Figure 4, it can be concluded that there are minor gender differences between Cramer's V values. For example, considering the social network, its relationship with FI is greater among women. Contrarily, for household size, a higher Cramer's V was recorded for men; wherein household size was categorized as a one-person, a two-person, a three-person, a four-person and at least a five-person household. The significance of these differences was verified by determining the confidence intervals with bootstrapping. This enabled us to assess whether the nature of the dependence of the individual's characteristics and FI was the same for women and men. Detailed information on the differences in the Cramer's V measure among women and men is presented in Table 4.

Table 4. Cramer's V values and their 95% confidence intervals.

Gender	Cramer's V	Std. Error	[95% Confidence Interval]	
		Age		
Women	0.050	0.007	0.032	0.061
Men	0.040	0.010	0.020	0.051
		Social network		
Women	0.083	0.008	0.066	0.095
Men	0.066	0.010	0.047	0.077
		At least three children		
Women	0.087	0.015	0.060	0.121
Men	0.068	0.016	0.037	0.099
		Household size		
Women	0.077	0.008	0.059	0.089
Men	0.105	0.010	0.081	0.123
		Economic activity (employment status)		
Women	0.109	0.009	0.085	0.123
Men	0.109	0.010	0.086	0.126
		Marital status		
Women	0.105	0.007	0.089	0.116
Men	0.114	0.009	0.093	0.128
		Education		
Women	0.102	0.007	0.087	0.115
Men	0.118	0.010	0.096	0.138
		Social capital		
Women	0.127	0.013	0.101	0.149
Men	0.120	0.015	0.091	0.147
		Income groups		
Women	0.210	0.008	0.195	0.224
Men	0.191	0.009	0.171	0.207

Source: Own elaboration.

Based on the results presented in Table 4, as for each characteristic corresponding 95% confidence intervals for women and men overlap, it can be stated that there were no significant differences in the strength of FI dependency and individual characteristics among women and men. Therefore, the inclusion of all these characteristics in the logistic regression models seems to be justified.

3.3. Logistic Regression Models Results

In the next stage of the study, the logistic regression model was used to assess differences across gender in the EU controlling socioeconomic and demographic factors influencing FI. Firstly, the assumption of parallel regression for the ordered logit model was verified. Results shown in Table 5 indicate strong rejection of this assumption.

Table 5. The results of tests of parallel regression assumption.

Test	Chi-Square Statistics	df	χ^2 (0.05; 30)	p-Value
Brant	133.1	30	43.773	0.000
Wolfe–Gould	129.2	30	43.773	0.000
Likelihood ratio	125.7	30	43.773	0.000

The results in Table 5 therefore indicate that the ordered logit model is not appropriate for these data. In such a situation, generalized ordered or/and multinomial logit models should be considered. However, in order to compare the results for all three models given by Formulas (3), (5) and (6), their estimates are presented in Table 6. For the ordered logit model, one set of coefficients for all FI severity levels was estimated; however, this was different for the multinomial and generalized logit models. In the multinomial logit model, the first set of coefficients refers to mild FI (MFI) versus food secure (FS), the second set of coefficients compares moderate or severe food insecure (SFI) to food secure (FS). In the generalized logit model, the first set of estimates refers to any level of FI versus FS, the second set of estimates compares moderate or severe food insecure (SFI) to mild FI (MFI) or food secure (FS). Table 6 presents the basic results of the models' estimation. Results that are significant at a 0.05 level are marked in bold. Detailed results of the model estimation are presented in the Supplementary Materials.

Table 6. Ordered, multinomial and generalized ordered logit models' results. Country fixed effects are included in models.

Variable	Ordered	Multinomial		Generalized Ordered	
		MFI vs. FS	SFI vs. FS	FI vs. FS	SFI vs. MFI or FS
Women	**0.136**	**0.126**	0.170	**0.135**	0.166
Log HHsize	**−0.674**	**−0.505**	**−1.009**	**−0.640**	**−0.871**
At least 3 children	**0.665**	**0.451**	**0.964**	**0.622**	**0.851**
Social capital	**−0.645**	**−0.331**	**−1.056**	**−0.553**	**−0.914**
Social network	**−0.205**	**−0.254**	−0.117	**−0.216**	−0.104
Education (ref. elementary)					
Tertiary	**−0.872**	**−0.660**	**−1.371**	**−0.831**	**−1.256**
Secondary	**−0.420**	**−0.302**	**−0.582**	**−0.393**	**−0.495**
Age (ref. at least 70)					
Below 34	**0.320**	0.200	**0.537**	**0.293**	**0.474**
Age 34−54	**0.447**	**0.240**	**0.789**	**0.404**	**0.706**
Age 55−69	**0.329**	**0.277**	**0.406**	**0.322**	**0.327**
Marital status (ref. single (never been married))					
Married	**0.001**	**0.001**	0.0005	**0.001**	0.0003
Widowed	**0.443**	**0.473**	**0.458**	**0.464**	**0.335**
Divorced or separated	**0.597**	**0.453**	**0.839**	**0.571**	**0.701**
Domestic partner	**0.324**	**0.288**	**0.435**	**0.313**	**0.380**
Employment status (ref. unemployed)					
Employed fulltime for an employer	**−0.553**	**−0.498**	**−0.725**	**−0.610**	**−0.541**
Fulltime self-employed	**−0.527**	**−0.762**	−0.285	**−0.689**	−0.110
Out of workforce	**−0.619**	**−0.614**	**−0.711**	**−0.687**	**−0.542**
Part-time employee (want)	0.052	0.067	0.008	0.024	−0.091
Part-time employee (do not want)	**−0.556**	**−0.796**	−0.292	**−0.691**	−0.099
Income quintile group (ref. first quintile group)					
Second quint. group	**−0.786**	**−0.548**	**−1.160**	**−0.738**	**−0.975**
Third quint. group	**−1.269**	**−0.999**	**−1.786**	**−1.224**	**−1.490**
Fourth quint. group	**−1.537**	**−1.299**	**−1.966**	**−1.496**	**−1.659**
Fifth quint. group	**−2.118**	**−1.766**	**−2.876**	**−2.063**	**−2.518**
Cut1	**−0.683**	-	-	-	-
Cut2	**0.868**	-	-	-	-
Constant	-	−0.018	−0.272	**0.641**	**−0.891**

When analyzing the results concerning gender significance, it can be pointed that different results for the ordered logit model and for the other two models were obtained. Ordered logit models results indicated statistically significant difference between women and men in all FI categories (severity levels). This was not confirmed by the results of multinomial and generalized ordered logit models, according to which moderate or severe food insecurity among women does not significantly differ than among men. However, it should be underlined that the results presented in Table 5 provide evidence that the parallel regression assumption was violated. Thus, the use of ordered logit model leads to the misleading conclusion regarding the gender differences.

The same is true for the social network—no statistically significant difference has been found here in terms of moderate or severe food insecurity. On the other hand, the significance of social capital and education was recorded in all FI categories. When it comes to household composition, household size and at least three children turned out to have a significant impact on FI.

Taking into account age, a higher probability of FI among people under the age of 70 than among people over 70 was generally found. Marital status turned out to be an important differentiating factor for FI. Compared to single (never been married), other individuals experienced FI more often. The only exception were married respondents, where there was no significant difference in moderate or severe food insecurity.

The status in the labor market turned out to be an influential factor. In particular, fulltime employed for an employer and those being out of workforce were less FI than unemployed. However, no significant difference between fulltime self-employed and unemployed regarding moderate or severe food insecurity was found. Moreover, as expected, belonging to a specific income group was important for IF. Individuals from the higher quintile groups were less vulnerable to FI than those being in the lowest quintile group.

4. Discussion

Food insecurity in CEE is caused not only by low income, but also by other overlapping issues. As some studies indicate, FI also applies to people who are not poor [43]. Thus, there is a need to identify various socioeconomic and demographic correlates of FI for a better understanding of the problem.

4.1. Gender and Food Insecurity

The main focus in this study is gender differences regarding experiencing FI in various categories (severity levels). To explore this, first bivariate analyses were performed. Applying chi-square test, it was found that gender is a factor that significantly differentiates FI. In addition, investigating the prevalence of food security and mild food insecurity, a better situation for men compared to women was demonstrated. However, analyzing moderate or severe FI, no difference with respect to gender was found. It should be emphasized, however, that the differences in CEE are smaller than in some regions of the world, e.g., Latin America [7,36,45].

During the next stage, gender differences in food insecurity controlled for socioeconomic and demographic characteristics were examined. To investigate this issue, the ordered logit model, generalized ordered logit model and multinomial logit model were used. The application of multinomial and generalized ordered models lead to similar conclusions. On the other hand, the results for gender differences found via the ordered model differ from those obtained using the other models. However, it has been shown that the ordered logit model does not meet the assumption of parallel regression. Therefore, inference about the role of individual characteristics should be made on the basis of multinomial and/or generalized ordered models. It is worth mentioning that many authors do not verify this assumption. This can lead to misleading conclusions regarding the association of FI with socioeconomic and demographic factors. Specifically, the results of ordered logit model estimation indicate that women are more moderate or severe food insecure than men. However, this was not confirmed by the results obtained from the multinomial and generalized ordered models.

One of the reasons why women may experience greater mild FI compared to men is that women are primarily responsible for day-to-day food supply decisions and food provisioning in their households [64,65]. Broussard [45] suggests that they may therefore be more aware of the problems in meeting their food needs before these problems become serious. Gender inequalities, still deep-rooted in many societies, might be a contributing factor [6,26]. Despite the fact that women are increasingly involved in paid work, the share of domestic tasks and care work is still not equal. This results in a double burden for women and, consequently, greater susceptibility to stressful situations [66]. Additionally, women tend to experience higher levels of anxiety, frustration and depression than male when reacting to stress [67]. As Broussard suggests [45], men because of shame, pride or other reasons might not be so willing to report less severe experiences compared to women.

The findings regarding the relationship between FI and gender are consistent with those of Broussard [45] revealing the gender difference with respect to mild FI in the EU but there was no significant difference at the 0.05 level regarding moderate and severe FI. However, the study results differ from those obtained by Grimaccia and Naccarato [40,50] who applied ordered logit. In the above-mentioned studies, women experienced more FI compared to men. Perhaps this discrepancy is the result of the ordinal logistic regression model used by the authors [40,50].

The obtained results are important for the SDGs for gender equality. In the context of sustainable development, ensuring food security, including the proper nutritional status of girls and women, is of key importance [6]. Food security disruptions, especially in middle- and upper-income countries, are usually compensated by choosing foods with a lower nutritional value, which leads to excessive body weight gain and qualitative malnutrition [68]. FI might be associated with poorer diet quality and health status [69]. Anemia, caused by poor nutrition and deficiencies of iron and other micronutrients, contributes to maternal mortality and low birth weight [70]. Food insecurity can increase the likelihood of pregnancy complications and have a direct impact on the fetus development and the future health of both woman and child [71]. This can increase healthcare costs, hinder active participation in the labor market and consequently and have a negative effect on economic development [22].

4.2. Other Correlates of Food Insecurity

The other results of the present study are largely in line with empirical studies that use FAO's FIES data [42,45,50]. In accordance with previously mentioned authors [42,45,50], it was found that experiencing FI was associated with low levels of education. This may be due to the fact that better educated people are more aware of the importance of lifestyle, especially diet, for overall health and well-being. Consistently with Smith et al. [42], the study findings confirmed the positive impact of social capital in reducing the risk of experiencing FI. Thus, feeling that people could count on help from friends and/or family in need was an informal insurance. When it comes to social network, Broussard [45] and Smith et al. [42] found its dependence on all severity levels of FI. However, its significance in terms of experiencing moderate or severe FI has not been confirmed. The results only indicated that being satisfied with the ability to make friends matters in the mild FI experience. Furthermore, marital status was a characteristic playing an important role in the likelihood of experiencing FI. As Grimaccia and Naccarato [50], this study found that separated or divorced respondents more often experienced FI (on all FI severity levels) compared to single individuals. Contrary to Grimaccia and Naccarato's [50] results for the whole Europe, our findings indicated that single individuals were not more affected by mild FI than married respondents. However, as Grimaccia and Naccarato found, the region of Europe may matter in this regard. Specifically, they showed that the difference between these two groups in Eastern Europe was not significant at the 0.05 level. In addition, widowed and domestic partners were taken into account and the worse situation of these individuals compared to single individuals was presented.

The findings of Smith et al. [42] confirmed that the role of employment status depends on the FI severity level. Moreover, in line with Broussard [45], it was found that fulltime employed and out of the workforce were less vulnerable to FI than the unemployed. However, in the present study, employed fulltime for an employer and fulltime self-employed were additionally distinct. Furthermore, unlike Broussard [45], a part-time employee who wants be fulltime employed and a part-time employee who does not want fulltime employment were considered separately and their different FI situation compared to the unemployed was shown.

Age was another characteristic considered in the present work. A significant but weak relationship between age and FI was showed. It is difficult to directly compare our results with those of other studies in this regard. In the analyzed works, a slightly different way of including age in the models was adopted. Especially, Grimaccia and Naccarato [40,50] and Smith et al. [42] showed an inverted U-shape relationship between the age of the respondent and FI. This means that the most vulnerable to FI were middle-aged people. This result was largely confirmed in the present study, as a higher FI for people aged 34–59 compared to people 70 was found.

It is worth underlining the importance of our results on FI in the context of the COVID-19 pandemic. Recent research in countries such as Brazil [72], Mexico [38], the United States [73] and Poland [74] revealed that COVID-19 and national lockdowns have a substantial impact on FI status. Additionally, there is some evidence that women remain disproportionately affected by the socioeconomic fallout during the COVID-19 pandemic, struggling with the loss of jobs and livelihoods, disrupted education and increased burdens of unpaid care work. Between 2019 and 2020, women, who were already underrepresented in employment and the labor force, suffered steeper job losses than men. As women earn less, save less and are the majority of single-parent households, their capacity to respond to the economic crisis is therefore less than that of men [75]. Unfortunately, data from 2020 and 2021 are not available to us. Nevertheless, in order to be able to understand the impact of the pandemic on FI, it is essential to have a reliable baseline for comparison. Thus, in the light of the COVID-19 pandemic, the present results contribute by providing a baseline for comparing the experience of pre- and post-pandemic FS in CEE in future research. However, we are aware that the issue of FI requires continuous monitoring, which is a premise for further exploration in this area.

4.3. Study Strengths and Limitations

The research aimed to explore differences in the prevalence of FI between men and women in CEE, and to investigate the role of socioeconomic and demographic factors among women and men. The study adds to the understanding of the gender association with FI status (severity levels) in Central-Eastern Europe. It provides a cross-sectional analysis of a survey conducted by GWP. It explores this issue using FIES data validated worldwide by the FAO. These data include nationally representative samples of the population 15 years of age and older. Such data give the opportunity to identify the characteristics of population groups at a greater risk of FI. According to the FAO's recommendations, the severity of food insecurity was classified as mild, moderate or severe FI [36]. Due to a very low prevalence of severe FI, it was combined with a moderate FI, and finally three categories, food secure, mild FI, moderate or severe FI, were analyzed. It enabled us to distinguish between serious and less serious conditions of food insecurity. The differences between the categories are important for research as well as policy purposes.

It was showed that the results in terms of gender are sensitive to the modelling approach. Therefore, it is also important to check the assumptions used in the models. Apart from bivariate analysis, the study applies ordered, generalized ordered and multinomial logit models. In the present study, the assumption of parallel regressions imposed on ordered logit models has been rejected. Therefore, a multinomial logit model and a generalized ordered logit model were used. The conclusions from these two models are very similar—thus, the findings are robust.

This study is not without limitations. In FI analysis, it would be interesting to take into account the impact of other characteristics apart from those included in this research. For example, the individual situation with regard to the burdening of household income with fixed expenses (e.g., loan repayments, fixed house maintenance fees) might be crucial. It would also be worth taking into consideration the biological type of the household in which the respondent lives (i.e., whether the household consists of parents and children, or if it is a multi-generation unit, etc.). Unfortunately, the GWP do not provide detailed information on the above-mentioned issues.

Finally, it should be point out that these results are for combined data from several countries. It should be stressed that they may differ slightly from one country to another. However, the goal of the present study was to show the importance and complexity of FI with respect to gender in the wider CEE perspective.

5. Conclusions

The study provides a new insight into the gender–food insecurity relationship in Central-Eastern Europe. A slightly higher rate of mild FI reported by women compared to men was found. However, the present study highlights that the differences between women and men in terms of FI are not as large as in some regions of the world, e.g., Latin America, as no significant gender difference in moderate or severe FI was observed. In addition, after stratification by gender, it was demonstrated that economic activity, income, education, social network, social capital, household composition, marital status and age were significantly associated with women's as well as men's FI status. Thus, the mentioned factors influenced both women and men FI. It was observed that FI prevalence decreased with increasing severity. Importantly, the present study demonstrated that the results in terms of gender are sensitive to the modelling approach.

The identification of groups particularly vulnerable to FI may allow for the appropriate targeting of countermeasures against FI and their adaptation to people with different demographic, social and economic characteristics. Deeper understanding of the factors that are associated with FI should help to target the most vulnerable FI individuals as well as orientate policy recommendations.

The study results indicate that the policy should be particularly targeted at households with at least three children, individuals with low education, the unemployed and the lowest income groups. The present study highlights the important role of social capital. Hence, a large role to play for various social welfare centers serving not only material assistance but also psychological support, to ensure people that they have someone to count on when in need. Collaboration between government agencies and non-government organizations, including food banks, can be beneficial to reduce FI. Efforts to improve food security in CEE should be undertaken through policy. It would be useful to monitor the situation at different FI severity levels and not be limited only to people experiencing severe FI. Early intervention among mild FI individuals, with particular emphasis on women, could prevent the problem from worsening.

Policy should, first and foremost, promote healthy and sustainable consumption behaviors, support vulnerable households and individuals and reduce income poverty. However, to reinforce these findings there is a strong need for increased scope of research using more recent data and a wider range of explanatory variables. Further research should focus on the changes caused by the pandemic and the Russia–Ukraine war. Especially, an important aspect is the analysis of FI among people particularly hit by the effects of the COVID-19 pandemic. A new issue to be explored is the prevalence of FI among Ukrainian refugees, the largest group of which are women.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14095435/s1, Table S1. The ordered logit model results; Table S2. The multinomial logit model results; Table S3. The generalized ordered logit model results.

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Glossary

CEE	Central and Eastern Europe
FAO	Food and Agriculture Organization
FI	Food insecurity
FIES	Food Insecurity Experience Scale
FS	Food security
GWP	Gallup World Poll
MFI	Mild food insecurity
SDGs	Sustainable Development Goals
SFI	Moderate or severe food insecurity

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Systematic Review

The Dynamics of Youth Employment and Empowerment in Agriculture and Rural Development in South Africa: A Scoping Review

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Abstract: Over the years, South Africa has made significant investments aimed at transforming the agricultural sector to deliver on rural economic development and job creation. These investments have had varying levels of success; still, what is worrying is the high youth unemployment rate which is amongst the highest globally. We conducted a scoping review using the PRISMA-P guidelines to identify the challenges youth face in accessing sustainable employment in the agriculture sector. Peer-reviewed studies were retrieved from online databases (Web of Science, Cab Direct, and Science Direct) for 1994–2021. The findings showed that youth are still facing significant challenges in the demand and supply side of the labour market and lack of inclusivity in policy formulation and implementation, limiting their involvement in agriculture and rural development initiatives. Policies and strategies responding to these challenges exist, and the spectrum of support services provided are primarily focused on entrepreneurship. Yet, the implementation of programs and initiatives has not been successful. This could be attributed to the obstacles persisting in the sociopolitical environment in SA, causing additional barriers to program implementation. Therefore, to enhance youth involvement in agriculture and rural development, there is a need to connect more rural youth to support services, local employment programmes, and youth inclusion in policy formulation processes. Additionally, the focus of policy and programs should be broadened to cater to different youth knowledge and skill profiles.

Keywords: agriculture participation; empowerment; government programmes; employment; unemployment; youth inclusion

1. Introduction

As of the third quarter of 2021, the unemployment rate in South Africa (SA) reached a new record of 34.9%, increasing by 0.5% from the second quarter of 2021 [1]. The country currently has a youth unemployment rate of 66.5% [1], which is still among the worst globally [2,3]. The SA labour market is more favourable to men than women. The proportion of men in employment is higher than that of women, and the unemployment rate among men is lower than among women [1]. The unemployment rate among women was 37.3% in the third quarter of 2021 compared to 32.9% among men [1]. Yet the South

African population is female and young. Despite assurances of a better life in the post-apartheid era, the majority of the 'born free' generation of young South Africans continue to face high levels of poverty, unemployment, and limited opportunities for upward socioeconomic mobility experienced by their parents decades earlier [4–7]. Because of the legacy of apartheid, rural areas in SA are marginalized, underdeveloped, and distant from economic advantages and opportunities [7]. Thus, youth in rural areas face poorer employment prospects and migrate to cities to seek opportunities [8]. Agriculture, which is envisioned as a vehicle for rural economic development, could potentially turn this tide by creating employment opportunities for rural youths where they reside.

A South African's likelihood of being trapped in poverty is primarily determined by gender, race, and location [5,9,10]. Similarly, evidence emphasises the quality of education, socioeconomic background, policy design and implementation, the structure of the labour market, and lack of youth inclusivity as the main areas where challenges still exist [8,9,11–13]. Consequently, the combination of these factors produces a young workforce that is ill-prepared to compete in the economy, reinforcing spatial and gender inequalities, poverty, and unemployment [6,12]. Nonetheless, household-level barriers such as geographical isolation, low levels of social capital, lack of access to information, and the cost of seeking work hinder youth's employability [7,14]. Furthermore, since the COVID-19 pandemic began, skilled employment has been much more durable than unskilled and semiskilled jobs [15]. Thus, many unskilled youths have lost their jobs, adding to the already high numbers of unemployed youth.

Identifying and addressing the main drivers of poverty, inequality, and unemployment amongst the youth is essential for supporting them to reach their potential and contribute to economic growth and sustainable development [16]. A holistic approach to youth employment and empowerment is required to address the challenges affecting youth participation in the labour market [13]. Agricultural transformation in lower- and middle-income countries is essential in supporting emerging economies, eliminating poverty and hunger [17]. Furthermore, food systems outcomes influence human nutrition, food security, health, environmental, social, and economic results [18]. Unlocking opportunities in the food system, however, would necessitate the creation of decent jobs for young people by supporting them to build skills relevant to the job market while also improving income security [19].

It is also critical to identify food-system-related challenges to unlock opportunities for livelihood-enhancing strategies [20,21]. Green jobs have the potential for job creation, skills development, and new opportunities for youth to start niche businesses and ensure better quality jobs within the value chain [22]. However, they require a higher skill level, dedicated and structured training, and coordinated policy frameworks to develop the 'green skills' required [19,23,24].

Youth Empowerment in Agriculture

The youth empowerment element in policy is essential for accountability and reflects a commitment to support the enabling conditions that assist youth in taking charge of their own lives and well-being [25]. Jennings et al. [26], describe empowerment as a multilevel construct that can occur at multiple levels (e.g., individual, family, organization, and community). It includes social action processes, practical approaches, and applications that aim to increase control and mastery for improved equality and quality of life [26]. Equally, Martínez et al. [27], define youth empowerment programme activities as interventions that, based on young people's strengths, involve them in decision-making processes regarding the design, planning, and implementation of the programmes themselves, and award them an active, central role. The concept of empowerment can also be linked to power, participation, and education [28]. Moreover, government youth empowerment programs influence the development paths that youth can take [29]. Therefore, solid youth empowerment in agriculture ought to support the efforts to increase youth participation in agriculture [30].

However, the apartheid regime caused inequalities in the spectrum of skills relevant to the agriculture sector in SA, particularly regarding Agricultural Education and Training (AET). To address these challenges, various initiatives and programmes were introduced post-1994 as part of a transformation agenda [31]. This included increasing support to AET through supporting Agricultural Colleges and Universities of Technology, the external bursary scheme, introducing the Young Professional Development Programme (Internship) in 2004, and the master mentorship programme [32]. Moreover, to promote equal participation in the sector, other skills development programs were implemented through AgriSETA, extension services, and agricultural finance schemes through the Land and Agricultural Bank and Micro Agricultural Financial Institutions of South Africa (MAFISA) [33]. However, despite these efforts to mainstream youth into the sector, support programs have achieved limited success [31] with numerous initiatives lacking consistent support, monitoring, and evaluation [34,35], including the impact of government corruption [36] and lack of coordination between land, agriculture, and rural development policies [37,38].

The long-term vision and strategic goals of SA are outlined in the National Development Plan (NDP) [39]. Its core vision is to reduce poverty and inequality while ensuring that all South Africans attain a decent standard of living. However, the goals of this long-term plan can only be realised if and when SA draws on the energies of its entire people, including the youth. The implications of this long-term plan are addressed in other strategies such as the Medium-Term Strategic Framework (MTSF) and the New Growth Path (NGP) [40]. Though, as noted by several authors [41–43], these policies lack the necessary mechanisms to effectively address the socioeconomic challenges they aim to resolve. For instance, the Expanded Public Works Programme (EPWP) [44] and the Community Works Programme (CWP) are programmes that are outputs of the NGP. These programmes have been designed and implemented to create employment for low skilled youth in SA. However, they have been associated with vulnerable working conditions, do not provide sustainable job creation in the long term, and do not provide skills development [45–48]. South Africa's key policies such as the NGP and the NDP promote agriculture as a means to achieve all-inclusive growth, employment, and food security. In SA, agriculture accounts for 5% of the total employment [49] and can create more jobs rapidly, especially in rural areas where traditional industries are not incentivised to set up businesses. Thus, this scoping review investigates the challenges youth in democratic SA face to participate in the labour market, emphasising youth in agriculture and rural development. The specific objectives are to:

(a) Determine youth participation and empowerment in the agricultural sector in SA;
(b) Assess government policies, strategies, and programmes related to youth participation and empowerment in agriculture in SA to ensure equality and inclusivity of youth in the sector.

This review investigates the dynamics of youth employment and empowerment in agriculture and rural development in democratic SA. It begins by (i) exploring the primary factor determining youth participation in agriculture and shaping youth perceptions of the industry. Then, the review (ii) examines the main challenges experienced by youth in agriculture, (iii) describes additional factors preventing youth from securing sustainable employment in agriculture and rural development, (iv) addresses the main aspects to create an enabling environment for youth participation and empowerment, and lastly, (v) investigates policy focus and priority areas.

2. Materials and Methods

2.1. Literature Search

This desktop review was conducted using Arksey and O'Malley's [50] methodological framework for scoping reviews and the PRISMA-P guidelines for conducting systematic reviews [51]. The literature search focused primarily on government policies, strategies, and programmes related to youth participation and empowerment in agriculture and rural development in South Africa from 1994 to 2021. This period covers the post-apartheid era and overlaps with the African Youth Decade plan of action [52]. Grey literature and other relevant policy documents (regional policies set by international government organisations) were retrieved from websites of key development organisations in Africa's agriculture, for example, the Food and Agriculture Organization (FAO), African Union, Southern African Development Community (SADC), New Partnership for Africa's Development (NEPAD), Institute of Development Studies, and United Nations agencies, among others. The review of policies, strategies, and programmes was complemented by a secondary literature search of peer-reviewed research articles using online databases, namely, Web of Science, Cab Direct, and Science Direct, based on studies conducted on youth in agriculture in South Africa published between 1994 and 2021.

The PCC (Population, Context, and Concept) nomenclature was adopted to determine the eligibility criteria for identified documents, and it was also used as a screening tool (see Table 1 below). In terms of population, the study included young people between the ages of 15 and 35, as defined by the African Youth Charter [53], who are involved in agriculture. Aside from agriculture involvement, the context also included young people in universities/agricultural institutions or any other agricultural training program. The literature search terms/keywords were 'agriculture' with the synonyms 'farming', 'land management', and 'farm management'. The second keyword used was 'participation' with the synonyms 'involvement', 'engagement', and 'contribution'. The third keyword used was 'youth' with the synonyms 'young people', 'adolescents', and 'young adulthood'. The keywords were used in combination with each other. The use of singular and plural and synonyms for search terms was also applied, accounting for relevant keywords that may differ from one database to another. For example, for the search terms 'youth and agriculture', 'young farmers', or 'young people in farming' were used.

Table 1. The PCC (Population, Context, and Concept) nomenclature adopted to determine the eligibility criteria for screening and selection.

Include	Exclude
Population	
• Young people in agriculture between the ages 15 and 35 years old • Young people in universities/agricultural institutions between the ages 15 and 35 years old	• Focus on males only • Focus on females only
Context and Concept	
• Interventions researching the participation or empowerment of youth in agriculture • Intervention/study creating or identifying opportunities for youth participation in an agriculture program • Studies researching youth perceptions, awareness, or attitude towards agriculture • Program or intervention analysing social or political environment factors affecting the participation of young people in agriculture • Interventions or studies conducting research that addresses a challenge or limitation faced by youth in agriculture • Government policies, strategies, and programmes related to youth participation and empowerment in agriculture for South Africa from 1994 to 2021 • Qualitative and quantitative studies	• Literature reviews/review papers or studies with no primary data • Studies not conducted in South Africa/not of relevance to South Africa • Studies on food insecurity, diets, or nutritional status of youth • Farm injuries in young workers • Youth urban migration • Studies focusing on gender gaps concerning youth employment challenges or opportunities

After that, the peer-reviewed journal articles, policy and strategic documents were divided and analysed. The documents were separated to ensure that the content of larger documents did not skew or offset the analysis. As noted by Alves and Lee [54], a joint analysis tends to skew word frequency and word query results on qualitative data analysis software such as QRS NVivo, in favour of the lengthier documents.

2.2. Data Analysis

2.2.1. Peer-Reviewed Journal Articles

For the peer-reviewed journal articles, the documents retrieved from the search were exported to the QRS NVivo 12 qualitative data analysis software [55]. A search query for the 20 most common words in the data set was conducted and word trees were generated (see Supplementary Materials, Figure S1). The number 20 was selected to give a snapshot of broad focused themes and connections within the data set related to opportunities and challenges for youth participation in agriculture. These were then translated into themes or 'nodes' for further analysis [55]. These nodes contained classifications such as 'developmental initiatives', 'support required', 'youth characteristics', 'youth participation', and 'demographical challenges'. Further classification of the data set was carried out to code passages of the data under the appropriate node. Then, these nodes were further organized into cases based on topics. The topics included awareness of initiatives and programmes, youth interests and aspirations, mentorship, inclusion, training and experience, and entrepreneurship.

Then, to establish the factors determining youth participation and empowerment in agriculture, an explore diagram was generated to investigate the connections and links between the nodes and cases. The focal point of this explore diagram was the 'awareness of initiatives and programmes' case. Subsequently, a comparison diagram was created to show the relationships and similarities between negative and positive youth perceptions of agriculture. Afterwards, using the crosstab query and matrix coding functions within NVivo, aspects of the data set and results from the previous analysis were further analysed for patterns and connections. These patterns and relationships were explored to establish additional factors and challenges that youth face to secure sustainable employment in the agriculture and rural development sector.

2.2.2. Policy and Strategic Documents

The Content Analysis (CA) methodology was used in analysing strategic documents. Content analysis is a systematic method useful for analysing patterns, understanding context, and interpreting meaning in documents [56,57]. It is popular in the humanities and social science disciplines and has been used in analysing legislation [54,58,59]. In this study, CA was considered suitable for analysing trends and patterns in government policies, strategies, programmes, and youth empowerment initiatives in agriculture in SA. Although we argue the effectiveness of using CA in understanding the context of documents, we acknowledge the limitations of this methodology. There are risks associated with validity and rigour which may occur from possible personal biases [57]. To mitigate the risk of bias, two researchers initially performed the policy analysis separately, met to discuss their results, and obtained a consensus to increase validity. This was further reviewed by key experts in the field and thereafter reviewed by officials from the Department of Agriculture, Land Reform and Rural Development (DALRRD), and the Food Agriculture Organisation (FAO SA). Moreover, Figure 1 below maps the process followed during the analysis for transparency.

Deductive content analysis was used to explore the choices made about the policies' content [60]. Based on the study's objectives, the components of interest in policy and strategic documents are listed in Figure 1. Consequently, the main codes and themes for the analysis emerged from those components of interest. The contents of the policy documents from the areas of interest were extracted and pasted into Microsoft Word files for each record. These Word files were then exported to the QSR NVivo 12 qualitative data analysis software [55]. This allowed for a more in-depth interpretation of each component and avoided distortions that would arise and skew the software-aided analysis favouring the larger documents [54]. After that, the documents were coded under the predetermined codes, and new subcategory codes such as 'priority areas' and 'distribution of resources' emerged. Then, these nodes were further organized into cases based on topics. The topics included entrepreneurship, agriculture production, mentorship, creating an enabling environment, socioeconomic challenges, and inclusion. Once the coding was concluded, a more in-depth analysis of the categories was carried out to determine patterns, causal relations, and conducting word frequency queries to find the most frequently occurring words and concepts. These relationships were visualised using tree diagrams and graphs as per study objectives.

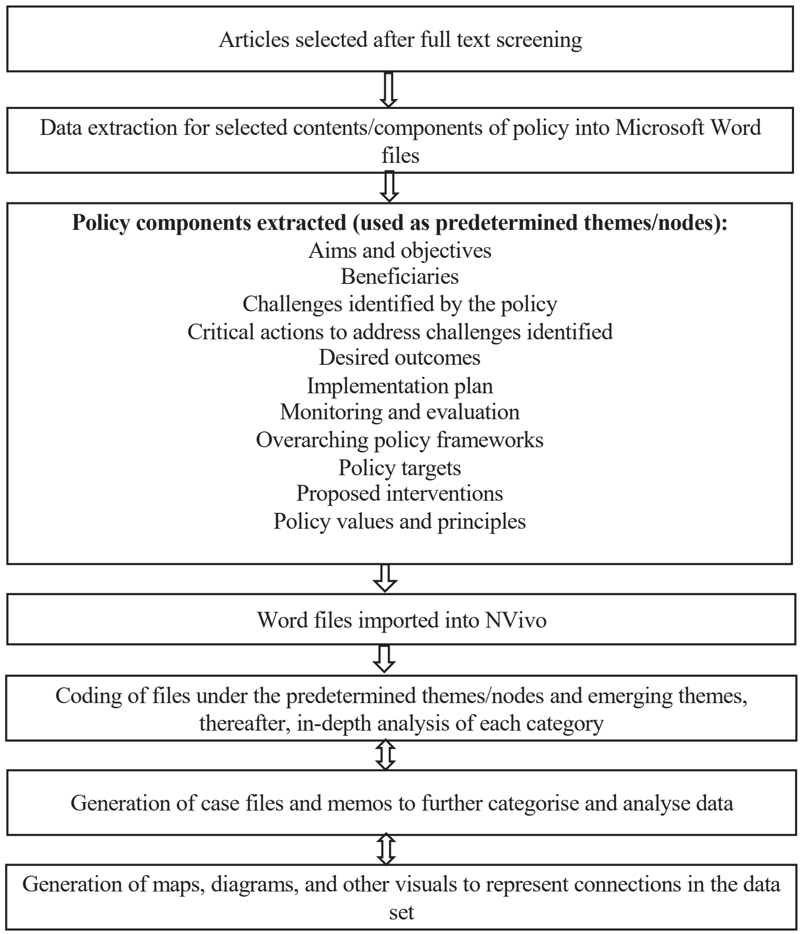

Figure 1. Data analysis process followed for policy and strategic document analysis.

The first section of the results (cf., Section 3.1) presents the findings of the literature search and the characters of the studied articles. Section 3.2 presents the results on youth participation in agriculture and its associated factors. In Section 3.3, the challenges experienced by youth in agriculture in SA are presented. This also includes additional factors preventing youth from securing sustainable employment in the agriculture and rural development sector, whereas Section 3.4 of the study reports on elements to be addressed to create an enabling environment for youth participation and empowerment. Lastly, Section 3.5 reports on the government strategies and programmes related to youth participation and empowerment in agriculture and the proposed policy interventions and priority areas are outlined in Section 3.6.

3. Results

3.1. Literature Search Results

The PRISMA flowchart (see Figure 2) and the conduct and reporting of scoping reviews [61,62] were used as a guideline for reporting the review results. Although the literature search examined the period 1994–2021, no peer-reviewed literature published before 2006 was retrieved. In total, the literature search result found 80 studies after duplicates were removed. At the abstract screening stage, a total of 34 records were excluded, and 46 records were assessed for eligibility. From there, a total of 11 studies were excluded at the full-text screening stage. The most common reasons for exclusion were the lack of primary data and irrelevance towards research objectives. In the end, the analysis included a total of 35 documents (14 peer-reviewed documents and 21 policy documents), see Supplementary Materials, Tables S1–S3, for a summary of included and excluded documents. Most of the peer-reviewed documents were studies conducted in the Limpopo province (n = 5), followed by KwaZulu–Natal (n = 3), Mpumalanga province (n = 3), and the Eastern Cape province (n = 2). Only one study [63], researched all provinces in SA. The policy documents included policies and strategies on agricultural education and training, generic youth development and empowerment, and agriculture development (finance, support services, and entrepreneurship) (see Supplementary Materials, Table S2).

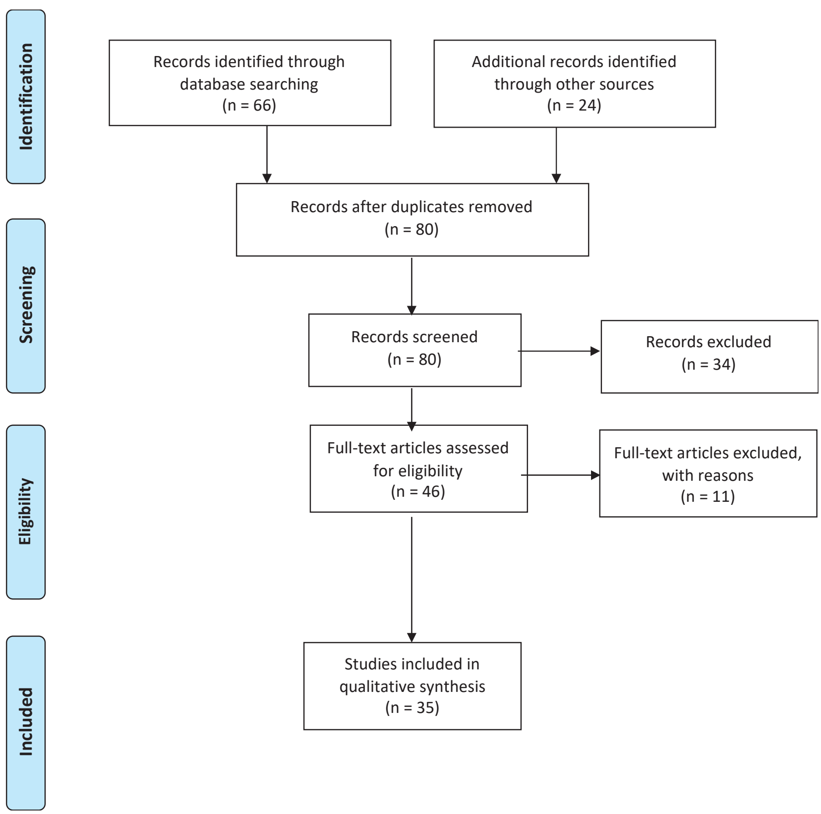

Figure 2. PRISMA flow diagram outlining protocol adopted in the scoping review based on the Preferred Reporting Items for Systematic Review and Meta-analysis Protocols (PRISMA-P) 2015 statement [51].

3.2. Youth Participation in Agriculture

According to the Youth Leadership Institute [64], youth engagement is the active, empowered, and intentional partnership with youth as stakeholders, problem solvers, and change agents in their communities. The analysis showed that the primary factor determining youth participation in agriculture and shaping youth perceptions of the industry is awareness of initiatives and programmes. As seen in Figure 3, awareness is fundamental as it is connected to participation, perception, aspirations, interest, and access to resources and information. It is also highlighted as a key recommendation from studies analysed. As shown in Figure 4, creating awareness of initiatives and programmes can be accomplished through various stakeholders such as schools, the private sector, government interventions, and development initiatives. However, awareness is also inhibited by demographical challenges such as being in remote rural areas [65], lack of social capital or having limited access to a network of people who are willing to share information [66–68], and access to the Internet and digital literacy [69]. This further marginalises youth in rural areas. Moreover, when comparing the difference between youths who have a negative perception of agriculture with those who have a positive perception of the industry (see Figure 4), awareness of initiatives and programmes is central in shaping youth perceptions.

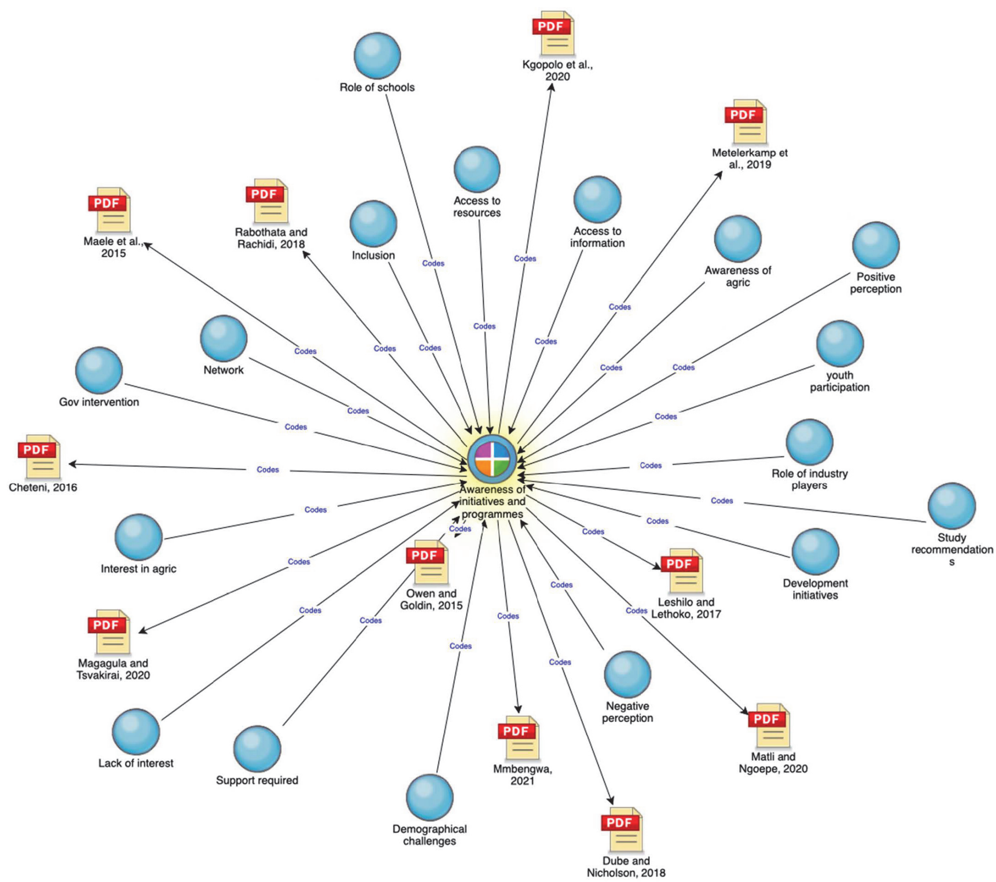

Figure 3. An explore diagram generated in NVivo to investigate the connections and links between the nodes (nodes based on pre-existing and emerging themes) and cases (cases based on topics). The focal point of this explore diagram was the 'awareness of initiatives and programmes' case.

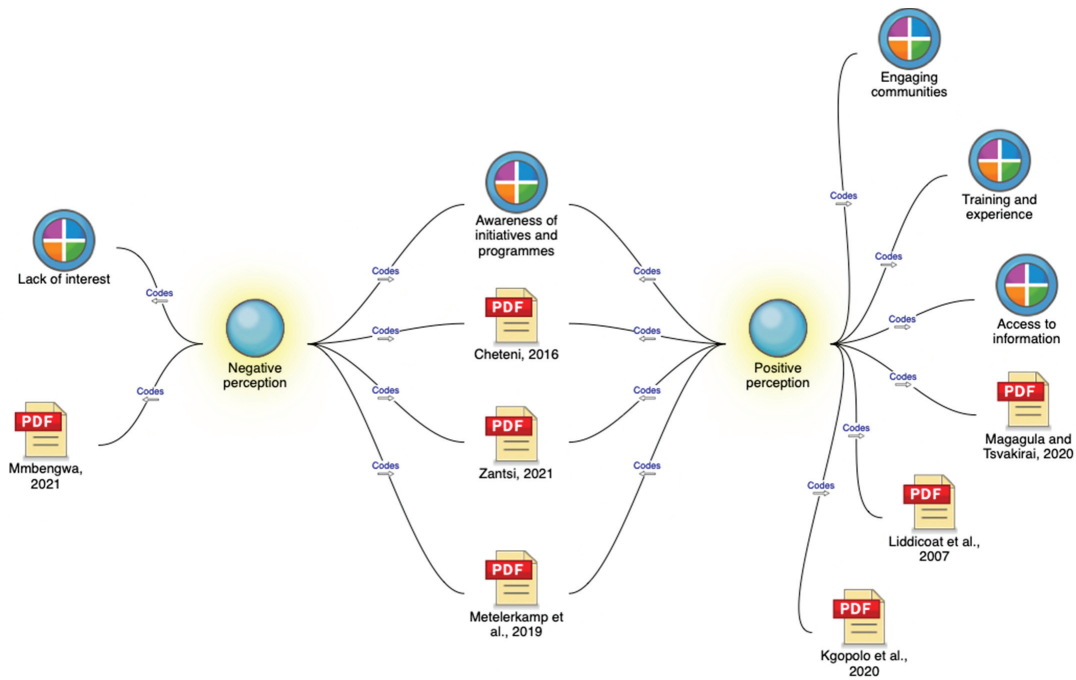

Figure 4. A comparison diagram showing the relationships and similarities between negative and positive youth perceptions of agriculture (extracted from NVivo).

3.3. Challenges Faced by Youth in Agriculture in SA

Based on the analysis of issues stated in the studies included in this review, the main challenges experienced by youth in agriculture in SA can be categorised into two broad clusters: the demand and supply side of the labour market (see Figure 5). The demand side considers factors related to the labour market structure in a national and regional context [70]. The supply side refers to the features and characteristics of both the individual young person and their households [71]. These barriers can cause lower economic participation rates and other long-term negative consequences related to employability and well-being [72]. The factors categorised demand cluster are (i) government regulations, (ii) lack of a relationship with stakeholders, (iii) limited support from the government, (iv) limited support from private sector players, and (v) lack of youth inclusion in development programs, amongst others. The factors categorised supply cluster are (i) lack of access to credit and finance, (ii) lack of access to information, (iii) lack of awareness of initiatives and programmes, and (iv) lack of entrepreneurship education, amongst others.

The factors categorised under the demand and supply clusters regulate the economic environment conditions for youth in agriculture and those seeking employment in the industry. Moreover, the choices young people make in terms of their career interests, aspirations, and participation are a function of these factors and socioeconomic challenges summarised in Table 2. For example, as seen in Table 2, the lack of entrepreneurship skills [63,69,73] was a significant contributor in discouraging youth to pursue business. Other socioeconomic challenges included limited digital literacy skills amongst youth seeking employment [69], and the impact of low levels of education on entrepreneurial aspirations and success owing to limited literacy and numeracy skills [68,73]. Furthermore, the limited support for young farmers, unemployment, and lack of work experience contributed to the lack of interest in agriculture and entrepreneurship [36,74].

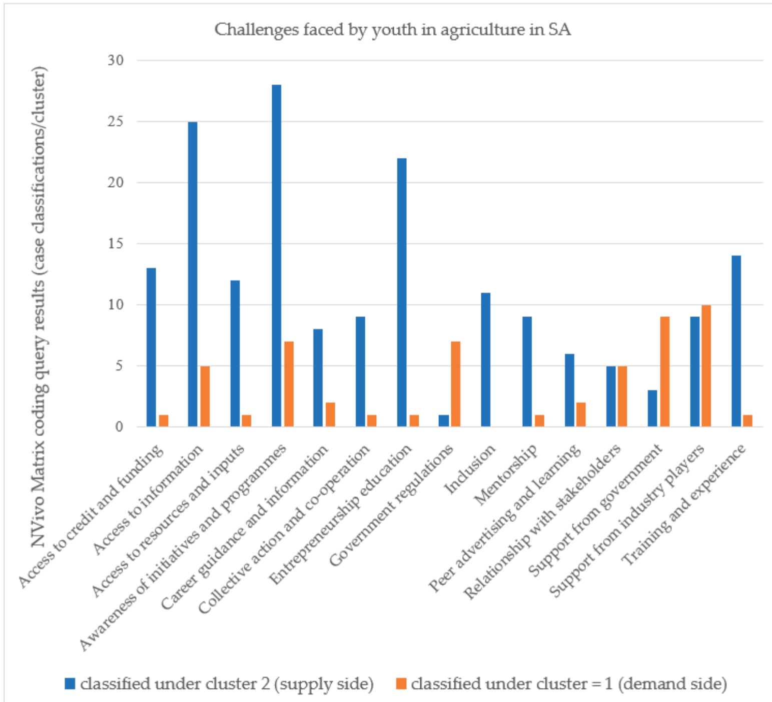

Figure 5. A graphical representation of challenges for youth in agriculture based on the analysis of issues stated in the studies included in this review. The main challenges were categorised into two broad clusters: the demand and supply side of the labour market.

Table 2. Additional factors preventing youth from securing sustainable employment in the agriculture and rural development sector (adapted from NVivo crosstab results).

Nodes	Lack of Interest	Securing Employment	Support for Farmers	Total
Support required	0%	0%	60%	12.5%
Aspirations	0%	0%	0%	0%
Demographical challenges	0%	18.75%	40%	20.83%
Digital literacy	0%	50%	0%	33.33%
Education levels	33.33%	0%	0%	4.17%
Entrepreneurship	33.33%	0%	0%	4.17%
Gender	0%	0%	0%	0%
Unemployment	33.33%	31.25%	0%	25%
Total	100%	100%	100%	100%

The shading in the cells represents patterns and relationships in the matrix amongst factors preventing youth in securing employment. The shade intensity increases with the percentage value.

3.4. Creating an Enabling Environment for Youth Participation and Empowerment

The analysed studies presented four main reoccurring themes of aspects that need to be addressed to create an enabling environment for youth participation and empowerment. These themes, as shown in Figure 6, are (i) education, (ii) mentorship, (iii) stakeholders/industry players, and (iv) communities. Education is essential for providing career guidance information and awareness of agriculture careers at secondary school levels [65,74]. At the tertiary level, it is also essential for anchoring entrepreneurship skills and aspirations [63,69,73], whereas mentorship provides guidance and support as youth navigate their careers [65,75]. This support can also be provided by industry role players in creating awareness and sharing information related to initiatives and programmes available [65,73,75]. Moreover, social interactions in communities play a role in overcoming knowledge barriers, providing a network of support and communal learning to overcome social challenges [65,66].

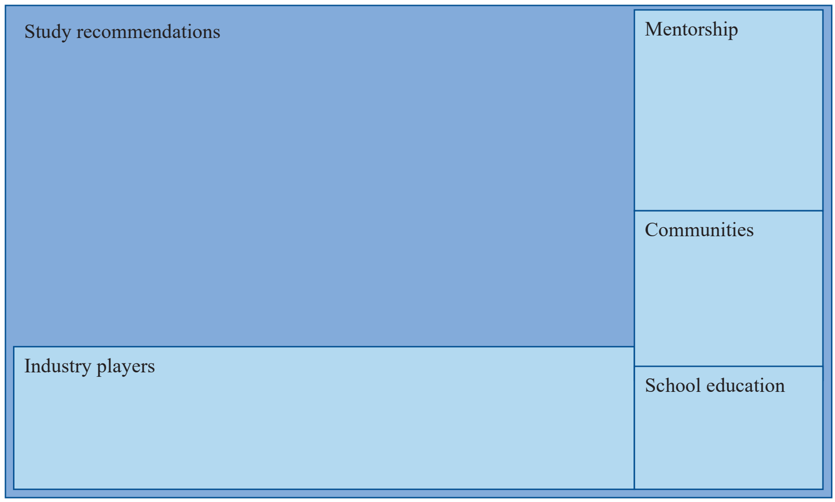

Figure 6. A hierarchy diagram generated in NVivo of the main themes presented as recommendations from studies analysed in the review.

3.5. Government Strategies and Programmes Related to Youth Participation and Empowerment in Agriculture

The central focus of the strategy and policy documents included in this review is entrepreneurship. Entrepreneurship is the primary medium through which policy promotes economic transformation, stimulates youth inclusion in the economy, and creates jobs (see Figure 7). It is also the central theme in proposed interventions and support services, for example, youth enterprise development support, financial support services, awareness programs and initiatives, capacity development through education, and industry/business regulations. Although the study's focus is on youth participation in agriculture and rural development, most of the youth enterprise development support mentioned in policy includes other industries—for example, tourism, construction, infrastructure development, and social entrepreneurship. The emphasis on entrepreneurship also means that the support services being provided through policy and regulation, awareness campaigns, and incentives are mainly targeted at entry-level enterprise development and youth interested in owning businesses to encourage the creation of employment opportunities for their peers. Moreover, the overemphasis on the economic aspect undervalues other enabling factors that need to be addressed to facilitate youth participation and empowerment.

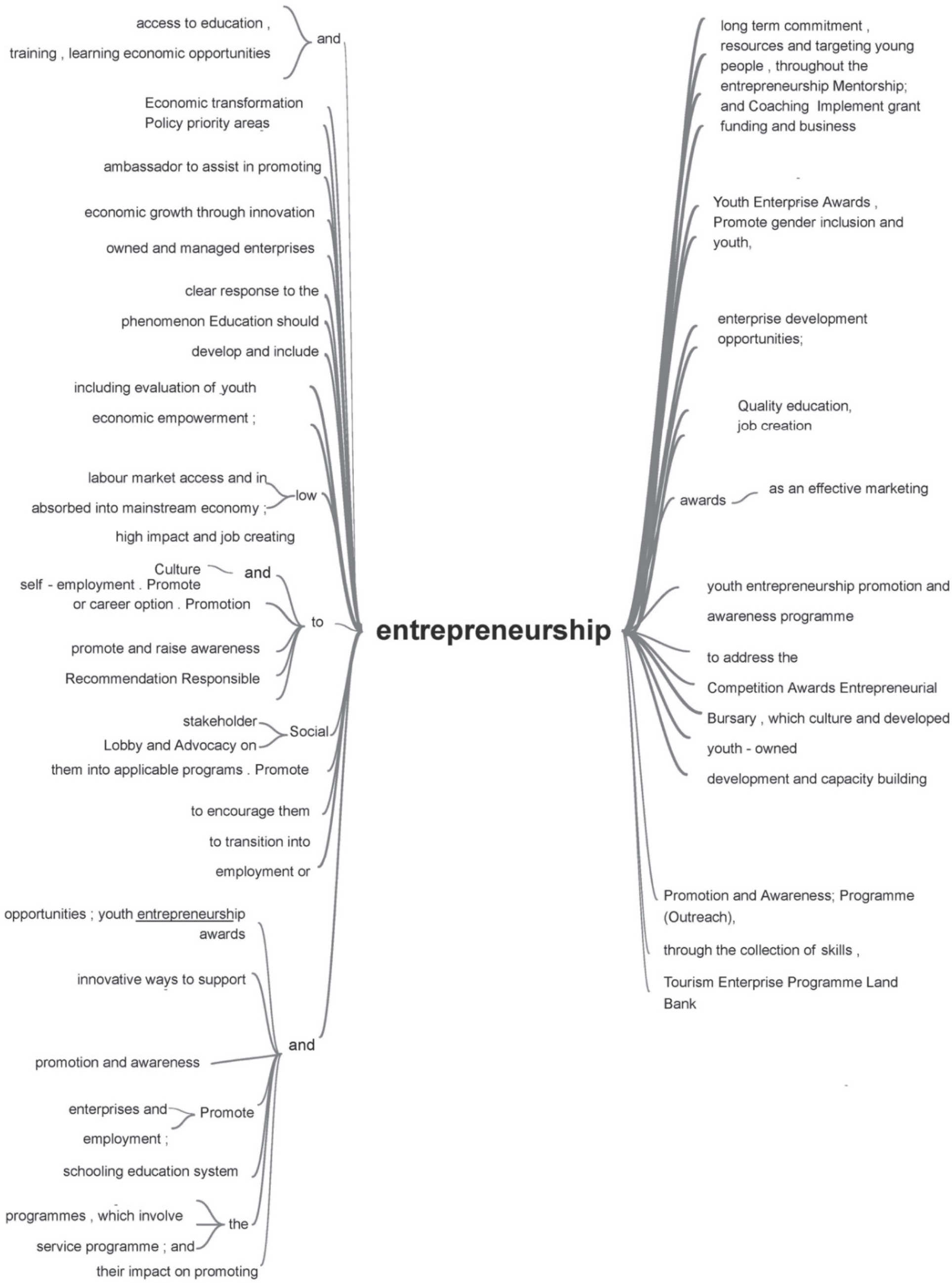

Figure 7. NVivo text search query results for the term 'entrepreneurship' within the data. Entrepreneurship emerged as a key topic classified under cases (second-order category).

3.6. Proposed Interventions and Priority Areas

The leading ten proposed interventions are presented in Figure 8. The emphasis is again on (i) entrepreneurship, by developing and facilitating training workshops, programmes, and financial support for youth-owned Small, Medium, and Micro Enterprises (SMMEs) and cooperatives; (ii) addressing socioeconomic challenges that create barriers for youth to access the labour market, reducing levels of crime and violence, substance abuse, promoting health, well-being and HIV/AIDS prevention campaigns; (iii) improving agricultural productivity and increasing investments in support services such as rural infrastructure, storage and processing, markets, improving land ownership, and changing the image of agriculture as a career and livelihood choice amongst youth; (iv) promoting regulations and frameworks intended to support Black South Africans to actively participate fully in the agricultural sector as owners, managers, professionals, skilled employees, and consumers; and (v) creating sustainable job opportunities for youth through industrial growth.

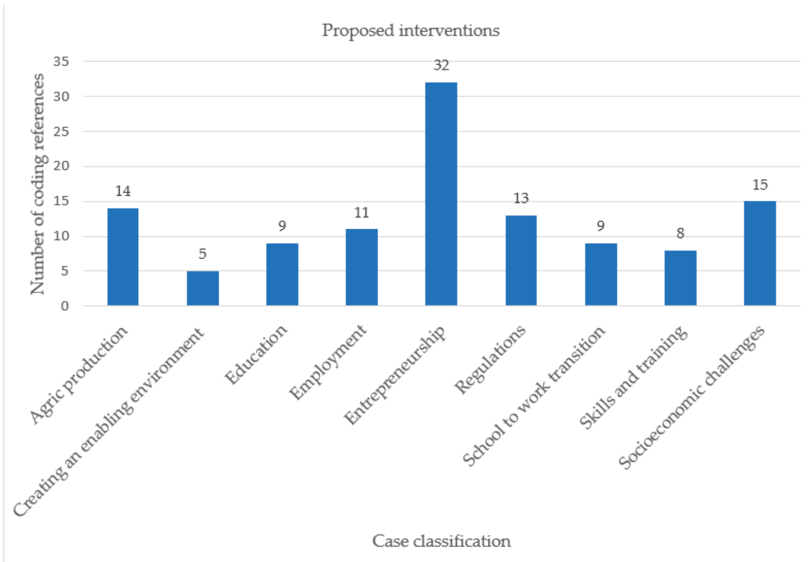

Figure 8. A graphical representation of the classification of proposed policy interventions (second-order category based on topics).

Other proposed interventions include promoting better quality education through linking outcomes of school and tertiary institutions with labour market requirements; additionally, making career guidance a compulsory part of the schooling curriculum, improving access to education by providing multiple forms of education to meet the diverse needs of young people and the labour market, and developing the capacity of teachers and trainers. Furthermore, other interventions include developing youth skills through introducing training programs at local, regional, and national levels for entry into the labour market; creating an enabling environment for promoting youth economic empowerment and equipping young people to deal with socioeconomic challenges.

4. Discussion

From a social aspect, the legacy of apartheid laws and regulations left many people in rural areas in SA faced with poor economic prospects, inequality, unemployment, and poverty. Demographical challenges such as being in remote rural areas, lack of social capital, and limited access to the Internet remain prevalent in hindering youth's ability to participate in the economy. Similarly, Graham et al. and Abay et al. [76,77] found that economic opportunities appear to be quite limited for many young people in rural areas, including graduates. Additionally, Wilkinson et al. [78] discovered that the three most common barriers to youth employment in Mpumalanga (SA) were lack of skills, lack of information on job openings, and overall lack of jobs. Youth are distributed across various economic landscapes, and their opportunities differ accordingly. Although since 1994 the government has made progress in policy formulation and planning, the youth are still faced with the same deteriorating socioeconomic challenges that hinder meaningful participation in the mainstream agriculture economy [31,79]. These socioeconomic challenges keep youth disconnected and excluded from opportunities that globalization and the changing political landscape may offer. Therefore, the heterogeneous landscapes in which youth exist should be considered and accounted for during policy design and implementation. This will ensure that policies are implementable in various contexts and are also responsive to context-specific challenges and opportunities for youth in agriculture. Thus, our results agree with Wilkinson et al. [78], that there is a need to connect more rural youth to local employment programmes that could be useful to them.

Although addressing socioeconomic challenges that create barriers for youth to access the labour market is reflected amongst the key proposed interventions in policy, the results suggest that the implementation has not been successful. Similarly, Diraditsile [29] also found that government youth empowerment programs in Botswana are well designed with admirable provisions for youth empowerment. However, the implementation is poor; officials have limited capacity and youth are barely involved in formulating and implementing interventions meant to benefit them.

The evidence suggests the need for multi- and transdisciplinary approaches. The co-dependency nature of the sustainable development pillars within various socioeconomic contexts requires commitment and partnerships between all key societal actors/stakeholders [80]. Stakeholders play a role in overcoming social and economic barriers and facilitating the necessary private–public and public–civil-society interactions needed to overcome challenges. For example, the results also indicate that creating awareness of initiatives and programmes can be accomplished through partnerships between schools, industry players, government interventions, and development initiatives. Youth awareness of initiatives and programmes is fundamental as it is connected to participation, perception, aspirations, interest, and access to resources and information. Moreover, improving youth's awareness of and access to employment resources already available in their local area is essential to increasing their chances of participation in the economy [78].

This, however, may be challenging to achieve in SA. Sutherland [38], highlights the significant inconsistencies related to the roles assigned by the government to the private sector over time in general and sectoral policies. Challenges of incoherency in policy, poor economic policies, and lack of coordination in SA emerged as early as 1996, shortly after democracy [37]. Additionally, Mmbengwa et al. [81] argue that incubation programs that seek to attract youth to start their enterprises in SA are often under-resourced, riddled by financial corruption, and hindered by poor publicity. Social cohesion is essential for these partnerships to create awareness and increase youth participation in agriculture. Social cohesion builds a foundation for growth and development through promoting inclusivity and participation while encouraging strategies to reduce inequalities in the domains of activity (economic, political, and sociocultural) [82].

Nonetheless, Todes and Turok [83] caution that marginalised communities in SA are suspicious of state-sponsored initiatives and are impatient for tangible progress. Consequently, this causes disturbances and disagreements amongst stakeholders on project goals and priorities, ultimately preventing projects from proceeding. The evidence suggests a breakdown in trust between government and communities. By actively encouraging social cohesion and fostering partnerships between societal actors, the government can restore confidence in the community over time. Additional effort is also required to include youth and other society members through meaningful engagement, co-designing, co-implementation, and setting up community structures that can hold government officials to account for progress on community projects. This will aid in addressing the labour market barriers experienced by youth in agriculture by promoting inclusivity, creating opportunities for mentorship, access to information, entrepreneurship education, and improving the effectiveness of policies. Moreover, opportunities to participate in the economy and attain a decent standard of living will be improved for young South Africans.

From an economic aspect, entrepreneurship is the primary medium in which policy promotes economic transformation, stimulates youth inclusion in the economy, and creates jobs. Consequently, most of the support services provided through policy and regulation, awareness campaigns, and incentives are mainly targeted at entry-level enterprise development and youth interested in owning businesses. Very few programmes and interventions lead the youth into the mainstream agricultural economy. Whereas policy emphasis on youth involvement in nonfarm employment is important [84]. The agricultural sector offers other opportunities in nonfarm activities throughout the value chain [77]. However, programmes and interventions do not elaborate on how young people will be integrated into the value chain, nor do they extensively cater for educated and skilled youth seeking employment.

Nonetheless, the emphasis on the economic aspect also undervalues other enabling factors that need to be addressed to facilitate youth participation and empowerment. For example, the results highlight the lack of entrepreneurship skills and the impact of low literacy and numeracy skills on business success as key contributors in discouraging youth to pursue business, further emphasizing the importance of multi- and transdisciplinary approaches to address key enabling factors and barriers in youth empowerment and economic participation. For example, this can be achieved by integrating already existing policies such as the Agricultural Education and Training (AET) strategy, with policies focused on addressing challenges in the agriculture sector such as AGRI BEE. The joint effort of these policies would address challenges experienced by youth in agriculture while promoting better quality education, linking school outcomes with the job market's needs, and providing career guidance. Additionally, increasing access to education through delivering multiple forms of education would meet the diverse needs of young people and develop the capacity of teachers and trainers.

5. Conclusions

This scoping review aimed to investigate the challenges youth in democratic SA face to participate in agriculture and rural development programmes. Specifically, the study investigated youth participation and empowerment in the agricultural sector in SA, and assessed relevant government policies, strategies, and programmes related to youth participation and empowerment in agriculture to ensure equality and inclusivity of youth in the sector. The results showed that, although progress has been made since 1994 towards promoting youth participation in agriculture, youth still faced significant challenges that limited their effective participation in agriculture. In general, youth are still faced with the same socioeconomic challenges that hinder meaningful participation in the mainstream agriculture economy. Moreover, these socioeconomic challenges perpetuate the exclusion of youth from opportunities that globalization and the changing political landscape may offer, including their awareness of opportunities, initiatives, and programmes targeted at youth. This is particularly true for rural youths, and those with low levels of education. This perpetuates a vicious cycle, which entrenches exclusion and inequality as opposed to inclusion and equity. Additionally, youth face obstacles in the demand and supply side of the labour market, lack of inclusivity in policy formulation and implementation, lack of entrepreneurship skills, receive poor quality education, and have limited available support for agripreneurs. Thus, the combination of these factors limits youth's ability to participate in the labour market.

The evidence suggests the need for multi- and transdisciplinary approaches. All societal actors have a role in overcoming barriers to youth empowerment and participation in agriculture. Currently, the political and social climate in SA does create additional obstacles to the successful implementation of programs. South Africa needs better sectoral (public, private, and civil society) coordination and collaboration in planning policies to promote social cohesion that can facilitate implementation. This also includes improvements in the institutional capacity at all spheres of government for better program implementation.

Moreover, a holistic approach for interventions targeted at youth empowerment and promoting youth participation in the economy is recommended. Policies need to be informed from a broader perspective of sustainable development. This also requires additional efforts from the government to encourage collaboration between societal actors and stakeholders together with coordination and co-implementation between government sectors and departments to address socioeconomic barriers preventing youth from successfully participating in the economy as employers and employees. Additionally, the focus of government policies and programs should be widened to cater to youth's diverse economic needs and career aspirations throughout the agricultural value chain. There is a need for holistic and systematic policies that focus on broader youth participation and empowerment in the food system other than just entrepreneurship. Furthermore, effort needs to be directed towards education and awareness as enablers that can facilitate youth participation in agriculture. Within the context of this review, education is essential for providing career guidance information, anchoring basic skills and aspirations towards agriculture activities and entry points that youth can choose to participate in. Awareness of opportunities, initiatives, and programmes in agriculture is linked to youth perceptions, aspirations, and interests. Furthermore, there is a need for increased effort to connect youth to support services already available in their areas.

6. Limitations

The results of the study should be considered in light of some limitations. Because of the search inclusion and exclusion criteria used for this study, other publications may be excluded. The search was limited to studies published between 1994 and 2021. This period covers the post-apartheid era. Furthermore, the selection of primary studies focused on programs or interventions that have been explicitly designed for youth between the ages of 15 and 35 years. Thus, data presented in this study are from papers relevant to the study's objectives. Moreover, the articles retrieved during the search mainly conducted research on youth in rural areas. Therefore, the results presented in this study are biased towards youth in rural areas vs. youth in peri urban and urban areas. For future research, there is a need to broaden the scope of the research to ensure the inclusion of the full spectrum of themes related to youth and agriculture; however, this should consider the tradeoffs between breadth vs. depth.

7. Recommendations and Policy Implications

The results suggest that youth face numerous socioeconomic challenges that affect the type of economic opportunities they have access to, including their awareness of employment opportunities and programmes targeted at youth. Moreover, the focus of government policies and programs is narrow, with a lack of youth inclusivity in policy formulation and implementation, lack of entrepreneurship skills, poor quality education, and limited available support for agripreneurs. Thus, the combination of these factors limits youth's ability to participate in the labour market. The implementation of government programs to address these issues has not been effective. Moreover, the political and social climate in SA does create additional barriers to the successful implementation of programs. Based on evidence found in this scoping review, this study therefore recommends:

- Investments need to be made to improve the institutional capacity at all spheres of government for better program implementation. Additionally, an effort is required to maintain the accountability and integrity of government in society. This is necessary for better program implementation and functional partnerships with the private sector, industry role players, and society. We need better sectoral (public, private, and civil society) coordination and collaboration in planning policies—collaboration and coordination will facilitate a social compact that can facilitate implementation.
- To better equip agricultural graduates, practical agribusiness training should be included in the undergraduate curriculum of agriculture qualifications. This can be achieved by providing support to implement policies such as the AET strategy

together with upscaling capacity development programs such as Future Farmers Foundation and the Junior LandCare programme.

- There is a need to connect more rural youth to local employment programmes that could be useful. Additionally, ensure that youth in various socioeconomic contexts have access to opportunities advertised on online platforms such as AgriStaff, SA NGO pulse portal, puff and pass, and Career Junction.
- More effort is needed to connect youth involved in farming with support and initiatives available in their local areas. This could be achieved through partnership and advertisements by community structures, for example, schools, local clinics, churches, traditional authority councils, and established nongovernmental organisations with local communities. Alternatively, upscale existing support services such as Harambee and AFASA.
- The spectrum of support services provided through policy, regulation, and incentives should be broader and cater to different youth knowledge and skill profiles, other careers in the value-chain, and not just entrepreneurship. Moreover, for youth interested in entrepreneurship, the support provided should sustain long-term career growth and not only entry-level enterprise development. There is room for policies to focus on other forms of youth participation and empowerment other than just entrepreneurship. Moreover, there needs to be education and awareness around the various aspects of the agricultural sector, activities, and entry points that youth can choose to participate in.
- Young people must be active participants in all youth empowerment programmes, and the participation should recognise differences and inequalities between urban and rural youth and gender. More effort needs to be directed towards creating opportunities for youth (representative of all socioeconomic backgrounds) to participate actively in policy formulation, program design, and implementation.
- Policies need to be informed from a broader perspective of sustainable development, which understands that the economics are embedded within the social and environmental dimensions, all of which are underpinned by governance. Moreover, the results show that the issues that affect youth are systemic, and a broader focus beyond just the traditional understanding of agriculture is needed. This calls for a food systems approach as opposed to a specific focus on just agriculture. Furthermore, such an approach could also integrate with other systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14095041/s1, Figure S1: NVivo search query results for the 20 most common words in the data set, Table S1: Characteristics of studies included in the review, Table S2: Strategies, reports, and policy documents included in the review, Table S3: Reasons for exclusion for articles removed at full screening stage.

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Influence of Agricultural Chains on the Carbon Footprint in the Context of European Green Pact and Crises

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Abstract: Agriculture and related activities generate a significant amount of greenhouse gas emissions with environmental and biodiversity implications. Based on the European objectives proposed by the Green Pact, this paper assesses the carbon footprint of agricultural chains for European OECD member countries. The period analysed is 2000–2019, and the method applied is panel data, specific to OLS models. We opted for three research directions: one is general, one is geographical and one is in temporary dynamics. The general analysis shows that in the European region, the organically cultivated area and economic growth reduce the carbon footprint, while fertilisers, aquaculture production, investments in road infrastructure and agricultural area determine its increase. The geographical analysis outlines the existence of two clusters, one consisting of Member States where agricultural chains reduce their carbon footprint and one consisting of a larger number of Member States, including the major European agricultural powers, where agricultural chains increase the carbon footprint. The temporary analysis reveals that the EU has changed its paradigm since 2008–2009. Economic growth has been slowly decoupling from the carbon footprint since 2016, and the rest of the factors analysed have become more environmental since the late 2010s. The EU has positioned itself towards achieving the objectives set by the Green Pact at a slow pace, justified by the heterogeneity of members' national characteristics, in addition to its purpose not to harm the food security of the population. In order to achieve the objectives proposed by the Green Pact, it is necessary to focus on more extensive organic farming and traditional production methods, more extensive efforts to reduce nitrogen surplus in fertilizer content, to support short agri-food chains and to identify new production techniques, including the use of nanotechnology and high-performance technologies. Local agricultural chains are crystallizing into a possible solution to the insecurity generated by energy and food crises, political conflicts, pandemics, under the observation that organic products should be excluded from the category of luxury commodity.

Keywords: carbon footprint; agricultural chains; economic growth; organic farming; economic crises

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1. Introduction

Climate change and environmental degradation are major current concerns. The main objective, of the EU through the Green Pact, according to the European Commission (2021) [1], is for the EU to become a competitive and resource-efficient economic formation. They intend to eliminate greenhouse gases by 2050, and to decouple the process of economic growth from the use of resources, without omitting any person or region. European policies in the fields of climate, energy, transport and taxation will be in line with the goal of reducing greenhouse gas emissions by at least 55% by 2030, compared to the 1990s. The Green Pact focuses its actions in eight directions, i.e., climate, environment and oceans, energy, transport, finance and regional development, industry, agriculture, research and innovation. The European Commission (2021) [1] considers the European agricultural and food system to be a standard of safety and security in terms of supply, nutrition, and quality, however, this standard should become a benchmark in terms of sustainability. There would be social, environmental, health and economic benefits. This is the reason why the EU ensures food security in the context of climate change and biodiversity, to reduce the impact of the agricultural and food system on the environment and climate, to strengthen food resilience and determine a global transition to competitive farm-to-consumer sustainability [1].

The above context motivates us to assess the carbon footprint of agricultural chains in the case of European OECD member countries. The carbon footprint refers to a certain amount of greenhouse gas emissions, relevant to climate change, associated with human activity related to production and consumption, although etymologically, it would be described as an exclusive measure of dioxide emissions. Carbon results directly or indirectly from an activity or is accumulated over the life cycle of a product [2]. It is also believed that the carbon footprint measures the intensity of greenhouse gases in products, bodies and processes which take place worldwide [3]. In the paper, we refer to the definition provided by Pandey and Agrawal (2014) [3] according to which the carbon footprint measures the intensity of greenhouse gas emissions for various activities and services.

In Europe, the agricultural sector is very different among regions [4], and agricultural sustainability is not high enough. Agriculture is the largest contributor to anthropogenic greenhouse gas emissions; therefore, the quantification of various specific and related activities is essential [3]. The mechanisation of agriculture has greatly increased productivity and production, contributing to industrialisation but there are implications for the environment, especially concerning the carbon footprint [5]. Agriculture is the main source of nitrogen pollution due to increasing product demand and inefficiency along the entire food supply chain, from the production of synthetic fertilisers to waste management [6]. It generates 20% of anthropogenic greenhouse gas emissions due to fuel consumption, land use change, soil cultivation, nitrogen oxide emissions, animal waste and enteric fermentation [7]. Within the agri-food chain, the agricultural stage bears the highest impact on final products and on the environment [8], but supports food security too. Climate change and biodiversity destruction due to anthropogenic action require a change in vision and in the understanding of the system in which agricultural and food policies operate [9]. European governance structures are not well adapted to the current challenges of climate, biodiversity loss and agri-food insufficiency, and among different areas of economic policy such as agriculture, trade, health, environment and at different levels of governance we observe the manifestation of conflicting objectives and the lack of synergy which requires common sustainable agricultural policies [10]. The great challenge of European agriculture is to adapt production according to the growing demand for food while conserving natural resources and the environment [11].

Green Pact is an important step in the decision to calibrate the European economic activity to planetary and human needs. We will assess the carbon footprint of European agricultural chains starting from the analysis of the current scientific framework, after which we will present the methodology, analyse the results and draw conclusions.

2. Literature Review

Agriculture has a complex multiplier effect in all sectors of the economy. The role of agriculture and its effects on the carbon footprint are an important scientific concern. Agriculture is related to two challenges of global sustainability, climate change and biodiversity loss [12]. It is associated with problems related to pollution, disruption of nutrient cycles, scarcity of drinking water, hunger, poverty and the struggle for resources. Intensive agriculture, as shown by Garske et al. (2021) [12], is responsible for about a quarter of the carbon footprint and three quarters of biodiversity loss, and if the reporting includes the entire food sector, the percentage increases. Schiavon et al. (2021) [13] note that there is a vicious circle between agricultural production and climate change in which agriculture is a trigger and a victim, which is why climate and energy targets provide for a 40% reduction in emissions by 2030 for all sectors of the economy, which implies changes including in agriculture as well. Jehlićka et al. (2020) [14] note that the technologically and economically sophisticated industrial agri-food system, adopted almost globally and a landmark for less developed countries, contributed to soil degradation, biodiversity loss and climate change, thus calling sustainability into question.

The carbon footprint began to increase with the mechanisation of agriculture, and the maximum threshold was reached in the first decades of the agricultural industrialisation process, according to Aquilera et al. (2019) [5]. The carbon footprint can be traced from the direction of five economic sectors, i.e., energy, industry, construction, transport and AFOLU (agriculture, forestry and other land uses). A study by Lamb et al. (2021) [15] for the period 1990–2018 reveals that at the European level there was a modest decarbonisation of energy systems, and the region was the only one in the world to reduce its carbon footprint since 2010. Europe pollutes the most through energy systems, industry, transport and, to a lesser extent, through AFOLU. The EU has reduced its carbon footprint by 8% since the early 2000s, the main determinant being technology, but the effort is minor and visible only in 2007–2008 [16].

The calculation of the carbon footprint of food production systems for 14 European countries covering 65% of global food production in the period 2000–2014 showed that the carbon footprint decreased and its determining factors were GDP per capita, population density, nitrogen fertiliser production, agricultural area, animal production and per capita energy consumption per capita [17]. Crippa et al. (2021) [18] consider that agriculture and agricultural land are sources of the highest contribution to the carbon footprint, followed by retail, transport, consumption, fuel production, waste management, industrial processes and product packaging. According to the study by Crippa et al. (2021) [18], in 2015, 27% of emissions were from developed countries, 73% from developing countries, and over 71% were associated with land use for agricultural purposes. Tubiello et al. (2021) [19] show that the agricultural area, the energy consumed on the farm, the transport of products and food waste disposal significantly contribute to the carbon footprint. Renner et al. (2020) [20] also claim that agriculture generates half of the carbon footprint.

Therefore, agriculture provides food security for the population, and is the basis of the economy and economic growth, which is why we propose to analyse the research hypothesis, (H_1), according to which *the economic growth of the European OECD member states is decoupled from the carbon footprint*.

Organic production contributes positively to agricultural and natural biodiversity compared to the conventional one [21]. Meier et al. (2015) [22] consider that organic farming has a low impact on the carbon footprint compared to conventional agriculture if the cultivated area is analysed. The impact increases if the quantity produced is analysed, especially under the influence of chemicals contained in fertilisers. Stoi et al. (2020) [23] consider that organic production is a solution to environmental problems such as global warming, biodiversity loss and desertification. Organic farming adds value to local economies, however, the demand for organic products is low [24], and the decision to consume organic products is related to environmental issues. Based on these ideas, we propose to analyse the research hypothesis, (H_2), according to which *the expansion of organically cultivated areas in OECD member states reduces the carbon footprint*.

Fisch-Romino and Guivarch (2019) [25] assessed the need to invest in transport infrastructure, given that this activity is one of the largest emitters of greenhouse gases since the 1970s. The transport effect on the carbon footprint must be reduced if we want to keep the global temperature rise under two degrees Celsius. Analysing the relationship between transport infrastructure and the carbon footprint for OECD countries for a period of about 150 years, Churchill et al. (2021) [26] conclude that transport infrastructure determines the long-term carbon footprint. Investments in road and air transport infrastructure increase the carbon footprint, while those in railroad infrastructure contribute to its reduction, according to the conclusions of Erdogan's study [27] for 21 OECD countries in the period 2000–2015. Road transport is responsible for 74% of emissions from the entire sector [27]. Therefore, investments determine the quality of the environment by promoting the use of conventional vehicles, which contribute to the increase of carbon footprint. The same study argues that investments in infrastructure involve constructing roads which cause biodiversity loss, degradation of drinking water sources, and which change the destination of land.

Given that transport is the second most important determinant of the carbon footprint, Georgatzi et al. (2020) [28] analysed the relationship between emissions and transport activity for 12 European countries between 1994 and 2014. The results of the study show that investments in transport infrastructure do not affect carbon footprint. They are located at the intersection of climate and development issues and, although they do not reduce the absolute carbon footprint, they reduce the intensity of pollution, except for those in road infrastructure which have a neutral effect.

Fertilisers are an important component of the agricultural chain, necessary for food security, which contributes to carbon footprint increase [29]. Agriculture depends on large amounts of fertilisers and pesticides and, according to a study conducted by Tripathi et al. (2020) [30], excessive use of chemicals and technology has led to severe environmental degradation, more specifically to soil pollution and biodiversity degradation with irreversible effects on long term. The shift from the use of chemical to organic fertilisers increases agricultural productivity in a sustainable way according to a study by Koondhar et al. (2021) [31]. The authors claim that, in the long run, reducing the carbon footprint in agriculture by 10% leads to increased production. Improper use of fertilisers is the reason of the increase in the carbon footprint [32], which is why the main challenge in organic agriculture is precisely the improvement of fertiliser management [33]. Organic farming involves the use of methods which exclude the intake of chemicals, consequently the use of fertilisers in small quantities reduces the carbon footprint, but also the agricultural yield [34].

Aquaculture is a developing sector, with a growth rate of about 6%, which increases its carbon footprint without an accurate estimate of its impact, only the certainty that it will increase. In 2030, anthropogenic emissions from aquaculture production will likely account for 5.72% [35]. Aquaculture production contributes to the carbon footprint through energy consumption, transport and feed. The contribution of this activity to the carbon footprint is low according to Maulu et al. (2021) [36] but compared to other activities in the food sector it is significant. MacLeod et al. (2020) [37] argue that aquaculture production has modest effects on the carbon footprint, but they increase post-production. The direct and indirect contribution of aquaculture production to food security is important, but not harmless to the environment. The authors claim that in 2017, approximately 0.49% of the carbon footprint was caused by aquaculture production. According to Gephart et al. (2021) [38], aquaculture production negatively affects the carbon footprint, but not as much as land use. The conclusions of this paper lead us to analyse the research hypothesis, (H_3), according to which *fertilisers, agricultural area, aquaculture production and investments in transport infrastructure reduce the carbon footprint in OECD member states*.

This context draws attention to the role of short production and supply chains. In Europe, short agri-food chains play an important but marginalised role. A study conducted in 15 European countries by Rivera et al. (2020) [39] shows that the European system is dominated by large agricultural producers, able to achieve increases in productivity, efficiency and economies of scale. Small producers, more traditional in production methods, are marginalised on the market, although they have an important contribution to agri-food security, support local biodiversity, contribute to environmental sustainability, maintain agricultural culture and resilience of local communities.

Agricultural area, road transport infrastructure, organically cultivated area, fertilizers, and aquaculture production are components of the agricultural chains. Their study is of interest in assessing the carbon footprint of European OECD member countries along with economic growth, an important process to ensure well-being. The importance of agricultural chains crystallizes two other research hypotheses, i.e., (H_4), *European agricultural chains reduce the carbon footprint of each European OECD state*, and (H_5) *the agricultural chains of European OECD member states have contributed, since the end of the first decade of the 2000s, to the carbon footprint reduction*.

The food security of the population depends on the agricultural sector efficiency. The COVID-19 pandemic, the Russian–Ukrainian conflict, and the energy and food crises have aggravated the problem of food security, given that more than 2 billion people already experience food problems [40]. In this context, we formulate another research hypothesis, (H_6), *local agricultural chains reduce food insecurity in conditions of sustainability in the context of worsening economic and social crises*.

3. Materials and Methods

3.1. Data

In this study we set out to assess the carbon footprint of agricultural chains for European OECD member countries based on six research hypotheses, as follows:

H1. *Economic growth of the European OECD member states is decoupled from the carbon footprint;*

H2. *The expansion of organically cultivated areas in OECD member states reduces the carbon footprint*;

H3. *Fertilizers, agricultural area, aquaculture production and investment in transport infrastructure reduce the carbon footprint in OECD member states;*

H4. *European agricultural chains reduce the carbon footprint of each European OECD state;*

H5. *The agricultural chains of European OECD member states have contributed, since the end of the first decade of the 2000s to the footprint reduction;*

H6. *Local agricultural chains reduce food insecurity in conditions of sustainability in the context of worsening economic and social crises;*

For this purpose, the indicators analysed describe the period 2000–2019. They were taken from the OECD (Organization for Economic Cooperation and Development) [41], World Bank [42] and FAO (Food and Agriculture Organization) [43] websites. Because data for certain years are missing, we covered the deficiency by calculating an arithmetic mean between the values of the previous and/or subsequent years. The study of the effects of agricultural chains on the carbon footprint was developed for European OECD member countries except Luxembourg. The exclusion of this state from the analysis was due the lack of data for long periods in the case of several indicators.

We considered the carbon footprint as the amount of greenhouse gas emissions, because we started from the consideration that not only is carbon dioxide harmful to the environment, but also the rest of the components of greenhouse gases. Greenhouse gas emissions include, according to OECD description, carbon dioxide, methane, nitrogen oxides, chlorofluorocarbons, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride and nitrogen trifluoride, resulting from human activities (OECD). Because we believe that all these components affect the environment and biodiversity, not just carbon dioxide, we considered the carbon footprint equivalent to the amount of greenhouse gases. This indicator is the dependent or explanatory variable of the study because we want to see the extent to which certain characteristics of agricultural chains increase or decrease the carbon footprint and thus the results can be extrapolated in the decision area.

As the activities which ensure agri-food production lead to economic growth and improvement of people's quality of life, and growth, in turn, is reflected in the economic and social environment, we introduced in the group of independent variables gross domestic product per capita, which represents the gross value added by economic agents active on the territory of a country in relation to the number of inhabitants and describes the process of economic growth. To describe the agri-food chains, we opted for the analysis of the following: the fertiliser amount-nutrients used per unit of arable land, i.e., nitrogen, potassium and phosphate fertilisers; the agricultural area - land intended for agriculture, cultivated and with pastures; the organically cultivated area-extensively cultivated areas, by traditional methods; the investment in road infrastructure as transport is an important step along the agri-food chain; the aquaculture production-a branch of agriculture which deals with the breeding of aquatic animals and plants for sale. All indicators relate to each country population. The empirical analysis is based on seven variables, six of which determine the carbon footprint measured by the amount of greenhouse gas emissions and are specific to agricultural and agri-food chains.

As we see from Figure 1, Germany is the largest polluter in Europe, followed by France, Italy, Poland, Spain and the Netherlands. The differences between the amount of emissions of these countries are significant. For Germany, the year 2016 is representative for a maximum of GHG amount. France and Italy emit relatively similar amounts of emissions. Italy issued higher GHG quantities than France only in the period 2002–2009. Poland and Spain are on relatively close trends but lower than those already mentioned. In the period 2001–2008, Spain emitted higher GHG amounts compared to Poland. The Netherlands has followed a relatively steady trend in emissions, similar to other European countries which are not polluters of the calibre of the states already mentioned. In the case of the Netherlands, 2018 marks a significant reduction in pollutant emissions. All European countries have managed to stimulate the economy and achieve rising GDP per capita since 2013, with the most spectacular growth in Ireland. The financial crisis has been felt in all European countries. Between 2007 and 2013, growth slowed. European economies have felt the effects of the crisis at different times, and the recovery has taken place under the spectrum of time lags.

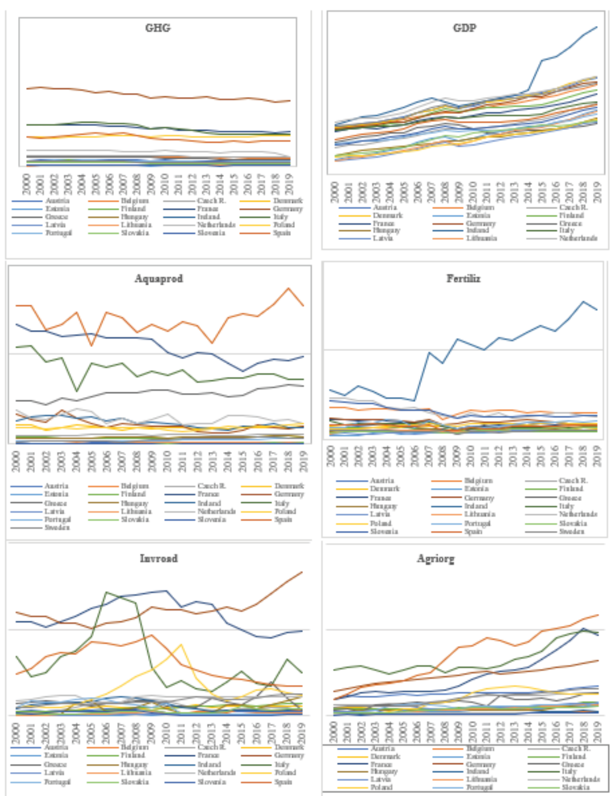

Figure 1. *Cont.*

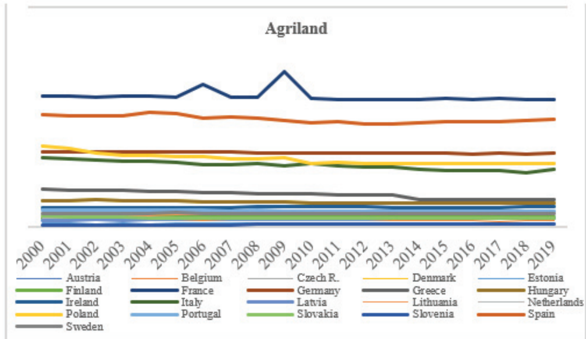

Figure 1. Indicators' evolution (1995–2019). Source: Graphs made by the authors based on the analysed indicators.

In terms of aquaculture production, the Mediterranean countries are the main European producers. From this point of view, Spain stands out, on a strongly fluctuating trend which we also notice in the cases of Italy and Greece. France is the second largest producer of European aquaculture, although production followed a downward trend until 2015, severely affected by the 2009 crisis, after which growth was resumed. The Netherlands, Germany and Denmark are among the European aquaculture producers, but with much more modest production compared to the Mediterranean countries.

All European countries use fertilisers in quantities which, for the most part, do not produce major differences among them. There are exceptions, such as Ireland, which uses far more amounts of fertilisers than the rest of the world. The trend is highly fluctuating and growing for Ireland. The Netherlands, Slovenia and Belgium use fertilisers in much smaller quantities than Ireland, but higher than other European countries. If until 2004 the Netherlands was the second largest European user of fertilisers, Belgium has been in this position since 2008.

Germany has been making the highest investments in transport infrastructure since 2014. France was the European leader in invroad from 2007–2014. Italy had a strong increase in this variable in period 2005–2006. Subsequently, the trend fluctuated, declining below the 2006 level. Spain recorded a maximum value of these investments in 2009 but subsequently the trend has slightly decreased. Poland is one of the countries which steadily increased the value of these investments until 2011, after which the decrease was significant. Sweden experienced a visible increase in invroad in 2017 at a level similar to that of Italy and Spain. The rest of the European countries are not leaders in terms of invroad. Some of them made significant investments at certain times, others made relatively constant investments during the period under review.

Regarding the organically cultivated area, the trend for the period 2000–2019 is upward for most European countries. Some of them are notable for the increase in organically cultivated areas. Spain made the highest progress; Italy and France also; both decoupled from the upward trend only in 2018, Italy by maintaining a relatively constant area of organically cultivated areas, and France by reducing them after a period of strong growth. Germany, Austria, Poland, Sweden, Greece also fall into the category of economies which supported organic farming to a greater extent than the rest of the European countries whose progress was almost visible.

European countries keep the cultivated area relatively constant. The states with the highest cultivated areas are France, Spain, Germany, Italy, Poland, with quite large differences among them, but also Greece, Hungary and Ireland. In some cases, the cultivated area is decreasing, an aspect also supported by Fitton et al. (2019) [44] which emphasizes that the reduction of cultivated area takes place in parallel with the change in attitude towards food and the need to reduce waste.

In Figure 2, the relationship is shown between the dependent variable (GHG) and each of the six independent variables as we already as we have already explained.

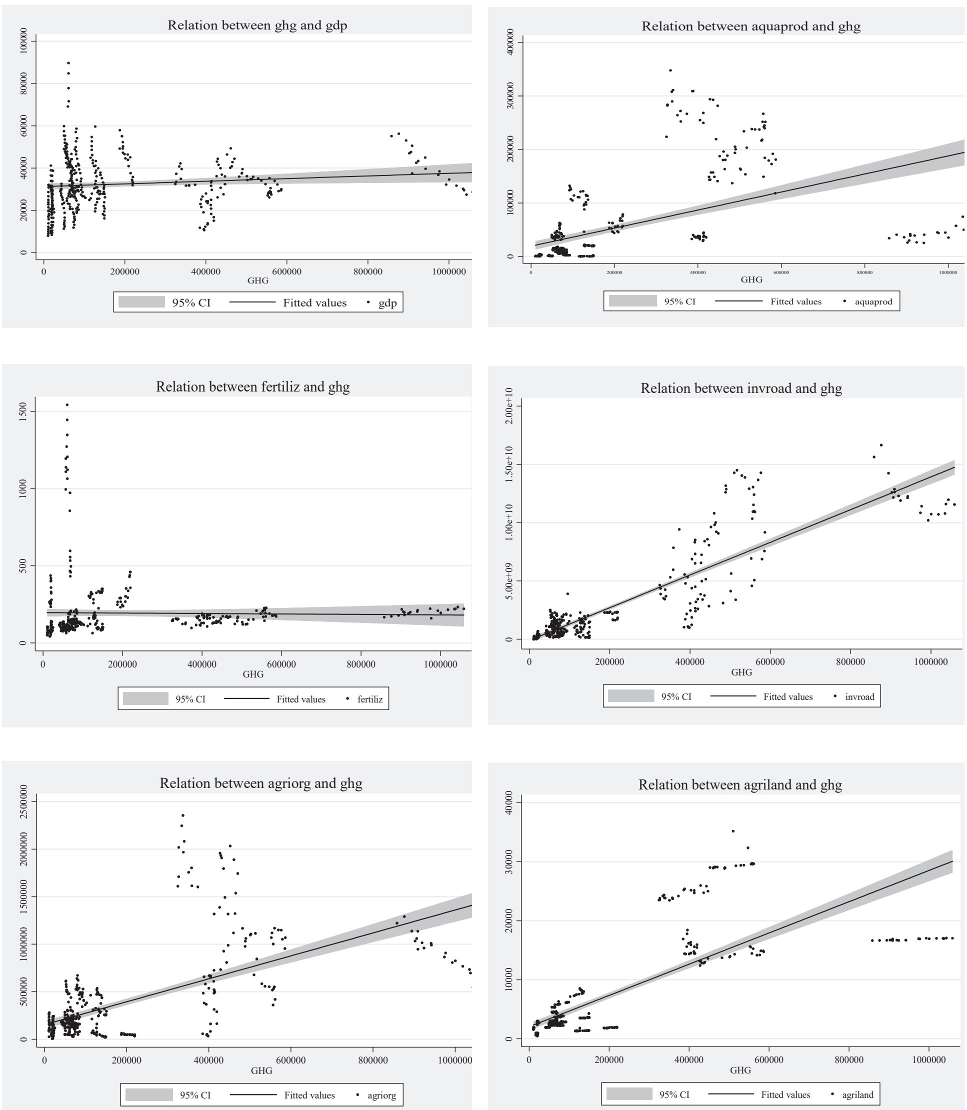

Figure 2. The Relation between Variables.

3.2. Method

The method we apply for the validation of the first research hypotheses ($H_{1–5}$) is Panel Data or Cross-Sectional Time-Series Data. The aim is to assess the carbon footprint of agricultural chains in the case of European OECD member countries under the influence of specific variables in agricultural chains. The analysis of the carbon footprint under the influence of variables specific to agricultural chains involves three directions, i.e., a general one, for all European OECD member countries analysed, the second direction, geographical, for each country, and the third one, in temporary dynamics. We used the Fixed Effects model following the application of the Hausman test. It explores the relationship between explanatory variables and the result variable. Each European country has its own characteristics which influence the explanatory variables. The fixed effects model eliminates the effect of invariant characteristics over time so, we evaluate the net effect of explanatory variables on the result variable. Another assumption of the model is that the time-invariant characteristics are unique and they are not correlated with other individual characteristics.

The general equation of the model is:

$$Yit = \beta_i X_{it} + \alpha_i + u_{it} \tag{1}$$

where:

α_i (i = 1,..., n)—the unknown intercept for each country;

y_{it}—the dependent variable or result;

X_{it}—the independent or explanatory variable;

β_i—the coefficient of the independent variable;

u_{it}—the error term; i represents the countries; t represents time.

$$u_{it} = \mu_i + \eta_i + v_{it} \tag{2}$$

where:

u_{it}—the error term or discrepancy variable;

μ_i—the unobservable, non-time-changing cross-sectional specific effect which estimates the effect of the variables not included in the model specific to the country and on the dependent variable;

η_i—the temporary specific effect which does not change in the transversal structures, estimating the effect of the variables not included in the model, at time t, on the dependent variable;

v_{it}—variable error among units (countries) and in space.

We start from the presumption that μ_i and η_i are fixed parameters, uncorrelated with errors, the sum of them is zero, and the estimation method is that of the smallest squares.

Equation (1) can be written by inserting dummy variables in the form below (Equation (3)).

$$Y_{it} = \sum_{j=1}^{N} \alpha_j d_{ij} + x_{it}\beta + u_{it} \tag{3}$$

where d_{ij} = 1 if i = j or d_{ij} = 0 in other way. The parameters α_j and β can be estimated with ordinary least squares. The same estimation is obtained whether the regression is performed as a deviation from the individual mean α_j which involves removing individual effects by transforming the data. The Fixed Effects term is justified by the fact that the intercept may vary between countries but not over time. The estimated coefficients of the fixed effects model cannot be influenced by time-invariant characteristics omitted from the analysis such as culture, religion, gender, and race.

To choose between the two models, Fixed Effects and Random Effects, the Hausman test will be performed. It determines whether the fixed effects and random effects estimators are significantly different. The difference between the estimators results from the existence of correlation between x_{it} and $\alpha_{j.}$

The null hypothesis of the Hausman test is H_0: cov(x,e) = 0 and the alternative hypothesis is cov(x,e) $\neq$ 0. If the null hypothesis is true, then the estimators-least squares and instrumental variables-are consistent. In this case the most efficient estimator (least squares) will be chosen. However, if the alternative hypothesis is true, we opt to use the least squares estimator. In other words, if after applying the Hausman test we accept the null hypothesis and reject the alternative one, the appropriate model is Random Effect. Conversely (our case), if we reject the null hypothesis and accept the alternative one, the appropriate model is Fixed Effect.

To validate the latest research hypothesis, (H_6), we apply specific methods to the literature analysis, inductive and deductive, including the results of the panel methodology applied for the first research hypotheses.

4. Results and Discussions

The first step in the empirical analysis is to choose between the two possibilities of the given panel data methodology. After applying the Hausman test the results (chi2(6) = 31.03 and Prob > chi2 = 0.0000) lead to the rejection of the null hypothesis and the acceptance of the alternative that is: the model fitted with our analysis is Fixed Effects.

After applying Fixed Effects, the model equation can be written:

$$\begin{gathered} ghg = (-1.53 \times 10^{-9}) - 0.036 \times gdp + 0.148 \times aquaprod + 0.039 \times fertiliz + \\ 0.064 \times invroad - 0.097 \times agriorg + 1.128 \times agriland \end{gathered} \quad (4)$$

where:

ghg—the amount of greenhouse gases or carbon footprint;
gdp—the gross domestic product per capita;
aquaprod—the aquaculture production;
fertiliz—the amount of fertilizer used per unit of arable land;
invroad—the investments in road transport infrastructure;
agriorg—the organically cultivated area;
agriland—the area cultivated for agricultural purposes.

The first research direction, which involves assessing the carbon footprint under the influence of variables specific to agricultural chains, is general, covering the whole group of analysed European OECD member countries. The model is statistically significant as is shown by the value of F (6.393) of 85.30 and that of the *p*-value of 0.0000. The results show that 56.56% of the carbon footprint variation is due to the variation of the explanatory variables over time, that 43.44% is due to the variation of the variables among countries, and 42.03% is due to both the variation among countries as well as to temporary dynamics (Table 1). This last value of the coefficient of determination allows us to estimate the statistical significance of the model.

Table 1. Nonstandardized coefficients and characteristic values of the Fixed Effect model.

Variable	β	t	$p > \lvert t \rvert$	[Confidence Intervals 95%]	
gdp	−0.0362	−5.51	0.000	−0.0491	−0.0233
aquaprod	0.1479	6.49	0.000	0.1031	0.1927
fertiliz	0.0391	4.38	0.000	0.0215	0.0566
invroad	0.0642	5.59	0.000	0.0416	0.0868
agriorg	−0.0966	−9.33	0.000	−0.1169	−0.0762
agriland	0.1284	2.09	0.037	0.0078	0.2491
_cons	-1.53×10^{-9}	−0.00	1.000	−0.0067	0.0067
R2	within			0.5656	
	between			0.4344	
	overall			0.4203	
rho			0.9936		

Source: author's calculations based on data from the OECD, World Bank, and FAO (STATA 13).

The particularities of the explanatory variables of the European OECD member countries such as interclass coefficient illustrate more than 99% of the variation in the carbon footprint. The explanatory variables are directly related to the carbon footprint in a relationship of medium to significant intensity, according to the value of the correlation coefficient (r = 0.659).

The model shows two direct relationships and four indirect relationships among variables as the value of non-standardised coefficients shows. A positive evolution of economic growth and organically cultivated area reduces the carbon footprint, while the increase in aquaculture production, fertiliser amount, agricultural areas and investments in road transport infrastructure lead to its expansion.

The non-standardised coefficients fall within the confidence intervals and, according to the t values, the explanatory variables have a significant influence on the carbon footprint, an aspect certified by the *p*-values. The increase by one unit of GDP per capita and of the organically cultivated area reduces the amount of emissions by 0.036 and 0.097, respectively. On other hand, the increase in aquaculture production, fertilisers, investments in road transport infrastructure and in agricultural area by one unit increases the carbon footprint. Therefore, the first conclusion of the empirical analysis is that European OECD member states should support economic growth. Moreover, in the agri-food chain framework, they should expand the areas cultivated organically and adapt to other specific activities, such as aquaculture production, production and use of fertilisers, and the manner of performance of agricultural activities and investments in road transport infrastructure to the new requirements of agricultural sustainability. The first research direction validates the first two research hypotheses, H_1 and H_2, and rejects the third one, H_3.

Aquaculture production and investment in road infrastructure have the strongest negative impact on the environment and biodiversity, as t values show, followed by fertilisers and agricultural area. The results suggest the need to expand organically grown areas using traditional and extensive but less productive methods compared to the conventional ones, to properly calibrate the number of fertilisers and to support short agri-food chains which do not involve long-distance movement of products, all on the background of European economic growth.

It is demonstrated that the carbon footprint can be acted upon by using traditional methods of agricultural production, by using biofuels, by reducing the demand for fuel and feed [5], by reducing the amount of chemical fertilisers used, by cultivating varieties adapted to the local environment, by increasing carbon storage in the soil and minimising the transport distance between markets [7]. The transition from high-input agriculture to low-input agriculture, i.e., to traditional organic farming, may be a solution to reduce the carbon footprint, but the extent of coverage of the consumer demand is not known [7].

Land use for agricultural purposes is one of the main factors with an impact on biodiversity in the EU, which places pressure on the environment [45] and the use of large amounts of fertilisers generate surpluses of nutrients harmful to water, which is why it is necessary to optimize their use in agriculture [12].

According to the OECD (2021) [41], European agricultural and aquaculture production accounts for 16% of total globally, and estimates show a downward trend until 2030 due to slow growth in Western European countries but also the fact that sustainability has become a priority in the economic and consumer policy.

Transport infrastructure planning is essential in any carbon footprint reduction strategy because it is at the intersection of climate and development imperatives, and the impact of environmental policies on infrastructure investment is ambiguous [25]. Food transport involves, in addition to pollution generated by moving from one location to another, the pollution caused by refrigerants used for products requiring special forms of transport [45].

The second direction of research assesses the carbon footprint under the influence of country-specific variables. It outlines two European clusters (Table 2). One consists of ten countries where agricultural chains reduce the carbon footprint (Belgium, the Czech Republic, Hungary, Ireland, Latvia, Lithuania, Portugal, Slovenia, Slovakia and Sweden). In the case of the other cluster, agricultural chains contribute to increasing the carbon footprint (Denmark, Estonia, Finland, Germany, Italy, the Netherlands and Poland). There are four additional countries outside these two clusters., four countries remain. In the case of two of them, France and Spain, only the increase in agricultural area reduces the carbon footprint, so we consider that they are falling to the second cluster, the one of the countries where agricultural chains extend the carbon footprint. Regarding the other two, Austria and Greece, only two variables each reduce the carbon footprint in the case of their growth with one unit: economic growth and organic farming in the case of Austria, and aquaculture production and agricultural area in the case of Greece.

Table 2. The variable's influence on the pollution reduction in temporary dynamics by countries.

Country	β_i	$p > \lvert t \rvert$	β_{gdp}	$p > \lvert t \rvert$	$\beta_{aquaprod}$	$p > \lvert t \rvert$	$\beta_{fertiliz}$	$p > \lvert t \rvert$	$\beta_{invroad}$	$p > \lvert t \rvert$	$\beta_{agriorg}$	$p > \lvert t \rvert$	$\beta_{agriland}$	$p > \lvert t \rvert$
Austria	−0.1804	0.000	−0.0685	0.000	0.2349	0.000	0.0156	0.000	0.0869	0.000	−0.1508	0.000	0.6623	0.000
Belgium	0.0948	0.001	0.1931	0.000	0.2164	0.000	0.1948	0.000	0.2137	0.000	0.0527	0.044	0.3262	0.000
Czech R.	0.1117	0.000	0.1579	0.000	0.1857	0.000	0.2394	0.007	0.2269	0.000	0.1935	0.000	0.1698	0.000
Denmark	−0.2339	0.000	−0.0923	0.002	−0.1947	0.000	−0.0900	0.000	−0.0986	0.002	−0.2038	0.000	−0.0799	0.000
Estonia	0.3659	0.000	−0.3849	0.000	−0.2681	0.000	−0.2706	0.058	−0.2649	0.000	−0.4080	0.000	−0.1219	0.000
Finland	−0.1628	0.000	−0.0892	0.003	−0.0982	0.002	−0.0634	0.000	−0.0738	0.022	−0.1739	0.000	0.0224	0.464
France	0.8619	0.000	1.7998	0.000	1.1812	0.000	1.8327	0.000	1.5735	0.000	1.9793	0.000	−0.3809	0.110
Germany	3.3066	0.000	3.7305	0.000	3.6222	0.000	3.7376	0.000	3.4668	0.000	3.8811	0.000	2.5867	0.000
Greece	−0.2519	0.000	0.0497	0.114	−0.1924	0.000	0.1395	0.000	0.1145	0.000	0.0717	0.004	−0.2346	0.000
Hungary	−0.2826	0.000	−0.1869	0.000	−0.1069	0.001	−0.0682	0.041	−0.0783	0.016	−0.1966	0.000	−0.3026	0.000
Ireland	−0.4431	0.000	−0.0395	0.195	−0.2219	0.000	−0.1489	0.014	−0.1007	0.002	−0.2408	0.000	−0.2223	0.000
Italy	1.3707	0.000	1.7761	0.000	1.3296	0.000	1.8190	0.000	1.6826	0.000	2.0828	0.000	0.8954	0.000
Latvia	−0.4162	0.000	−0.4411	0.000	−0.3028	0.000	−0.3057	0.000	−0.3001	0.000	−0.4256	0.000	−0.2284	0.000
Lithuania	−0.4017	0.000	-0.3843	0.000	−0.2679	0.000	−0.2653	0.000	−0.2601	0.000	−0.3951	0.000	−0.2648	0.000
Netherlands	0.2551	0.000	0.5161	0.000	0.3368	0.000	0.4895	0.000	0.4666	0.000	0.3475	0.000	0.5786	0.000
Poland	0.9618	0.000	1.2507	0.000	1.2728	0.000	1.3728	0.000	1.3173	0.000	1.3239	0.000	0.3329	0.004
Portugal	−0.2008	0.000	−0.1325	0.000	−0.0616	0.050	−0.0456	0.172	−0.0518	0.109	−0.1495	0.000	−0.1192	0.000
Slovakia	−0.2760	0.000	−0.2688	0.000	−0.1536	0.000	−0.1559	0.000	−0.1568	0.000	−0.2869	0.000	−0.0937	0.003
Slovenia	−0.4155	0.000	−0.3575	0.000	−0.2723	0.000	−0.2905	0.000	−0.2708	0.000	−0.4397	0.000	−0.0946	0.009
Spain	0.4342	0.025	1.1955	0.000	0.4124	0.000	1.2559	0.000	1.1266	0.000	1.5492	0.000	−0.5284	0.006
Sweden	−0.1570	0.000	−0.1011	0.001	−0.1179	0.000	−0.0939	0.005	−0.1242	0.000	−0.1394	0.000	−0.1202	0.000

Source: author's calculations based on data from the OECD. World Bank and FAO (STATA13).

The number of countries where agricultural chains are contributing to the carbon footprint contraction is significant, but not enough to characterise European agriculture as environmentally friendly. The ten states are from different regions and development groups. National characteristics are those which justify geographical and economic heterogeneity.

The second cluster, comprised of countries where agricultural chains have a polluting effect, includes European economies with developed agricultural sectors, such as Germany, Italy and France. This dichotomous situation shows that there is a need, in the EU, to adapt agricultural chains, so that their harmful effects on the environment diminish over time. The results of the second research direction partially validate the fourth hypothesis, H_4, as agricultural chains do not reduce the carbon footprint in all European OECD Member States.

Studies show that there are differences among European regions in terms of agricultural sustainability. Mediterranean and Central countries have the highest contribution (Guth and Smędzic-Ambrožy, 2019) while, for developed Western European countries, sustainability has become a priority.

There are studies that identify, in the European area, three clusters in terms of sustainability and argue that agriculture is characterised by moderate sustainability [46]. In Central European countries, agriculture has a high economic value, in the Mediterranean it bears a more positive influence on the environment compared to the rest of the regions, and in Eastern countries it contributes significantly to job creation. In contrast, Fanelli (2020) [47] notes that the countries of Central Europe represent the group characterised by the highest degree of sustainability, and the Eastern states represent the group characterised by high agricultural intensity. A study by Czyżewski et al. (2021) [48] reaches other conclusions, namely that Western European countries are the group where the intensification of agricultural production is increasingly sustainable, especially in states such as the Netherlands, Belgium, Denmark and Northern France, and the countries of Central and Eastern Europe and Greece are facing the most difficult situation in terms of sustainability.

The third research direction assesses, in temporary dynamics, the carbon footprint under the influence of variables specific to agricultural chains. The fact that in European countries a real interest in reducing pollution caused by agricultural activity is demonstrated by the influence of the variables analysed on the carbon footprint on temporary dynamics (Table 3).

Table 3. The variable's influence on the pollution reduction in temporary dynamics by year.

Year	β_{gdp}	$p > \|t\|$	$\beta_{aquaprod}$	$p > \|t\|$	$\beta_{fertiliz}$	$p > \|t\|$	$B_{invroad}$	$p > \|t\|$	$\beta_{agriorg}$	$p > \|t\|$	$\beta_{agriland}$	$p > \|t\|$
2001	0.0026	0.922	0.0116	0.648	0.0083	0.754	0.0082	0.750	0.0143	0.533	0.0115	0.656
2002	−0.0063	0.813	0.0226	0.374	0.0051	0.848	0.0026	0.919	0.0154	0.501	0.0124	0.632
2003	0.0043	0.872	0.0290	0.253	0.0191	0.470	0.0141	0.586	0.0329	0.152	0.0299	0.246
2004	−0.0011	0.967	0.0369	0.147	0.0216	0.414	0.0118	0.649	0.0347	0.131	0.0301	0.244
2005	−0.0124	0.651	0.0333	0.191	0.0178	0.501	0.0021	0.936	0.0356	0.121	0.0253	0.327
2006	−0.0259	0.365	0.0291	0.252	0.0173	0.513	−0.0068	0.796	0.0392	0.089	0.0220	0.394
2007	−0.0451	0.131	0.0184	0.467	0.0024	0.927	−0.0171	0.513	0.0340	0.140	0.0215	0.406
2008	−0.0702	0.023	0.0093	0.715	−0.0104	0.696	−0.0388	0.138	0.0215	0.353	0.0023	0.929
2009	−0.1220	0.000	−0.0524	0.040	−0.0670	0.012	−0.0910	0.001	0.0265	0.253	−0.0658	0.011
2010	−0.1084	0.000	−0.0281	0.272	−0.0518	0.050	−0.0673	0.010	0.0001	0.994	−0.0281	0.282
2011	−0.1404	0.000	−0.0515	0.045	−0.0754	0.001	−0.0886	0.001	−0.0191	0.414	−0.0516	0.049
2012	−0.1574	0.000	−0.0610	0.018	−0.0916	0.000	−0.0968	0.000	−0.0281	0.232	−0.0635	0.016
2013	−0.1773	0.000	−0.0703	0.007	−0.1057	0.000	−0.1077	0.000	−0.0412	0.080	−0.0762	0.004
2014	−0.2108	0.000	−0.1049	0.000	−0.1353	0.000	−0.1345	0.000	−0.0658	0.005	−0.1012	0.000
2015	−0.2096	0.000	−0.0954	0.000	−0.1266	0.000	−0.1260	0.000	−0.0461	0.053	−0.0917	0.001
2016	−0.2189	0.000	−0.1010	0.000	−0.1256	0.000	−0.1244	0.000	−0.0352	0.143	−0.0898	0.001
2017	−0.2259	0.000	−0.1009	0.000	−0.1229	0.000	−0.1238	0.000	−0.0235	0.331	−0.0859	0.001
2018	−0.2544	0.000	−0.1205	0.000	−0.1411	0.000	−0.1449	0.000	−0.0298	0.225	−0.1028	0.000
2019	−0.2684	0.000	−0.1210	0.000	−0.1444	0.000	−0.1478	0.000	−0.02961	0.230	−0.1091	0.000

Source: author's calculations based on data from the OECD. World Bank and FAO (STATA 13).

In the case of economic growth, the data are statistically representative since 2008, and in the case of aquaculture production, fertilisers, investments in transport infrastructure and agricultural land they are representative since 2009. With regard to the agricultural area, an exception is 2010, where the data are not statistically significant, and in the case of organically cultivated area, the only year for which we have statistically significant results is 2014.

The period 2008–2009 marks a change in the influence of European agriculture on the carbon footprint. Economic growth has led to a continuous and increasing reduction in the carbon footprint since 2016, aquaculture production has started to have less harmful effects since 2008, as well as the use of fertilisers. Investments in road infrastructure had a polluting effect until 2005, after which they were made at the same time as the slow reduction of the carbon footprint it generates. The positive effects of the organically cultivated area become visible from 2011, but the most significant impact on the reduction of the carbon footprint was recorded in 2014. The organically cultivated area has a fluctuating influence on the carbon footprint, but this effect was visible in the years 2018–2019, when it approached the level of 2014. The year 2009 marks the moment when the increase in the European agricultural area was achieved against the background of the carbon footprint decrease. The carbon footprint increased continuously and accentuated in the period 2009–2014, but afterwards, the expansion of European agricultural areas was achieved against the background of the carbon footprint reduction.

The European countries have taken measures to reduce the carbon footprint generated by agricultural activities since 2008–2009, even if not with spectacular results and not at a fast enough pace to solve the environmental problem generated by agricultural activities. The results of the third research direction validate the fifth research hypothesis, H_5.

Similar studies show that, in the period 1990–2015, industrialized states kept the carbon footprint relatively constant at about 24%, the developing states reduced it from 68% in 1990 to 39% in 2015, and the more energy-intensive economies, including European ones, had the lowest contribution to the carbon footprint of agri-food activities [18] due to land conversion and reduced deforestation [19]. However, developing countries are considered as the largest contributors to the carbon footprint resulting from the agriculture sector because agri-food activity accounts for more than half of total economic activities [19]. In terms of their contribution, Central European countries have the highest economic contribution, the Mediterranean countries have the highest environmental contribution, and the Eastern ones have the highest contribution to the labour market [46]. Although the contribution of agriculture to economic growth in Europe is low, at around 1.6% of GDP, 4.5% of the labour market, 1.2% of exports and 1.4% of imports [46], the pressure on the environment is high.

Considering that sustainability is based on extensive production methods and short transport distances [49], one of the potential solutions for adapting agricultural and food systems to meet economic, demographic, and environmental challenges to ensure more sustainable food systems in order to guarantee food and nutrition security is to focus on small producers and short agricultural and food chains. In Europe, small producers contribute to food security, support short chains and contribute to reducing the carbon footprint by strengthening and diversifying agri-food systems [50]. They should have access to technologies and practices which allow them to adapt to climate change, to receive support to increase their ability to connect to markets because, in the future, they will depend on social change [51]. In the EU, the number of small agricultural producers decreased and their activity is concentrated in their own proximity, which makes it easier for them to integrate into short chains [52]. Short agricultural and food chains, although they have a complicated, dynamic and fragile profile, closely related to the availability of products, guarantee their safe and unaltered supply from the producer to the final consumer [53]. Short-distance transport generates emissions in small quantities, depending on the mode of transport and logistics, and distribution is important as long as it generates 80% of emissions after the production and processing stage [54]. In addition, in order to reduce the impact of European agriculture on the environment, it is recommended to develop high-efficiency systems with low impact on the environment, based on techniques specific to both organic and conventional system [33]. The big challenge is to improve the efficiency of fertilisers and develop new kinds of fertilisers with a high degree of efficiency, and an important role in the agricultural sector will be played by nanotechnology, now in an infancy phase, but which will provide the solution to increase production in less aggressive conditions with the environment [55]. Simultaneously, it would be advisable for the consumers to adopt more sustainable and healthier choices, to change their diet to avoid waste, i.e., relieve pressure on the environment [56].

In the near future, a global overlap of crises is foreseen, such as food, water and energy crises. Prior to the COVID-19 pandemic, more than a quarter of the world's population did not have access to these products [57], with malnutrition affecting one in ten people, especially in developing and less developed countries [58]. The pandemic has worsened the global economic situation, and political conflicts are exacerbating the negative economic and social consequences. Conflicts have strong effects on trade, national income and global economic well-being. The costs are high and persistent, and the negative externalities are huge [59]. The economic effects of conflicts are devastating in the long run in the countries where they occur and in the neighbouring countries [60]. These aspects lead to economic and social crises. A crisis is defined as a threat, and is associated with uncertainty, which presents an unfavourable situation for the population [61]. Developing and externally dependent countries are very vulnerable.

Therefore, all agricultural and food chain stages (production, processing, distribution and consumption) have been affected by the COVID-19 pandemic [62], and the effects of the conflict in Europe significantly worsen the situation. According to the FOEE (2021) [63], Europe imports 60% of the products needed to meet the consumers demand, and dependence will increase in tandem with the price of energy and fuel. The situation created in Europe emphasizes the risks and the degree of dependence on imported products for the countries in the area. Most European countries fail to meet the consumer demand from their own production, more specifically Austria, Cyprus, Croatia, Czech Republic, Estonia, Finland, Germany, Greece, Italy, Latvia, Luxembourg, Malta, Portugal, Romania, Slovakia, Slovenia, and Sweden [64]. The population of developing European countries will have difficulty purchasing imported products because of the rising prices.

Crises create insecurity, but also opportunities for long-term, transformational change, leading to changes in patterns of political and economic interactions which would not have been possible otherwise [61]. One solution would be to reduce external dependence. This implies a focus on streamlining the agricultural sector and increasing production. In terms of sustainability, the goal would include a focus on the development of local agri-food chains. High energy costs discourage agricultural producers from carrying out intensive activities and in many cases limit them to traditional ones, which describe the seasonal agricultural cycle. Agriculture follows the pattern of seasonality correlated with the product life cycle, the climate and soil physical characteristics [65]. Reducing production affects food security and socio-economic stability, but local agri-food chains are crystallising as a possible solution, especially in countries where traditional agriculture is allowed by climate and relief conditions. In order to reduce the carbon footprint in agriculture, Farfan and Lohrmann (2019) proposed the elimination of pesticides and herbicides, fertilisers, and the reduction of water and transport. These solutions are in line with the development of local agri-food chains with the potential to support the environment and the demand of population in terms of reduced imports, rising prices due to shortages of fertilisers and rising energy prices. Therefore, agricultural chains, especially local ones, are seen as a solution for the environment and for the alleviation of food insecurity. Their development, the promotion and facilitation of consumer access is a way to support the population in benefiting from agri-food products made at lower costs compared to those resulting from intensive agriculture, in avoiding waste, losses and in optimising production. The performance of agricultural systems is extremely important [66], and changes in agricultural patterns are needed to support the food security of the population [67]. Of course, these effects are possible given the change in the producer behaviour in the agri-food sector because the supply of organic products should be excluded from the luxury goods market.

Understanding the role which agri-food chains play in alleviating food insecurity involves supporting small producers through economic policy, and cooperation of economic agents involved in all stages of the agri-food chain. Cooperation produces synergistic effects, including production costs and waste reduction, access to basic foodstuffs produced in sustainable conditions for the environment, local economy support and reduction of food insecurity. Therefore, agricultural and food chains are part of the agroecological system. Including organic farming, an agroecological system is a holistic approach in which we find ecological, economic, social elements [68,69] which are positively influenced by its proper functioning with the potential to revitalise the local economy and environment, and also to mitigate food insecurity during the energy crisis and the effects of conflicts among states. This conclusion validates the last proposed research hypothesis, (H_6).

5. Conclusions

In European OECD member countries, agricultural chains influence the carbon footprint. The results of the first research direction show that economic growth increases the carbon footprint, showing progress in meeting the targets set in the Green Pact for decoupling growth from resource consumption. An extension of the organically cultivated area bears a positive effect. In contrast, any increase in aquaculture production, fertilisers, investment in transport infrastructure and agricultural land increases the carbon footprint with harmful effects on the environment and biodiversity. Economic growth continues to represent a priority objective of economic policy in European countries, and in the field of agriculture it is recommended to shift towards organic farming, which is much more environmentally friendly. As long as the increase in agricultural areas does not reduce, on the contrary, it accentuates the harmful effects on the environment, it would be ideal for future food security to increase the share of organic methods in agricultural and aquaculture production, and to calibrate the number of fertilisers at an optimum level. Regarding the investments in road transport infrastructure, they are necessary and indispensable, but our results emphasize their harmful effects on the environment, so that, from the perspective of the subject under study, it is recommended to develop short agri-food chains. The results confirm, among other things, the conclusions reached by Aquilera et al. (2019) [5], Litskas et al. (2020) [7], Rivera et al. (2020) [39], Wood et al. (2020) [16], Mrówczyńska –Kamińska et al. (2021) [17], Churchill et al. (2021) [26], Erdogan (2020) [27], Walling and Vaneeckhaute (2020) [29], Tripathi et al. (2020) [30], but refute those reached by Georgatzi et al. (2020) [28] and Czyźewski et al. (2021) [48].

The results obtained on the second research direction divide the European countries in two main clusters. The first consists of ten European countries where agricultural chains bear a less harmful effect on the environment, but the major European agricultural powers are not part of this cluster. These are found in the second cluster, a larger one, formed by economies where agricultural chains increase the carbon footprint. This situation involves an effort to adapt the methods employed without reducing the potential and efficiency of the agricultural sector and without affecting the population's food security. Hence, this results in the need to adapt agricultural activities, so as to reduce the future impact on the environment by generating lower amounts of greenhouse gas emissions. It becomes necessary to adapt European and national economic policy measures as there is a great heterogeneity of the countries in the two clusters. This aspect draws attention to the differences in national characteristics of European countries. The results partially confirm those obtained by Dos Santos and Ahmad (2021) [46], Fanelli (2020) [47], Guth and Smędzic-Ambroży (2019) [4] and largely refute those obtained by Czyźewski et al. (2021) [48].

The results of the third research direction show that European countries have adopted and implemented in time measures to reduce the carbon footprint of agricultural activities. This effect has been visible since 2008–2009, where we see the pollution reduction under the influence of the increase of variable values analysed, but not at the level and pace necessary to alleviate the environmental and biodiversity problem. These results confirm those of Lamb et al. (2021) [15], Crippa et al. (2021) [18], Tubiello et al. (2021) [19], and Wood et al. (2020) [16].

Local agricultural and food chains, in addition to making a positive contribution to the environment, are becoming a valve for alleviating food insecurity in vulnerable and recession-stricken economies. However, one condition would be to exclude organic products from the luxury category.

This study completes the literature, adds value by researching the effects of agricultural chains on reducing the carbon footprint in the European region, geographically and in temporary dynamics. The results of the study are useful to theorists interested in the subject, but also to economic policy makers and agricultural producers. There are clear limitations of the study related to the indicators analysed, the methods applied, the lack of data for all European countries and for a longer period.

Assessing the effects of numerous components of European agricultural chains on the carbon footprint allows us to provide some recommendations: on the one hand, to rethink and adapt agricultural strategies, in particular, and economic ones, in general. On the other hand, to raise awareness in both producers and consumers regarding the effects arising from the current relationship among the environment, agriculture and the economy, so that they voluntarily change their attitude and behaviour.

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Article

Boom and Bust in China's Pig Sector during 2018–2021: Recent Recovery from the ASF Shocks and Longer-Term Sustainability Considerations

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Abstract: China's African swine fever (ASF) outbreaks, which started in 2018, severely damaged the country's pig and sow herds and created serious pork supply shortages. This resulted in high domestic market prices and record amounts of imports in both 2019 and 2020, but also severely impacted its domestic consumers. It casts doubts on whether China's long-standing self-sufficiency strategy, including its recently communicated 95% self-sufficiency target, can be sustained. Recent data, however, suggest that China is experiencing a rapid recovery in pig production, leading to depressed domestic market prices. This study characterizes the recovery process and analyzes the underlying drivers, such as active responses to the ASF outbreaks, a multiple-prong government initiative towards supporting the pig producers, de facto relaxations of newly introduced environmental regulations, large increases in domestic investment, and a reorganization of the pig sector, featuring more scale operations. However, the rapid recovery has also resulted in decreasing prices, economic losses of producers, and dampened export opportunities for China's trade partners. This paper, therefore, also analyzes these unintended consequences and explores supply-side measures that may enable the long-run viability of the self-sufficiency goal in the presence of high dependency on imported feed. Through a model-based numerical simulation analysis, we find that supply-side measures, such as yield improvement, can substantially reduce reliance on import feed but can only increase domestic pork production marginally, while technical efficiency improvement in pork production has the largest potential in boosting domestic pork production.

Keywords: African swine fever; pig production; China; sustainable development; self-sufficiency; computable general equilibrium model

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1. Introduction

Instability in agricultural commodity markets and extreme price fluctuations have long been a major concern for consumers, producers and policymakers and have attracted continuing research [1–8]. This is because sudden rises in prices reduce the real purchase power of consumers; in the case of staple food, rising prices can lead to increased hunger and poverty incidence, particularly in developing countries. Low commodity prices, on the other hand, can reduce the profitability of agricultural production and damage producer's incentives. Thus, governments have designed and applied various price stabilization instruments and programs to ensure the stability of agricultural markets and their long-term sustainable development, for example through buffer stocks, intervention prices, agricultural insurance, and income support programs. Despite these efforts, large swings in agricultural markets can still be observed.

One recent prominent example is the major decline in pig production and rising pork prices in China, the world's largest pork market, during the 2018–2020 period. Although the outbreak of African swine fever (ASF) as the main culprit and the associated economic costs and impacts on the global pork market have been analyzed [9–11], the rapid recovery of the sector and the ensuing collapse of pork prices have so far not been studied in the current literature. This gap raises important analytical questions on why the recovery has been achieved so quickly, and more importantly, on the unexpected "side effects" of the rapid recovery in both the short and medium terms. In the short term, market supply has quickly exceeded demand, leading to collapsed domestic market prices and resulting in widespread economic losses for producers. In the medium term, sustained losses could lead to the exit of producers from the sector, potentially causing another downward cycle, thus, impeding the sustainable long-term development of the sector. More generally, as a sector that is heavily dependent on imported feed (particularly soybean and maize) and that is operating at an overall lower efficiency, its long-term sustainability in supplying enough pork to the vast market of China ultimately rests on technological development and efficiency improvement [12,13]. Government initiatives that supported the recent recovery do not necessarily address this fundamental consideration.

Recent studies in the literature have either focused on the impacts of the ASF outbreaks on China's pig sector and the efficacy of government policy responses [11,14,15], or on its wider impacts on China's national economy [9] and the world economy [10]. In addition, the environmental impacts of reduced pig production have also been investigated [16]. However, these studies generally do not address factors underlying the quick recovery and the ensuing market and price movements. Studies [12,13,17,18] addressing the long-term prospects of China's pig sector are often outdated in respect to the new situation in connection with the ASF outbreaks and China's rising imports, thus, ignoring these vulnerabilities in China's pig sector. In light of these analytical gaps, the current study offers a timely empirical analysis rooted in economic theory and method to address the research gaps identified above for purposes of generating new insights into enhancing the sustainable development of the pig sector in China. Specifically, we first provide a qualitative analysis to account for the economic factors that have led to the sharp downturn and the ensuing quick recovery of China's pig sector and discuss the market effects of this dramatic cycle. Secondly, as the sector is mired in another potential downturn in a very short period of time, we apply a formal economic simulation model to quantify the domestic and world market effects of a set of supply-side measures that can potentially enhance the sector's long-term capacity.

The paper is organized as follows. Section 2 provides an overview of the recent development of China's pig sector and pork market. Section 3 describes the methodology applied in this study. Section 4 offers a qualitative analysis on the first research question, whereas Section 5 provides a model-based numerical analysis to answer the second research question. The last section summarizes the main findings of this study and provides a discussion on the policy implications of our findings.

2. China's Pig Production and Pork Market during 2000–2021

Pork is the most important meat choice of most Chinese consumers and the country is the world's largest producer and consumer of pork. The country's pork production increased from 39.7 million tons (46.8% of total world production) in 2000, to the highest level of 58.2 million tons in 2014 (52.2% of world total), before leveling off thereafter [19]. On the consumption side, China's domestic demand (which increased at an average annualized rate of about 3% during 2000–2015) had been largely met with domestic production up until 2015, implying nearly total self-sufficiency. Total consumption peaked at 58.7 million tons in 2014 (about 53% of total world consumption), followed by a small decline thereafter. As domestic production largely tracked the rising domestic demand, China's pork imports and exports were quite modest during the 2000–2015 period. On the export side, less than 0.5% of China's production were exported in recent years, mainly to its Hong Kong Special Administrative Region. On the import side, until 2015, less than 2% of China's domestic consumption were imports; however, from 2011, China's imports exceeded one-tenth of total world trade and reached the level of 15% in 2015. Overall, China nearly maintained total self-sufficiency until 2015.

Domestic production started to level off from the highest level of 58.2 million tons in 2014, triggered by shrinking pig and sow herds since late 2013. Against much more stable domestic consumption, large amounts of imports exceeding one million tons first occurred in 2016 and continued well into the first 9 months of 2021. China's pork imports as a share of its total consumption doubled between 2015 and 2016 (i.e., from 1.7% to 3.6%) and then rose to double digits in 2020. The recent import surge was aided by the ASF outbreaks, which led to only 42.6 million tons of pork production in 2019, roughly matching the country's production in the early 2000s.

The deterioration of China's pork self-sufficiency ratio, even before the ASF outbreaks, is not totally unexpected, as domestic supply has suffered from higher production costs and lower profitability [14]. Tightened environmental regulations have also resulted in the abandonment of pig farming in areas where such regulations are enforced [20]. In August 2018, when the ASF outbreak was first reported, China's sow herd had already dipped to 31 million heads, about 40% lower than the peak level observed six years earlier (Figure 1). The ASF outbreaks accelerated this downturn. As shown in Figure 1, around September 2019, China's pig and sow herds dropped to 190 million and 19 million, respectively, the lowest levels in recent memory, according to official statistics from China's Ministry of Agricultural and Rural Affairs (MARA) [21]. This creates a huge gap between domestic demand and supply, raising domestic market prices and opening up the opportunity for increased imports. Pork prices increased from around CNY20/kg at the end of 2018 to the highest level of CNY56/kg in October 2019, before hovering around CNY50/kg until January 2021 (Figure 2). In 2019 and 2020, China's pork imports surged to record levels (2 and 4.3 million tons), despite trade disputes with the US, which lowered China's imports from the latter country. Against the huge supply shortage, however, the record amount of imports (and the release of frozen pork from the national stockholding system) did little to quench the rising domestic price. As a result, consumer demand shrank considerably in both 2019 and 2020 to levels that had not been recorded since 2003.

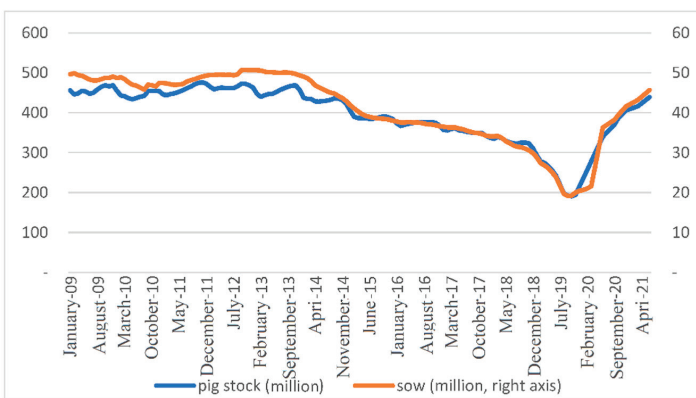

Figure 1. China's pig and sow herds: 2009–2021. Data source: www.gov.cn. (accessed on 16 January 2022).

Figure 2. Average pork prices in China: 2006–2021 (CNY/kg). Data source: www.caaa.cn. (accessed on 16 January 2022).

In June 2020, 8 months after China's pig production hit the lowest point, production capacity in China's pig farms started to show robust signs of recovery, as pig and sow herds rose to the levels of 340 and 36 million heads, respectively. Following these developments, pigs delivered for slaughtering also rose sharply, resulting in a much improved supply (Figure 1). With the shrinking gap between pork demand and supply, China's domestic pork price has experienced a sustained decrease since February 2021, around the time that Chinese consumers stocked up pork for the Chinese New Year's holiday. The latest data for October 2021 show that market price all but receded to the pre-ASF levels (Figure 2). By the end of 2021, China's sow herd reached 43.3 million and total pork production in 2021 was nearly 53 million tons, approaching recent "norm" levels.

The restored production capacity and market supply is undoubtedly good news for Chinese consumers. However, the sudden swing of market prices has also spelled trouble for large and small producers alike, resulting in intensive discussions on how to manage the exit of excessive production capacities, and on what future scenarios await producers.

In response to these challenges, the Chinese government for the first time issued explicit guidance on the long-term development of the pig sector and on pork supply in 2020. In an official opinion issued by the State Council in September 2020 [22], a 95% self-sufficiency target for pork was proposed. In August 2021, together with several other government agencies, MARA [23] issued another official opinion on promoting "sustainable and healthy development of the pig sector", reiterating the 95% self-sufficiency targets. In light of the damages from the ASF crisis, this target reflects the central government's determination to restore the domestic supply capacity but falls short of the *de facto* total self-sufficiency observed prior to 2015, perhaps indicating a pragmatic recognition that total self-sufficiency is not achievable. However, the 95% self-sufficiency rate implies nearly three million tons of annual pork imports, assuming domestic demand stays close to the average annual levels before the ASF crisis. Questions also remain on whether the seemingly scaled back self-sufficiency ambition can be realized and sustained in the longer term, considering China's rising production costs, limited resource base for feed production, and trade policy "space" for limiting imports [17].

3. Methods

3.1. Qualitative Analysis

To answer the first research question posed in this study, we offer a qualitative analysis to explain the main drivers underlying the rapid recovery but also leading to the subsequent collapse of market prices. Based on up-to-date policy information that has so far not been detailed in the literature, this qualitative analysis is rooted in an analytical framework of agricultural production function defined on multiple inputs. More specifically, pig farmers use various primary production factors, such as physical capital including building and farm machinery (denoted as $\boldsymbol{K}$), sow ($\boldsymbol{S}$), land ($\boldsymbol{T}$), labor ($\boldsymbol{L}$), purchased inputs, such as feed ($\boldsymbol{f}$), and other inputs, such as energy and veterinary medicine ($\boldsymbol{X}$), to produce pigs. We denote pig outputs as $\boldsymbol{Y}$, defined by the following equation:

$$\boldsymbol{Y} = \boldsymbol{A} * \boldsymbol{F}(\boldsymbol{K}, \boldsymbol{S}, \boldsymbol{L}, \boldsymbol{T}, \boldsymbol{f}, \mathrm{X}) \tag{1}$$

where the function $\boldsymbol{F}$ is increasing in each factor/input, holding constant all other factors/inputs, and the coefficient $\boldsymbol{A}$ is a productivity variable that measures the productivity level for a given combination of production factors and inputs. In the agricultural economic literature, specific functional forms, such as Leontief, Cobb–Douglas, Translog, and constant elasticity of substitution (CES) are used to parameterize the production function. In large multiple-product partial or general equilibrium simulation models, multiple level nested production functions are often specified to capture the differential substitutability of different inputs. For instance, in the well-known GTAP model [24], the output level $\boldsymbol{Y}$ is produced in a Leontief production function, combining individual purchased inputs and a value-added composite, the latter of which is produced through a CES function with individual primary factors, such as $\boldsymbol{K}$, $\boldsymbol{L}$ and $\boldsymbol{T}$.

To increase the output level $\boldsymbol{Y}$, it is necessary to increase the productivity level and/or increase factors and inputs used. Note that production factors such as physical capital ($\boldsymbol{K}$) and sow ($\boldsymbol{S}$) are fixed in the short term for individual farms, as it takes time to build up additional capacity. Therefore, when adverse events, such as ASF or other animal disease, lead to reduced sow herd, the negative impact on pig production cannot be alleviated immediately, potentially resulting in prolonged production disruption. Moreover, in the short-term, there are very limited possibilities to substitute other factors and inputs for reproductive sows for purposes of increasing pig production, leading to a situation where the level of production would fall in proportion to the reduction in the sow herd. When the sow herd continues at a lower level, idled physical capital, land, and labor would eventually exit the pig sector. In turn, this makes it harder for the pig sector to return to normal capacity in the short term, even when the sow herd expands. Conversely, if overcapacity exists in the pig sector, for example due to government subsidies and other incentives, it would also take time to "downsize" the capacity by reducing sow herd and for other production factors to exit the sector. During the adjustment period, overcapacity can result in excessive supply that may depress market prices and lead to losses for producers.

To restore the production capacity to the pre-ASF level, it is, therefore, crucial to prevent further decline in sow herds through effective ASF containment and to provide incentives for farmers to rebuild their sow herd. At the same time, complementary measures are also needed to facilitate the inflow of other production factors, such as capital, land, and labor. However, as pointed out earlier, excessive public assistance and private investment can result in overcapacity in the next period, paving the way for another wave of price fluctuations. In the qualitative analysis in Section 4 of this study, we follow this analytical framework to describe key government initiatives and structure changes that supported the recovery process and also discuss the aftermath of the rapid recovery.

3.2. Quantitative Analysis

Several long-term weaknesses in China's pig sector can hinder its future development, making it susceptible to future supply shocks. One particular weakness lies in the reliance on imported feed grains and oilseeds, particularly soybean and maize [13,17,18]. For instance, China's soybean imports exceeded 100 million tons in 2020, more than 5 times China's domestic production (Figure 3). This dependency has raised serious concerns on potential feed supply risks, such as those related to trade conflicts with major supplying countries. Another concern is about the pig sector's substandard feed conversion ratio and overall (in)efficiency [12,18], which lead to higher costs and contribute to the declining competitiveness of China's pork production, relative to imports. Potential supply-side measures to ensure the 95% pork self-sufficiency ratio may lie in the reduced reliance on imported feed grains and oilseeds, more efficient feed use, and improved technical efficiencies.

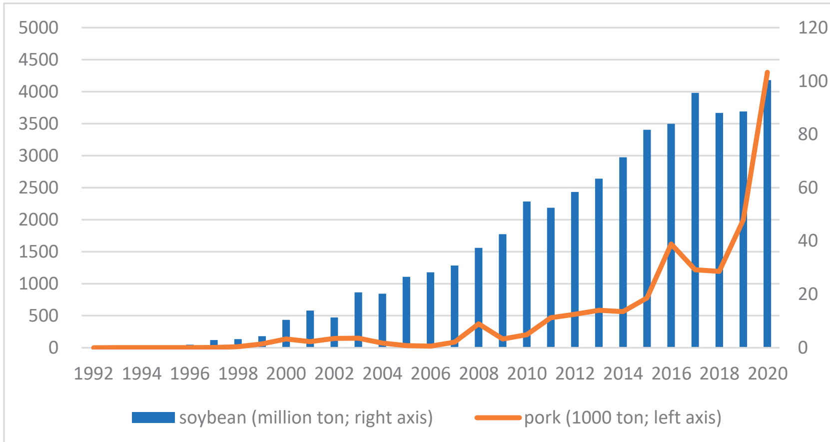

Figure 3. China's soybean and pork imports during 1992–2020 (source: UNCOMTRADE).

To answer the second question on strengthening the pig sector's long-term supply capacity, we use a quantitative economic model to simulate the potential impacts of the supply-side measures identified in the literature. To capture the extensive inter-sectoral linkages between feed and pig (and other livestock sectors) through intermediate uses and competitions for sources such as land, a multi-sectoral model is desirable for this analysis. As international trade for both feed grains/oilseeds, pork, and other animal food products is of interest in this analysis, the model should also cover multi-countries, including China and its main trading partners. In short, these considerations point to the use of a multi-sectoral and multi-country economic model that can simulate the effects of the various scenarios mentioned above. We, therefore, adopt the GTAP model, which is considered a standard computable general equilibrium (CGE) model that is widely used for the analysis of global economic issues, such as international trade, the environment, and climate change [24]. The GTAP model assumes perfectly competitive markets and constant returns to scale technology. Nested production with Leontief and CES production functions are used so that final outputs can be produced with intermediate inputs (e.g., feed grains) and primary production factors, such as land, capital, skilled and unskilled labor and natural resources, which are conceptually similar to Equation (1). On the demand side, demand of a representative private household follows a constant difference in elasticity demand function that is calibrated to income and price elasticities from the literature. The GTAP model tracks bilateral trade flows, linking all countries and regions in the model. In the standard GTAP model, land allocation is governed by a constant elasticity of transformation frontier. The version of the GTAP model used in this study is a variant used in Clora et. al. [25]. Definitions of the scenarios to be simulated with the model and modeling results are detailed in Section 5.

4. What Drives the Rapid Recovery of Pig Production in China? A Qualitative Analysis

The speedy recovery of China's pig sector has been driven by several factors, ranging from active responses to prevent the further spread of the ASF and the containment of outbreaks (i.e., preventing further declines of S in Equation (1)), extraordinary policy measures supporting the recovery of the pig sector (i.e., increasing S), large private investment (i.e., increasing ***K*** and ***T***), and structure adjustment that resulted in increased production scale (i.e., promoting productivity progresses).

4.1. ASF Containment

The outbreak of the ASF in China was first reported in August 2018. Official statistics suggests that there have been 160 ASF outbreaks since 2018, resulting in 1,193,000 pigs being culled [26]. However, as pointed out by other studies, these numbers likely underestimate the true severities of the impacts of the outbreaks, because of under-reporting and abandonment of pig farming by smallholders that were not included in official statistics [9,10]. The aggregated national statistics also indicate a much larger reduction in both pig and sow stocks (Figure 1), which is likely due to more pig death, culling, and losses of sows. In fact, data from the MARA show that, by December 2018, China's total pig herd had already decreased by 4.8% on a year-to-year basis, and its sow herd had decreased even more (by 8.3%) [27].

When ASF appeared in China in August 2018, the MARA activated the emergency mechanism to counter the ASF spread, by implementing a flurry of containment measures (see Table 1), including monitoring and reporting protocols, restrictions on cross-province pig transportations, suspension of slaughtering in affected areas, strict quarantine of infected farms/areas, elevated disinfections and safe disposal of culling of infected pigs [28,29]. On 13 September 2018, the Ministry of Finance (MOF) and MARA [30] jointly issued a notice on offering financial compensations to pig farmers in connection with mandatory culling. Initially, farmers received a compensation of CNY800 per culled pig, similar to the compensation scheme adopted during the foot and mouth disease outbreaks. Later, the compensation was increased to CNY1,200 per pig to ensure smoother implementation of the containment measures. According to official statistics, ASF outbreaks were down to 63 outbreaks, resulting in 390,000 culled pigs; in the first 8 months of 2021, there were only 11 minor outbreaks that led to 2200 pigs being culled, suggesting that the ASF outbreaks had been brought under control.

Table 1. Major government initiatives in containing the ASF outbreaks.

	Source	Document	Related Contents
10 August 2018	MARA	Notice on the prevention and control of ASF and strengthening the supervision of pig movement	Strengthen the risk management and control of the movement of pigs, strengthen the quarantine work on the origin and slaughter of pigs, strengthen the supervision and management of the slaughtering process of pigs, and strengthen the supervision and inspection of the circulation process.
31 August 2018	MARA	Notice on effectively strengthening the supervision of transporting pig and related products	Vehicles that transport all livestock and poultry, such as pigs, no longer enjoy the "green channel" policy for fresh agricultural products
13 September 2018	MOF and MARA	Notice on doing a good job in the Subsidy for the Compulsory Culling of ASF	Offering financial compensations to pig farmers in connections with involuntary culling. Initially, farmers received a compensation of CNY800 per culled pig, similar to the compensation scheme adopted during the foot and mouth disease outbreaks.

Sources: authors' compilation of publicly available government documents. See reference list. MARA: Ministry of Agricultural and Rural Affairs; MOF: Ministry of Finance.

4.2. Government Initiatives

Aside from the ASF containment measures, government agencies have been actively assisting in the recovery of the pig sector, having issued 19 major supporting measures that provide favorable conditions on land use, environmental impact assessment, and assess to credits to pig producers. These measures range from those initiated by MARA on directly assigning production targets to local governments, to joint initiatives from a number of ministries on supporting the expansion of farm infrastructure, provision of production bonuses and subsidies, favorable terms on land use, transportation, and finance, to specific measures supporting farms with scale operations (i.e., farms with at least 500 pigs). On 28 July 2021, the State Council decided to extend the supporting policies and prohibited the exercises of over-constraining environmental regulations. Furthermore, the State Council also announced a counter-cyclical mechanism to offer government assistance when production capacity drops below a certain threshold or when pig farmers suffer from large financial losses for three consecutive months.

China's rapid economic development has fueled rising demand for animal-sourced food products, which in turn placed considerable stress on the environment, not least due to soil and water pollutions [20,31]. This led to tightened environmental regulations on livestock and poultry production that have played a role in constraining the development of the sector. During the period of January 2014 to May 2018, a number of major policy documents, regulations, and guidelines concerning livestock and poultry regulations, and two environmental protection laws were issued (as summarized in Appendix A, Table A1). These regulations lay out specific rules on the prevention and management of pollutants from livestock and poultry production, specific zoning regulations on livestock and poultry farms and slaughtering facilities [32,33]. For instance, livestock operations already located within the non-production zones were required to be either closed or relocated by end of 2017 [34]. In administrative areas (e.g., counties) designated as the main pig production area, a production plan needs to be conceived and implemented so as to lay out both zones for pig production and zones where production is forbidden. In 2016, a technical guideline was issued to guide the planning of permitted and non-permitted zones [35]. In 2018, a new law introduced an environment protection tax on pig farms with scale operations. The introduction of these regulations, laws, and guidelines likely shrank China's pig herd, prior to the 2018 ASF outbreaks, as illustrated in Figure 1. In particular, the drive to be compliant with the new regulations led to significant cost hikes and exit of producers. Studies suggest that costs related to environmental protectioncan be as high as 40–50% of the total investment in setting up new pig production facilities [36,37]. The added costs were particularly onerous for smallholders, accelerating the exit of those producers with fewer than 50 pigs. During the period of 2007–2017, the number of pig producers with fewer than 50 pigs decreased from 80.1 million to 35.7 million (Figure 4). On aggregate, even though numbers of medium and large producers increased during the same period, nationwide production capacity still decreased.

To aid the recovery after the ASF outbreaks, several environmental regulations have been effectively relaxed. On 21 August 2019, the State Council abolished all local rules that are inconsistent with national laws and regulations regarding areas where pig farming is either prohibited or limited. In addition, the one-hectare limit placed on land used for constructing "auxiliary production facility" was also repealed. According to the Ministry of Ecology and Environment (MEE), from late 2019 to March 2020, the number of "no-pig" zones was reduced by 14,000. On 29 November 2019, the MEE and MARA [38] jointly decided to further relax the environmental assessment regulations on pig farms, allowing projects with less than 5000 pigs to skip the formal approval process; for larger projects with more than 5000 pigs, the approval processes will be further streamlined.

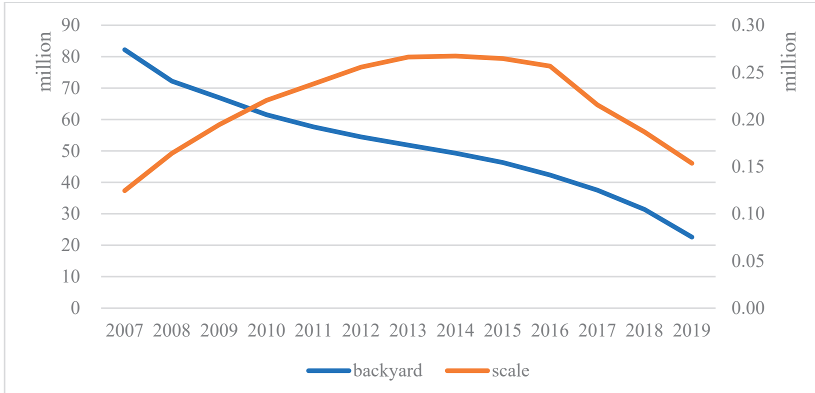

Figure 4. Numbers of pig farms with backyard operation (<50 pigs per farm) and scale operations (>50 pigs per farm). Source: China Animal Agricultural Year Books (various issues).

4.3. Investment and Structural Changes in China's Pig Sector

The persistently high prices during the ASF outbreak and the favorable credit, land use, and environmental policies attracted not only returning small producers but also large investors. On aggregate, the declining trend of small producers continues, resulting in rapid capacity recovery that is increasingly connected to rising production scales driven by large pig farms (Figure 4). In 2020, 57.1% of slaughtered pigs were from large farms with at least 500 pigs, as compared to 53% and 50.1% in 2019 and 2018, respectively [39].

These relatively large pig farms have played key roles in the recovery process. For instance, the top 9 corporate producers (including Muyan, Zhengbang, Wen's, New Hope Liuhe) delivered 10.3% of all slaughtered pigs in 2020, rising sharply from the share of 8.2% in 2019 and 6.9% in 2018. One of the driving forces behind the rapid expansion of the large farms is their ability to bear the costs related to the hygiene and biosecurity requirements in connection with ASF containment. In connection with their large operation scales, modern technologies adopted by large producers, such as better facilities and equipment, and farm management practices, allow these producers to be more productive. Access to credits and favorable land use and environmental assessment terms have also helped rapid recovery and expansions of sow and pig herds. Furthermore, some of the leading producers, such as Wen's, Muyuan, Aonong, and Tianbang, have invested in large vertical multi-storey breeding facilities to aid the expansion of their production scale. For example, a new pig facility by Muyuan can house 84,000 sows and produce 2.1 million pigs a year [40]. Last but not the least, these very large producers are increasingly engaged in operations that integrate sow breeding, pig production, feed production, and slaughtering. As shown in Appendix A Table A2, the top 9 largest producers in the country have all expanded their pig production during the 2016–2020 period and fully recovered any production losses suffered in 2019.

4.4. Aftermath of the Rapid Recovery

The rapid recovery of the domestic pig industry has greatly increased domestic pork supply, allowing consumers to resume their normal consumption levels at prices that are comparable to the pre-ASF levels (Figures 1 and 2). The fact that domestic market prices have dropped so quickly, however, also implies that producers may suffer from losses. Indeed, recent financial and news reports have suggested that many producers, including some of the largest corporate producers, incurred substantial losses in the third quarter of 2021. For some of the top producers, losses in the third quarter have negated the large profits realized in the first half of the year [41]. As market prices dipped below the average production costs, economic losses spread to the whole sector. In the fourth quarter of 2021, prices have somewhat rebounded; however, it is unlikely that the demand and supply balance will tip into producers' favor anytime soon, given the peaking production capacity [42]. Therefore, the very success of the rapid recovery in fact reveals further vulnerability in China's pig industry that lies in the high production costs. While some producers may be able to withstand the near-term financial losses, others may have to exit the market. It is unclear how policy makers in China will deal with this new situation. Early indications suggest that they may continue to offer incentives for producers so that they do not exit amass to endanger the hard-fought recovery. Another wild card is whether the seemingly successful control of the ASF can be sustained so that larger outbreaks would not flare up again to cause another round of disturbance.

The rapid rise in Chinese imports of pork during the 2016–2020 period has made China the dominant customer on the world pork market, with imports reaching the levels of 4.3 million tons in 2020 and 2.9 million tons in the first 8 months of 2021. Several leading pork exporters, such as Spain, USA, Brazil, Denmark, Netherlands, and Canada, have all increased their exports during this period and benefited from the favorable prices there. The recent recovery of domestic pig production and pork outputs and falling domestic market price in China suggest that this trend is unlikely to continue in the short term. Looking ahead, further development of China's pig industry will continue to be an important part of China's drive to achieve its long-term goal of food and nutritional security, as indicated by the newly declared 95% pork self-sufficiency goal.

Realizing that this goal would still suggest nearly 3 million tons of imports annually, assuming that China's total consumption remains within the recent range of 54–58 million tons per year. Further increase in demand in China in the coming years may push imports to even higher level. Thus, in the longer-term, China would remain the most important export destination.

5. Supply-Side Measures and Future Scenarios: A Quantitative Assessment

5.1. Possible Supply-Side Measures in China's Feed Grain/Oilseeds and Pig Sectors

Feed costs and the availability of imported feed are fundamental determinants of the scale of pig production in China. The current literature suggests a large gap between actual and potential soybean and maize yields in China, pointing to the possibility of reducing feed import dependency. For instance, Liu et al. [43] analyze detailed county-level data and find that the average soybean yield in China is about 2 t/ha (ton/hectare), while the attainable yield is 2.98 t/ha. Similarly, the actual and attainable yields for maize are, respectively, 6.4 and 9.4 t/ha. Eliminating these yield gaps can, therefore, lead to very large output gains. In the same study, the authors also assess the economic and environmental benefits of reduced fertilizer uses per unit of outputs through integrated soil-crop system management. Regarding feed conversion ratios, the feed industry and government authorities have endorsed expert recommendations on reducing the protein contents of pig feed from the prevailing 16% to 14% so as to achieve reductions in the use and imports of feed grains and oilseeds, without affecting pig production (www.gov.cn/xinwen/2018-08/31/content_5317931.htm accessed on 16 January 2022.). The literature also suggests that as a whole, China's pig sector still lags behind in terms of technical efficiency, despite the rising share of pig production from large modern pig farms in recent years. For example, Xu et al. [18] find that China's pig farms have an average technical efficiency of 0.6 (with 1 being the efficiency frontier); thus, there are large potential efficiency improvements to be realized.

5.2. Modeling Future Supply Scenarios

Based on the literature, we construct a set of counterfactual scenarios and conduct model simulations with the GTAP model to illustrate the potential impacts of adopting these supply side measures on China's pork markets. In the first scenario named FO (for "feed optimization"), an efficiency improvement is assumed to allow a per unit reduction in the feed used in the pig and poultry sector to track the two percentage point reduction in the protein contents of feed. This involves mainly feed derived from soybean and maize, as well as other grains and crop products. In the second scenario named AY (for "attainable yields"), we assume land productivities in soybean and maize production to rise from the base case so as to eliminate the gaps between the actual and attainable yield levels, as reported by Liu et al. [43]. In the third scenario (short-named "AY_FR", for "attainable yields" and "fertilizer reduction"), in addition to the yield shocks to soybean and maize (as in scenario AY), fertilizer use in soybean and maize are reduced, also according to Liu et al. [43]. In the fourth scenario, AY_FR_FO, we combine the shocks contained in both scenarios AY_FR and FO. Lastly, in the fifth scenario named AY_FR_FO_TE, in addition to the shocks contained in scenario AY_FR_FO, we introduce a total productivity shock in the pork sector so as to halve the observed efficiency gaps reported in Xu et al. [18]. We summarize the five scenarios in Table 2. In the standard GTAP model, land allocation is governed by a constant elasticity of the transformation frontier, with the elasticity of transformation set at 1. In these simulations, we set this elasticity to 0.01, to minimize the shifts in sectoral land use so as to mimic the yield gains on the existing crop patterns according to Liu et al. [43].

Table 2. Scenario design: changes in the relevant variables in China, % from base case.

	FO	AY	AY_FR	AY_FR_FO	AY_FR_FO_TE
Technical efficiency in feed use by the poultry and pig sector	12.5	0	0	12.5	12.5
Land productivity in soy production	0	47.4	47.4	47.4	47.4
Land productivity in maize production	0	49.1	49.1	49.1	49.1
Fertilizer use per unit of soy produced	0	0	0	16.2	16.2
Fertilizer use per unit of maize produced	0	0	0	15.7	15.7
Aggregate technical efficiency in poultry and pig sector	0	0	0	0	33.3

Note: FO refers to the feed optimization; AY: attainable yields; AY_FR: attainable yields and fertilizer reduction; AY_FR_FO: attainable yields, fertilizer reduction, fertilizer reduction, and feed optimization; AY_FR_FO_TE: attainable yields, fertilizer reduction, fertilizer reduction, feed optimization, and technical efficiency improvement. Source: own interpretation of results from the literature.

The five scenarios are each formulated as a set of exogenous shocks to the GTAP model, using an aggregated version of the most recent GTAP 10 database as the base case [44]. The aggregated database consists of 12 countries/regions (including China and its main feed grain/oilseeds and pork suppliers, such as Brazil, USA, Canada, Germany, Spain, Denmark, Netherlands, as well as several aggregated regions) and 32 sectors (including all the agricultural and food sectors listed in the disaggregated GTAP database, as well as several more aggregated manufacturing and services sectors).

5.3. Simulation Results

The main simulation results from the five scenarios, expressed as percentage changes from the same base case, are reported in Table 3. The fact that all five scenarios are simulated from the same base makes it possible to conduct cross-scenario comparisons of the magnitudes of the results. Such comparisons also allow for understanding the individual effect due to each of the supply side measures. For example, while the individual effects of FO or AY are directly reported in the FO and AY scenario, the effects of FR are approximately the difference between the results obtained from the scenarios AY_FR and

AY. By including more than one supply measure in the last three scenarios, the combined effects of these supply measures can also be revealed.

Table 3. Simulation results: changes in domestic outputs and market prices, and total imports in China (% from base).

		FO	AY	AY_FR	AY_FR_FO	AY_FR_FO_TE
Domestic outputs	oilseeds (soybean)	−0.48	14.48	15.91	15.23	14.35
	coarse grains (maize)	−1.09	2.63	2.88	1.68	0.39
	pork and poultry	1.38	0.47	0.52	1.86	26.50
Domestic market prices	oilseeds (soybean)	−0.46	−16.68	−18.05	−18.23	−18.23
	coarse grains (maize)	−1.10	−19.57	−21.25	−21.51	−21.52
	pork and poultry	−2.13	−0.51	−0.55	−2.59	−22.74
Total imports	oilseeds (soybean)	−0.41	−9.34	−10.15	−10.39	−10.24
	coarse grains (maize)	−1.78	−15.23	−16.53	−17.43	−18.05
	pork and poultry	−6.84	−1.33	−1.41	−7.90	−53.39

Note: FO refers to the feed optimization; AY: attainable yields; AY_FR: attainable yields and fertilizer reduction; AY_FR_FO: attainable yields, fertilizer reduction, fertilizer reduction, and feed optimization; AY_FR_FO_TE: attainable yields, fertilizer reduction, fertilizer reduction, feed optimization, and technical efficiency improvement. Source: own simulation results.

In the FO scenario (column FO in Table 2), the simulation results suggest that reduced feed demand, due to feed optimization, leads to lowered domestic production of soybean and maize in China (by 0.5% and 1%, relative to the base case) and increased pork production by nearly 1.4%. At the same time, China's total imports of soybean, maize and pork all decrease. As pork imports into China have a very small share in China's total pork supply, the 1.4% rise in China's domestic production leads to a disproportionately larger drop in imports (by nearly 7%). In the AY scenario, eliminating the gaps between actual and attainable yields of soybean and maize boosts soybean and maize production, particularly for soybean. The much larger increase in soybean outputs (14.5%) as compared to maize (2.6%) is due to the relatively larger yield gap in soybean (hence, larger productivity improvement in the scenario) and the inter-crop relocations of resources towards soybean production. Rising outputs of soybean and maize also help the pork output to expand, although by a much small amount (about 0.5%), due to the dominant share of imported feed used in pig production. Lowered soybean and maize prices in China (by 16.7% and 19.6%, respectively) and increased domestic outputs help limit soybean and maize imports (by 9.3% and 15.2%, respectively), thereby reducing China's feed import dependency. When combined with reductions in per unit fertilizer use (as in the AY_FR scenario), domestic outputs increase more compared to the AY scenario alone. Consequently, domestic market prices and imports drop more.

In the AY_FR_FO scenario, slightly smaller increases in the soybean and maize outputs are reported, as compared to the AY_FR scenario. However, increased domestic supply and more efficient use of feed result in larger increases in pork outputs (1.9%) and larger reductions in pork imports (by 7.9%). These results suggest that eliminating soybean and maize yield gaps and improving feed efficiency can achieve the duel objective of reducing feed and pork imports. In the AY_FR_FO_TE scenario, in addition to the other supply-side measures, technical inefficiency is halved in the pig and poultry sector. Simulation results from this scenario point to slightly smaller soybean and maize outputs (14.4% and 0.4%, respectively) as compared to the AY_FR_FO scenario; however, pork outputs increase by 26.5%, mainly due to the assumed efficiency improvement in pig production. This results in large drop of pork price in China and leads to 53.4% reduction in pork imports.

In summary, the simulation results illustrate the role of several key supply-side measures in tackling China's over-reliance on imported feed (particularly soybean) and in meeting its pork self-sufficiency goal. In particular, efforts to minimize the yield gaps in soybean and maize can directly reduce China's massive feed imports, which can also reduce the environmental pressure associated with deforestation in South America. However, this measure alone is not enough to abate China's massive appetite for pork imports. In contrast, without increasing feed imports, optimizing feed use can improve domestic pork outputs and reduce pork imports, but only to a quite limited extent. Improving the overall technical efficiency in the pork sector appears to be a more effective measure that can raise China's pork outputs and reduce its imports substantially.

6. Conclusions and Discussions

As the world's largest producer and consumer of pork, China has recently experienced a major hog cycle. This cycle can be traced to the gradual decline of sow and pig herds from 2013 that was accelerated by the ASF outbreaks in 2018, resulting in a drastic downturn that more than halved the country's sow and pig herds from the norm levels in late 2019. To make up for the domestic shortage of pork supply, China imported record high levels of pork; however, this proved to be insufficient to dampen the soaring domestic market prices. Ultimately, pork consumption contracted significantly, as expenditure on pork consumption is a major item on Chinese consumers' food budget. After China's pig production sharply declined in late 2019, a rapid rebound ensued, leading to a complete recovery in less than two years.

In this paper, we document both the effects of the ASF outbreak and the factors that have led to the rapid recovery of domestic production capacity and outputs in China. Through a description analysis of production, consumption and trade statistics, it appears that the downturn in China's pig production capacity (in terms of sow and pig herds) and outputs (in terms of slaughtered pigs) had already happened well before the ASF outbreaks and the pressure to imports had been built up ever since. This observation, which has not been sufficiently recognized in the literature, illustrates the important structural deficiencies in China's pig sector that need to be rectified. Recent data also suggest that China launched a strong response to the ASF outbreaks that paved the way for a rapid recovery in pig production and receding domestic market prices. This recovery has exceeded the expectations reflected in the recent literature (for example that of Ma et al. [11]). The underlying drivers of the strong recovery include rapid and strict reactions to the ASF outbreaks, a multiple-prong government initiative towards supporting the pig producers, de facto relaxations of some of the recently introduced environmental regulations, large increases in domestic investment, and a reorganization of the pig sector featuring more scale operations. All these measures contributed to supporting the fundamental determinants of sow and pig production, such as sow herds, capital, land, and labor. Additionally, the structural changes promoted by government authorities that favor large and more efficient producers appear to have helped in raising the sector's efficiency.

The V-shaped rebound from the depth of the ASF outbreaks has also resulted in some serious undesirable consequences, such as widespread economic losses in the pig sector in the second half of 2021, prompting discussions on exit strategies from the pig sector. Major pork exporters to the Chinese market are also facing uncertain future export opportunities in the coming period, due to lower market prices and weaker demand. This finding has so far not been discussed in the current literature, to the best of our knowledge. It also calls into question the long-term sustainability of China's recently declared 95% pork self-sufficiency goal, considering the country's high dependencies on imported feed grains and oilseeds, inefficient feed use, and overall lack of technical efficiency in pork production.

The second contribution of the current study is, therefore, based on an exploratory model-based numerical simulation analysis that investigates the potential impacts of a set of supply side measures. This numerical analysis addresses some of the long-term sustainability issues, such as dependency on imported feed, domestic feed yield gaps, feed conversion efficiency, and technical efficiency in pig production, as identified in the literature but have not quantified through a formal economic model [12,13,17,18,43,45,46]. The results from our analysis suggest that yield improvement can substantially reduce the reliance on imported feed but it can only increase domestic pork production marginally, while technical efficiency improvement in pork production has the largest potential in boosting domestic pork production, followed by feed optimization. These results connect to several studies in the literature and provide some additional insights. For instance, our results on the increased domestic soybean and maize production due to yield improvement are smaller than those obtained by Liu et al. that are based on the same yield assumption [43]. This is due to the fact that our model considers world market linkages and domestic price effects (i.e., rising domestic outputs tend to elicit lower domestic market price, thus limiting expansion of domestic production; similarly, the presence of cheaper soybean and maize on the world market also limits the extent of output expansion in China). The result concerning the importance of efficiency improvement in pig production echoes the findings from Zhang et al. [12]. Finally, the projected feed and pork imports under various configurations of assumptions enriches the results obtained in earlier studies that rely on demand side drivers only [17].

Our findings have direct policy implications for the sustainable development of China's pig sector. *First*, given the apparent domestic resource constraints to meet the rising animal food demand in China and the political preference for maintaining domestic self-sufficiency targets for both pork and feed, our results clearly point to the need to actively resort to supply-side measures to boost productivities in not only the pig sector but also the feed sector. The investments needed for implementing such supply-side measures can be substantial and the commitments are likely to be long-term for such measures to take effect. *Second*, while short-term support from government authorities appears to have worked well in restoring production capacity, the policy initiatives do not appear to have sufficiently addressed the structural issues identified in this work and in earlier studies. For instance, direct financial and other assistances, while tackling the immediate market shortage successfully, appeared to amplify and prolong the cyclic movements of market supply and market prices. This again points to reconsiderations in future policy design that should favor measures that address long-term supply constraints and structural limitations, rather than focusing on short-term fixes. *Last* but not the least, the role of imports in supplementing domestic production should not be ignored. To this end, the recently declared 95% pork self-sufficiency target appears to be a pragmatic choice that does allow for sizable imports from other major pig producing countries. Maintaining a stable import regime and allowing imports to compete with domestic production on equal footing will provide an important "stabilizer" for the domestic pork market.

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Appendix A

Table A1. China's environmental laws and regulations.

Time	Issued By	Regulations	Specific Clauses on Livestock Production
1 January 2014	State Council [32]	Regulations on Prevention and Control of Pollution by Scaled Livestock and Poultry Breeding Industry	China's first regulatory document specifically aimed at the prevention and control of pollution for livestock and poultry breeding. Clarified the division criteria of prohibited areas, applicable objects (livestock and poultry farms, breeding communities), incentives and punishments.
1 January 2015	State Council [33]	Environmental Protection Law	Clarified the site selection, construction and management of livestock and poultry farms, breeding communities, and designated slaughtering enterprises should comply with relevant laws and regulations.
April 2015	State Council [34]	Water Pollution Prevention and Control Action Plan	Scientifically delineates the prohibited areas for livestock and poultry breeding. Before the end of 2017, closed or relocated livestock and poultry farms (communities) and specialized breeding households in the prohibited areas according to law, and the Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta and other areas will be completed one year ahead of schedule.
August 2015	Ministry of Agriculture and Rural Affairs (MARA) [47]	Notice on Cooperating with the Delimitation of Prohibited Areas for Livestock and Poultry Breeding	Requires that the animal husbandry and veterinary administrative departments at all levels actively cooperate with the environmental protection department to do a good job in the delimitation of prohibited areas, and report the delimitation of prohibited areas in time.
November 2015	MARA [48]	Guiding Opinions on Promoting the Adjustment and Optimization of the Distribution of Pig Breeding in the Southern Water Network Area	Main producing counties should formulate a pig breeding plan. Local government closes or relocates large-scale pig farms according to law, and guides the transfer of pig breeding to non-overloaded areas.
May 2016	State Council [49]	Soil Ten Articles	Clearly and reasonably determine the layout and scale of livestock breeding, and strengthen the prevention and control of livestock breeding pollution.

Table A1. *Cont.*

Time	Issued By	Regulations	Specific Clauses on Livestock Production
November 2016	Ministry of Ecology and Environment (MEE) and MARA [35]	Technical Guidelines for Delimitation of Prohibited Areas for Livestock and Poultry Breeding	Basis for delineating prohibited areas throughout the country in the later period. Local environmental protection, agriculture and animal husbandry departments should follow the unified deployment of the local government, actively cooperate with relevant departments, and assist in the closure or relocation of existing farms that really need to be closed or relocated in the prohibited breeding area.
December 2016	State Council [50]	The 13th Five-year Ecological and Environmental Protection Planning	Before the end of 2017, all regions are required to close or relocate livestock and poultry farms (communities) and professional breeding households in prohibited areas according to law.
1 January 2018	State Council [51]	Environmental Protection Tax Law	An environmental tax will be levied on farmers with a herd of more than 500 pigs.
May 2018	MARA and MEE [52]	Implementation Plan for the Assessment of Resource Utilization of Livestock and Poultry Breeding Waste in 2017	The environmental governance of livestock and poultry breeding was included in the performance assessment of local governments, which further increased the intensity of environmental supervision.

Sources: authors' compilation. See reference list.

Table A2. Slaughtered pigs of large producers: 2016–2020 (million heads).

Corporate Producer	2016	2017	2018	2019	2020
Muyuan	3.11	7.24	11.01	10.25	18.12
Zhengbang	2.27	3.42	5.54	5.78	9.56
Wen's	6.60	19.04	22.29	18.52	9.55
New Hope Liuhe	1.17	2.40	2.55	3.55	8.29
Tianbang	0.58	1.01	2.17	2.45	3.08
COFCO	1.71	2.23	2.55	1.99	2.10
Aonong	0.11	0.22	0.42	0.40	1.35
Trs Group	0.14	0.54	0.68	0.84	1.02
Haid Group	0.32	0.46	0.70	0.74	0.98
Total	16.01	36.56	47.91	44.52	54.04

Sources: authors' compilation from various public data sets.

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foods

Article

Security Risk Level Prediction of Carbofuran Pesticide Residues in Chinese Vegetables Based on Deep Learning

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Abstract: The supervision of security risk level of carbofuran pesticide residues can guarantee the food quality and security of residents effectively. In order to predict the potential key risk vegetables and regions, this paper constructs a security risk assessment model, combined with the k-means++ algorithm, to establish the risk security level. Then the evaluation index value of the security risk model is predicted to determine the security risk level based on the deep learning model. The model consists of a convolutional neural network (CNN) and a long short-term memory network (LSTM) optimized by an arithmetic optimization algorithm (AOA), namely, CNN-AOA-LSTM. In this paper, a comparative experiment is conducted on a small sample data set of independently constructed security risk assessment indicators. Experimental results show that the accuracy of the CNN-AOA-LSTM prediction model based on attention mechanism is 6.12% to 18.99% higher than several commonly used deep neural network models (gated recurrent unit, LSTM, and recurrent neural networks). The prediction model proposed in this paper provides scientific reference to establish the priority order of supervision, and provides forward-looking supervision for the government.

Keywords: security risk assessment; carbofuran; vegetables; security risk level prediction; deep learning

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1. Introduction

With the improvement of people's living standards, consumers pay more and more attention to the quality and security of food. As an indispensable food in people's diet, the quality and security of vegetables is directly related to human health, and the security risk level of dietary intake of pesticide residues is an important performance to measure the quality and security of vegetables. As a common pesticide, carbofuran is a broad-spectrum, efficient, low residue, high toxicity insecticide, acaricide, and nematocide. It is easy to use, labor-saving, cheap, and can be applied to cotton, rice, sugar cane, peanut, corn, sugar beet and another 80 crops for pest control. However, its toxicity is high, and acute exposure can inhibit the cholinesterase activity in the body, leading to tears, vomiting, salivation, pupil narrowing, spasm, and serious cases of blood pressure drop or unconsciousness, but also has reproductive toxicity, developmental toxicity, gene toxicity, neurotoxicity and so on [1]. In addition, studies have shown that carbofuran has the effect of environmental hormones [2], which can act on the nucleus and cause genetic variation [3]. In April 2002, the Ministry of Agriculture of China proposed to stop accepting new registration of carbofuran, stop approving sub-packaging registration of highly toxic pesticides, and cancel the registration of carbofuran on citrus trees. In June 2002, the Ministry of Agriculture also announced that carbofuran should not be used or only have restricted use in vegetables, fruit trees, tea leaves and Chinese herbal medicines. However, due to its high efficiency and low cost, there are still reports of excessive levels of carbofuran in vegetables and fruits in many provinces [4–6].

Frequent food security incidents and increasingly stringent food security regulations in international trade have put forward higher requirements for food quality and security supervision [7]. Through food security risk assessment and early warning analysis, on the one hand, it can provide data support and supervision basis for market regulation, and on the other hand, it can provide reference for consumers to buy vegetables.

He et al. [8] measured the residues of 37 pesticides in Xinjiang jujube, assessed the risk of chronic dietary intake and acute dietary intake, and used the risk matrix to rank the risk of pesticide residue. Zhao et al. [9] studied the influence of cooking styles in southern China on the actual intake and long-term exposure risk of pesticide residues in vegetables, and analyzed the harm level of pesticide residues in four cooking styles to the human body. Fang et al. [10] evaluated the ingestion risk of pesticide residue in celery diet in China, and ranked the ingestion risk of each tested pesticide according to a pre-defined ranking matrix. D. et al. [11] evaluated the health risks of pesticide residues in fruits and vegetables in farms and markets in the West Indian Himalayas. Based on the prediction of chronic health hazards from estimated daily intake, organophosphorus were found to pose a health threat to children in the study area. Most of the existing literature has evaluated and graded individual vegetables or fruits, and most of the studies were conducted in different regions. There is little research about comprehensive security risk assessment and grading of pesticide residues in various vegetables in many provinces in China.

In risk prediction, deep learning methods such as long short-term memory network (LSTM), gated recurrent unit (GRU) and recurrent neural networks (RNN) can capture high-dimensional features and show temporal dynamic behavior appropriately [12]. These methods have been used in weather forecast or travel time prediction, achieving higher accuracy prediction [13,14]. Time series analysis can analyze the historical data of dynamic systems and predict the future operation mode [15]; therefore, this feature also meets the requirements of food security risk prediction. Yu et al. [16] used the autoregressive integrated moving average model (ARIMA) to predict pesticide residues in two vegetables in different seasons in Sichuan, China. Xin et al. [17] predicted the heavy metal content in lettuce leaves by deep learning combined with hyperspectral imaging technology.

This paper establishes a deep learning-based prediction model of security risk level of carbofuran pesticide residue in Chinese vegetables by analyzing 200,000 measurements of national monitoring sampling data of carbofuran pesticide residue contamination in vegetables in 2019. Firstly, the food security risk evaluation model is constructed. Based on the national sampling data of carbofuran in vegetables in 2019 and the weekly consumption data of vegetables in each province, the weekly index value of the evaluation model of each vegetable in each province is calculated. Then, the national sampling data are clustered by the k-means++ algorithm [18] to classify the security risk level based on the indexes calculated. Finally, based on the deep learning model, the historical data are used to predict the security risk evaluation indexes of vegetables in each province, and the distance between the predicted security risk evaluation indexes and the security risk level clustering center is measured to determine the security risk level. The model proposed in this paper quantifies the sampling data into security risk levels and predicts the evaluation indexes, which provides a scientific reference for establishing the priority of supervision and provides a forward-looking basis for government supervision.

2. Materials and Methods

2.1. Materials

2.1.1. Data Sources

The data in this study comes from the national food security sampling data in 2019, covering 20 provinces. The vegetables are divided into eight categories, including legumes vegetables, leafy vegetables, solanaceous vegetables, bulb vegetables, melon vegetables, roots and potato vegetables (except potatoes), brassica vegetables and potatoes, with a total of 13,222 samples. According to the maximum residue limit for pesticide from the Food of National Food Security Standard, the content of carbofuran is determined. China's national food security standards set the limit of carbofuran in legumes vegetables, leafy vegetables, solanaceous vegetables, bulb vegetables, melon vegetables, roots and potato vegetables (except potatoes), brassica vegetables and other vegetables as 0.02 mg/kg, and the limit of carbofuran for potatoes is 0.1 mg/kg, higher than the limit of other vegetables.

The vegetable data of residents' consumption comes from the fifth Total Diet Study [19]. This survey adopts stratified and multi-stage cluster random sampling method proportional to the population to carry out a dietary questionnaire survey on the main food consumption of residents in 20 provinces of China.

2.1.2. Data Preprocessing

According to the principle of Credible Assessment of Low-level Contaminants in Food, proposed at the second meeting of WHO Global Environmental Monitoring System/Food Contamination Monitoring and Assessment Programme (GEMS/FOOD), when the proportion of undetected data is less than 60%, all undetected data are replaced by 1/2 of the detection limit (LOD), and when the proportion of undetected data is higher than 60%, all undetected data are replaced by LOD [20]. As the undetected data of carbofuran in this study is far less than 60%, 1/2 LOD value is assigned to all undetected data in this study for statistical calculation.

2.2. Security Risk Assessment Model

According to the security risk assessment method and the purpose of setting the model, based on the main influencing factors of health risks caused by food contaminants, the Nemerow integrated pollution index (NIPI), the acute exposure assessment (AEA), and the chronic dietary exposure assessment (CDEA) are used as the three indexes of the security risk assessment model. The median (P50) and 97.5 quantile (P97.5) of carbofuran in vegetables are used to calculate the exposure of carbofuran at different pollution levels.

2.2.1. Nemerow Integrated Pollution Index

The Nemerow integrated pollution index can reflect the characteristics of food pollution, and it is used to evaluate the pollution of air [21], heavy metals in soil [22,23], rice [24] and vegetables [25–27] by researchers. In this paper, the Nemerow integrated pollution index is used to calculate the pollution degree of carbofuran from sampling samples based on sampling data of each province, and the expression is as follows:

$$P_{i,j} = \frac{X_{i,j}}{S_j} \tag{1}$$

where, $P_{i,j}$ is the pollution index of vegetable j in province i; $X_{i,j}$ is the detected value (mg/kg) of carbofuranin vegetable j in province i; and S_j is the national limit standard of carbofuran in vegetable j (mg/kg).

$$P_{c(i.j)} = \sqrt{\frac{P^2_{\max(i,j)} + P^2_{ave(i,j)}}{2}} \tag{2}$$

where, $P_{c(i,j)}$ is the Nemerow integrated pollution index of vegetable j in province i; $P_{\max(i,j)}$ is the maximum pollution index of vegetable j in province i; and $P_{ave(i,j)}$ is the mean value of pollution index of vegetable j in province i.

2.2.2. Acute Exposure Assessment

Acute exposure assessment of food is widely used as an index of the acute impact of agricultural and veterinary drug residues [28–30] and microorganisms on human health. This index is to evaluate the exposure amount of a certain substance consumed by diet within 24 h. In this paper, the point assessment method is used to calculate acute exposure assessment. The expression is as follows:

$$EDI_{97.5(i,j)} = \frac{F_{97.5(i,j)} \times C_{\max(i,j)}}{W} \tag{3}$$

where $EDI_{97.5(i,j)}$ is the 97.5 percentile of daily intake of carbofuran from vegetable j per kilogram of body weight in province i (mg/kg bw), $F_{97.5(i,j)}$ is the 97.5 percentile (P97.5) of consumption of vegetable j in province i (kg/d), $C_{\max(i,j)}$ is the maximum detected value of carbofuran of vegetable j in province i (mg/kg), and W is the average body weight of residents (60 kg).

2.2.3. Chronic Dietary Exposure Assessment

The chronic dietary exposure assessment represents the risk of chronic dietary intake of carbofuran based on the average daily intake of carbofuran per kilogram of body weight in the population. The expression is as follows:

$$EDI_{50(i,j)} = \sum_{j'}^{j} \frac{F_{i,j'} \times C_{i,j'}}{W} \tag{4}$$

where $EDI_{50(i,j)}$ is the average daily intake of carbofuran from vegetable j per kg of body weight in province i (mg/kg bw), $F_{i,j'}$ is the average consumption of fine vegetable j' in province i (kg/d), $C_{i,j'}$ is the average content of carbofuran in fine vegetable j' in province i (mg/kg), and W is the average body mass of residents (60 kg).

2.3. Security Risk Classification Based on K-Means++

The security risk assessment model of carbofuran in vegetables is established by integrating the Nemerow integrated pollution index, the acute exposure assessment, and the chronic dietary exposure assessment. Based on the security risk assessment model, food security risks are classified. In this paper, clustering algorithm is used to select the optimal security risk level division to reduce the influence of subjective factors. Cluster algorithm is a process of dividing a given sample into multiple clusters to mine the deep information of data. Its goal is to make the samples in the same cluster have high similarity, and the samples in different clusters have low similarity. The k-means++ algorithm has good selection of initial sample points, good support for high-dimensional data, and can achieve good clustering performance in the arbitrary shape of sample space, which is suitable for analyzing model data of this study.

The advantage of k-means++ is that there is no need to artificially determine the initial clustering centers. The basic idea of selecting initial seeds in this algorithm is that the distance between the initial clustering centers should be as far as possible, and the specific process is as follows:

(1) Select a point randomly from the set of input data points as the first clustering center.
(2) For each point x in the data set, calculate the distance D(x) between it and the nearest cluster center (referring to the existing cluster center).
(3) A new data point is selected as the new clustering center, and the selection principle is as follows: the point with larger D(x) has a higher probability of being selected as the clustering center.
(4) Repeat (2) and (3) until k cluster centers are selected.
(5) The k initial clustering centers are used to run the standard k-means algorithm.

2.4. CNN-AOA-LSTM Security Risk Level Prediction Model Based on Attention Mechanism

2.4.1. Framework of CNN-AOA-LSTM Model

This paper proposes a CNN-AOA-LSTM security risk level prediction model based on attention mechanism [31], as shown in Figure 1. Security risk assessment indexes for each vegetable in each province are predicted, which are used to calculate the security risk level. The model is divided into five layers: data layer, CNN layer, attention mechanism layer, AOA-LSTM layer, and prediction security risk level layer. The structure of the neural network model is shown in Figure 2.

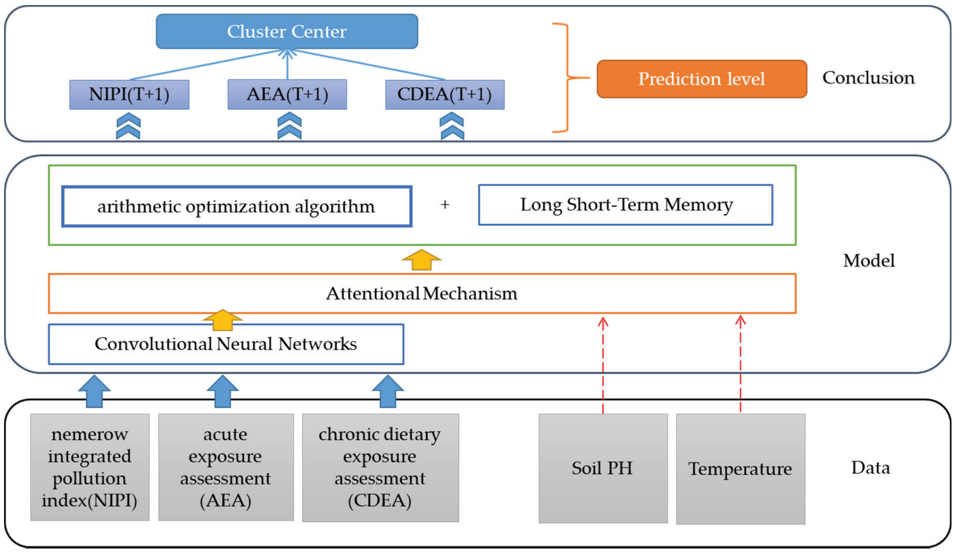

Figure 1. CNN-AOA-LSTM food security risk level prediction model based on the attention mechanism.

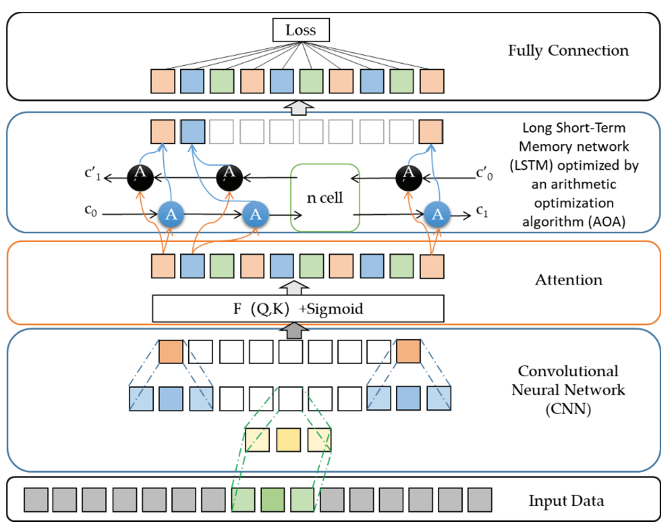

Figure 2. The structure of the neural network model.

Firstly, CNN is used to extract the features of historical food security risk assessment index data. The convolutional layer expands the depth, the pooling layer reduces the number of parameters by dimensionality reduction, and the fully connected layer transforms the features into one-dimensional vectors to complete feature extraction.

Secondly, this paper introduces the attention mechanism to allocate the probability weight to enhance the proportion of useful information. Due to the drug properties of carbofuran, the PH of soil has a certain influence on its absorption and decomposition. On the other hand, Deutsch et al. [32] has shown that higher temperatures produce more crop-eating pests. Hence, vegetable farmers often spray more pesticides, especially in the summer. Moreover, the interval between spraying time and harvest time is not fixed. If the degradation of pesticides is not enough, the levels of pesticide residues will be higher. Therefore, this paper introduces Chinese soil PH value and the air temperature as input of attention layer.

Thirdly, since this paper is a small sample data set, the selection of hyperparameters is particularly important. The feature matrix introducing attention is input into the AOA-LSTM neural network to learn the change rule of security risk assessment index data to predict future security risk assessment indexes, and the LSTM hyperparameter selection is optimized through AOA [33], so as to improve the prediction accuracy.

L. et al. [33] proposed that model optimization was carried out by using the definition of the four operators of addition, subtraction, multiplication and division in mathematics. The error of LSTM network is a fitness function, and the role of AOA is to find a group of optimal hyperparameters to minimize the network error. In the algorithmic exploration phase, multiplication strategy and division strategy are used for global search, which can improve the dispersion of solutions, enhance the global search and overcome premature convergence, and realize global search. In the algorithm development phase, the addition and subtraction strategies are used to reduce the dispersion of the solutions, which is conducive to the full development of the population in the local range and strengthen the local optimization ability of the algorithm.

Finally, the predicted security risk assessment indexes are output by the output layer, which are used to measure the nearest distance between the comprehensive assessment indexes and the cluster centers, and to classify security risk levels.

2.4.2. Attention Mechanism Based on PH of Soil and Temperature

China has a large amount of land, and the PH value of land in different regions varies greatly [34]. Moreover, the PH of the same mineral soil also changes slightly over time [35], and the reason is that the PH decreases during growing season of the crop as a result of acid production by microorganisms and higher plant roots. In addition, it has slight influence on soil PH by some conditions, such as rising and falling soil moisture, which causes salt to move in and out of the soil layer, affecting soil PH; therefore, rainfall can affect the PH of soil. Xie et al. [35] has concluded that the disappearance rate of Carbofuran is positively correlated with the PH of soil.

In addition, Deutsch et al. [32] has found that as temperatures rise, almost all insects speed up their reproduction and metabolism, with disastrous consequences for the world's food supply.

The national meteorological data of each province in 2019 can be obtained from the China Meteorological Science Data Sharing Service network, including temperature and rainfall.

According to Chinese soil PH distribution, rainfall and expert consultation, soil PH $p_m^{i,j}$ on day j of the week i for each province is added into the matrix P_m, where m is one of the 20 provinces mentioned above, i is week i, and j is day j of week i ($j = 0, 1, \ldots, 6$). The annual soil PH distribution matrix is obtained in Formula (5). Each value in the matrix is set to reciprocal and normalization, and we get $\widetilde{P_m}$.

$$P_m = \begin{bmatrix} p_m^{0,0}, \ldots, p_m^{0,j}, \ldots, p_m^{0,6} \\ \vdots \\ p_m^{i,0}, \ldots, p_m^{i,j}, \ldots, p_m^{i,6} \\ \vdots \\ p_m^{53,0}, \ldots, p_m^{53,j}, \ldots, p_m^{53,6} \end{bmatrix} \quad (5)$$

$$\widetilde{P_m} = \begin{bmatrix} \widetilde{p_m^{0,0}}, \ldots, \widetilde{p_m^{0,j}}, \ldots, \widetilde{p_m^{0,6}} \\ \vdots \\ \widetilde{p_m^{i,0}}, \ldots, \widetilde{p_m^{i,j}}, \ldots, \widetilde{p_m^{i,6}} \\ \vdots \\ \vdots \widetilde{p_m^{53,0}}, \ldots, \widetilde{p_m^{53,j}}, \ldots, \widetilde{p_m^{53,6}} \end{bmatrix} \tag{6}$$

In terms of the national meteorological data in 2019, the temperature $t_m^{i,j}$ on day j of the week i for each province is added into the matrix T_m, and the letters have the same meaning as above. Finally, we get the national temperature distribution matrix as in Formula (7). Then each value in the matrix is set to normalization, and we get $\widetilde{T_m}$.

$$T_m = \begin{bmatrix} t_m^{0,0}, \ldots, t_m^{0,j}, \ldots, t_m^{0,6} \\ \vdots \\ t_m^{i,0}, \ldots, t_m^{i,j}, \ldots, t_m^{i,6} \\ \vdots \\ t_m^{53,0}, \ldots, t_m^{53,j}, \ldots, t_m^{53,6} \end{bmatrix} \tag{7}$$

$$\widetilde{T_m} = \begin{bmatrix} \widetilde{t_m^{0,0}}, \ldots, \widetilde{t_m^{0,j}}, \ldots, \widetilde{t_m^{0,6}} \\ \vdots \\ \widetilde{t_m^{i,0}}, \ldots, \widetilde{t_m^{i,j}}, \ldots, \widetilde{t_m^{i,6}} \\ \vdots \\ \widetilde{t_m^{53,0}}, \ldots, \widetilde{t_m^{53,j}}, \ldots, \widetilde{t_m^{53,6}} \end{bmatrix} \tag{8}$$

The input NIPI, AEA and CDEA indicators for seven weeks are extracted by CNN and the hidden layer vector I_n is obtained, as shown in Formula (9), where n_t, a_t, c_t are the feature vector of NIPI, AEA, CDEA in seven weeks, respectively.

$$I_n = [n_1, \ldots, n_t , a_1, \ldots, a_t, c_1, \ldots, c_t] \tag{9}$$

According to expert consultation, set the thresholds of $\widetilde{P_m}$ and $\widetilde{T_m}$ are set, which are δ_p and δ_t, respectively. C represents the importance sequence. Then we get the attention score in Formula (11), where W is the learnable parameter matrix, and k_i is the sequence of I_n.

$$C = \sum_{i}^{i+7} \sum_{j=0}^{6} \left[1 \text{ or } 0 \text{ if } \widetilde{p_m^{i,j}} > \delta_p \right] \text{or} \left[1 \text{ or } 0 \text{ if } \widetilde{t_m^{i,j}} > \delta_t \right] \tag{10}$$

$$e = {I_n}^T \tan\mathrm{h}(W[C; k_i]) \tag{11}$$

Softmax function is used to normalize the attention score and get the weight of each feature vector in Formula (12).

$$a = softmax(e) = \frac{\exp(e)}{\sum \exp(e)} \tag{12}$$

Finally, the model combines the calculated attention influence vector with the CNN hidden layer vector to optimize the model extraction result, as shown in Formula (13).

$$Attention(NIPI, AEA, CDEA) = \sum a \cdot I_n \tag{13}$$

3. Results

3.1. Data Set and Experimental Parameters

3.1.1. Data Set

In this paper, security risk assessment indexes for each vegetable in each province are predicted, and the total length of time series for each vegetable in each province is 53 weeks in the experiment. The pre-processed data set is divided into a training set, validation set and test set, and the ratio is 6:3:1 according to the number of the sample data set.

3.1.2. Experimental Environment

For the experimental environment, the operating system was a 64-bit Windows 10 operating system, the processor was Intel CORE i7-9700F@3.00GHz eight-core, the memory was 16 GB, and the graphics card was Nvidia GeForce RTX3060.

An open-source deep learning framework based on PyTorch (https://pytorch.org/ (accessed on 26 February 2022)) is used to construct a deep learning model for experimental platform development.

3.1.3. Experimental Parameters

The attention mechanism-based CNN-AOA-LSTM model is composed of two convolutional layers, two pooling layers and the full connection layer, and Relu, as shown in Formula (14), is the activation function.

$$f(x) = \max\left(0, W^T x + b\right) \tag{14}$$

where W represents the weight vector, b represents the bias vector, and x represents the input vector, which comes from the output vector of the neural network at the upper layer. W and b are network parameters that can be learned.

The first convolutional layer has 64 convolutional kernels, and the size is set to 1×4. The second convolutional layer has 32 convolutional kernels with a size of 1×3 and a step size of 2. The pooling layer selects the maximum pooling mode, and then connects to the full connection layer for transformation and output. The AOA-LSTM network contains two hidden layers with 30 and 20 cells, respectively.

3.2. Model Evaluation Indexes

The prediction of the security risk level is affected by the combination of the above three evaluation indexes; therefore, it is necessary to evaluate the performance of the single evaluation index of the three indexes and the accuracy of the security risk level determined by the indexes.

3.2.1. Prediction Performance Evaluation Indexes

This paper adopts root mean square error (RMSE) and mean absolute error (MAE) to evaluate the predictive effectiveness of the NIDI, AEA and CDEA evaluation indexes in the proposed food security risk level prediction model. The calculation method of these two indexes is as follows:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \widetilde{(x_i} - x_i)^2} \tag{15}$$

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n} |\widetilde{x}_i - x_i| \tag{16}$$

where x_i is the actual value of the evaluation index of the week, and $\widetilde{x}_i$ is the predicted value of the risk evaluation index of the week.

3.2.2. Prediction Accuracy Evaluation Index

In this paper, three evaluation indexes are adopted: precision, recall rate and F1. Specific calculation methods of various indexes are as follows:

$$P_i = \frac{TP_i}{TP_i + FP_i} \tag{17}$$

$$R_i = \frac{TP_i}{TP_i + FN_i} \tag{18}$$

$$F1 = \frac{2 * P * R}{P + R} \tag{19}$$

In the precision calculation Formula (17) (precision hereinafter referred to as P), TP_i represents that the model predicts the number of the positive class as positive classes, and FP_i. represents the model predicts the number of the negative class as positive classes.

In the Formula (18) for recall (recall hereinafter referred to as R), TP_i represents the that the model predicts the number of the positive class as positive classes, and FN_i that the model predicts the number of the positive class as negative classes.

The data set used in this paper is a balanced data set. Because precision and recall are a pair of contradictory quantities when P is high, R tends to be relatively low, and when R is high, P tends to be relatively low, so to better evaluate the performance of the classifier, generally use F1 score as an evaluation criterion to measure the comprehensive performance of the classifier

3.3. Security Risk Assessment and Classification

3.3.1. Security Risk Assessment Indexes

In order to comprehensively evaluate the hazard of carbofuran in vegetables, first we calculated the weekly NIPI, AEA and CDEA values of each vegetable in each province from January to December 2019 by the analytic hierarchy process (AHP). Taking Beijing as an example, the data set of security risk assessment indexes for eight vegetables is shown in Figure 3.

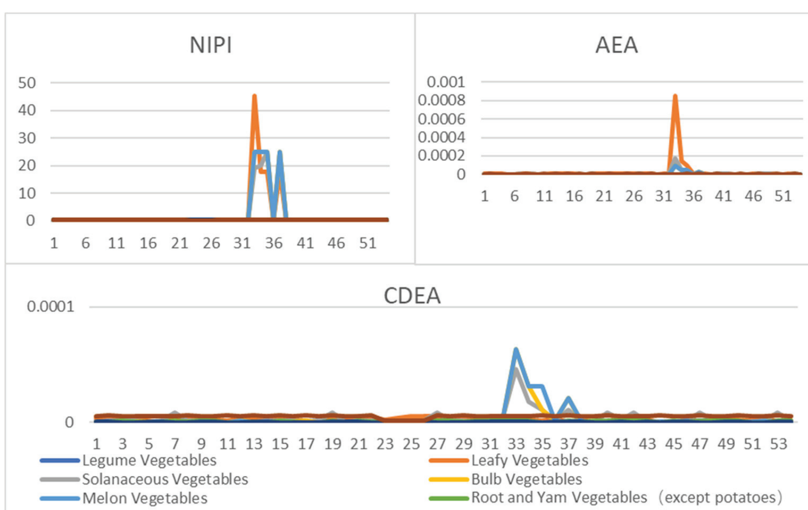

Figure 3. Food security risk assessment indexes of eight kinds of vegetables per week in Beijing from January to December.

3.3.2. Security Risk Classification

After obtaining the food security risk assessment indexes, it can be seen that different indexes differ greatly in order of magnitude. In order to avoid the impact of the assessment effect caused by the neglect of indexes with a smaller order of magnitude, data normalization is necessary [36]. In this study, NIPI, AEA and CDEA are selected as features based on the k-means++ clustering algorithm.

Silhouette coefficient is a means of evaluating the clustering effect. It was first proposed by J. [37] in 1986. It can be used to evaluate the influence of different algorithms or different operating modes of algorithms on clustering results on the basis of the same original data. In this paper, silhouette coefficients are used to measure how many clustering categories are best. Figure 4 shows the fractions of silhouette coefficients for the clustering categories from 3 to 7.

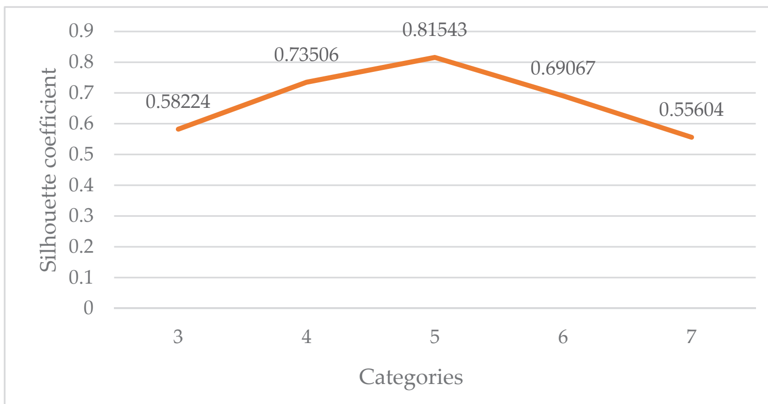

Figure 4. Silhouette coefficients for the clustering categories from 3 to 7.

As shown in Figure 4, the silhouette coefficient of category 5 in the clustering result is the largest, indicating that the instances in the cluster are compact and the distance between clusters is large. Therefore, the normalized data set is divided into five categories by the k-means++ algorithm, and the indexes of each cluster center are shown in Table 1. The distance between the cluster center and the origin is calculated according to the normalized index, and the security risk levels of categories 1–5 are defined as low–high, respectively.

Table 1. Security risk assessment indexes of five cluster centers.

Category	NIPI	AEA	CDEA	Risk Level
1	0.52750	0.0000019	0.0000012	Low
2	5.83879	0.0000447	0.0000253	Medium-low
3	21.31902	0.0001640	0.0000419	Middle
4	27.97410	0.0004820	0.0002343	Medium-high
5	36.80964	0.0007220	0.0003487	High

The clustering results of security risk levels based on the k-means++ algorithm are shown in Figure 5. Among them, NIPI, AEA and CDEA are represented by three-dimensional system of coordinate, and security risk level is represented by color. In the following, future security risk assessment indexes will be divided into specific security risk levels based on clustering centers.

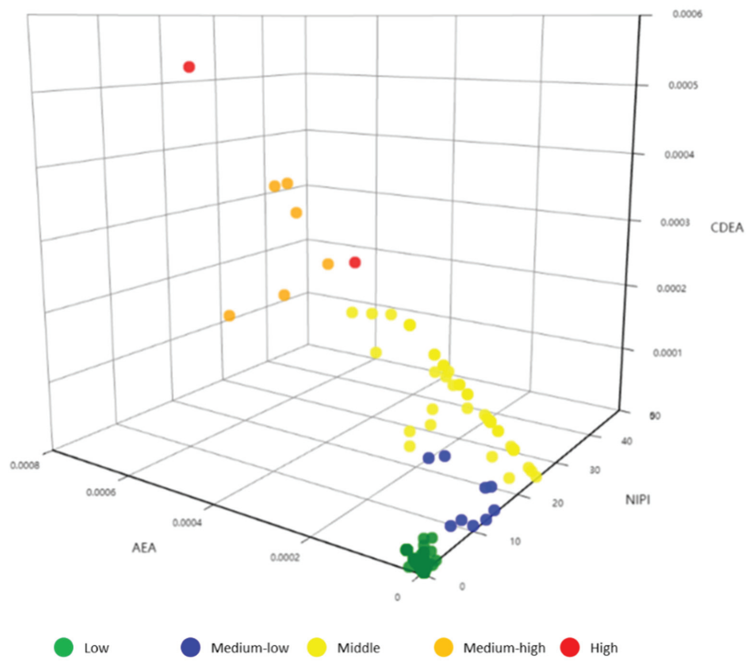

Figure 5. K-means++ clustering results.

3.3.3. Analysis of Security Risk Classification Results

The statistics of security risk assessment indexes of the five clustering centers are shown in Figure 6. The three clustering indexes increase successively with the increase of security risk level, and the indexes of categories 1 and 2 are much smaller than those of categories 4 and 5. It can be seen that the security risk level of categories 1 and 2 is relatively low, while that of categories 4 and 5 is relatively high. The distribution of security risk levels is shown in Figure 7. Vegetables with low and medium-low security risk levels account for 88.6% of the total risk, and vegetables with medium-high and high security risk levels account for 6.0%.

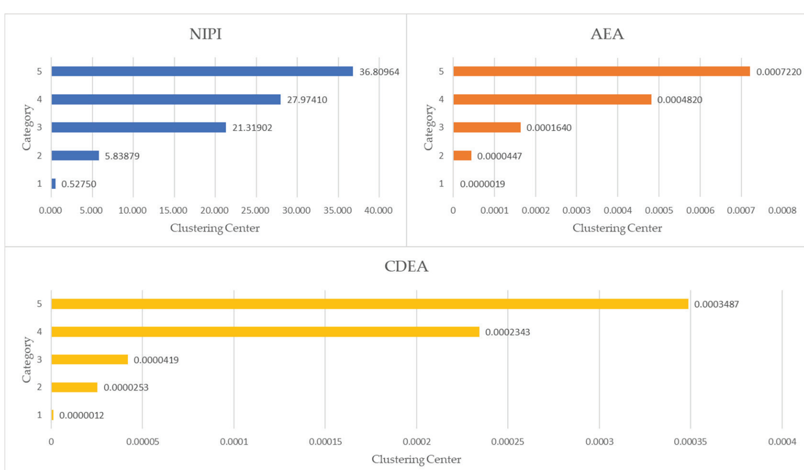

Figure 6. Distribution of different indexes in five cluster centers.

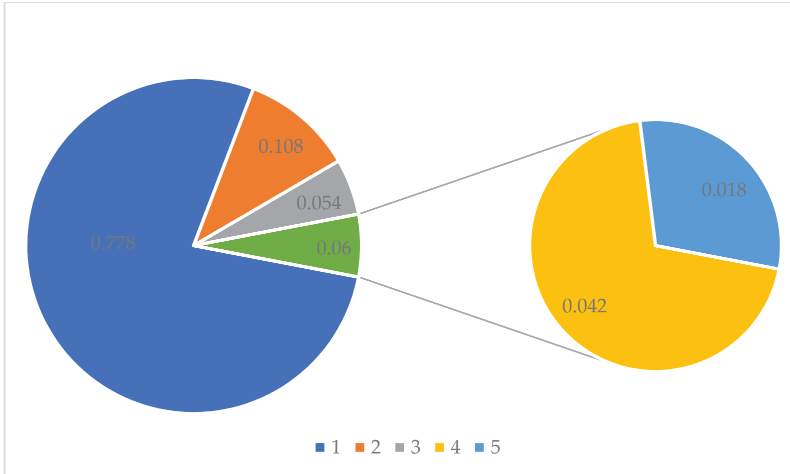

Figure 7. The proportion of five security risk levels.

3.4. Security Risk Level Prediction Model of CNN-AOA-LSTM Based on Attention Mechanism

In order to prove the effectiveness of the CNN-AOA-LSTM model based on the attention mechanism, a series of comparative experiments are carried out in this paper. At present, LSTM, GRU and RNN are the best neural network models for time series analysis; therefore, this paper adopts LSTM, GRU and RNN models as comparison models. Food security risk assessment indexes of each vegetable in each province are predicted, respectively, and then distinguish the security risk level. The experimental results of several common models are given and compared with the prediction model proposed in this paper.

Similarly, taking Beijing as an example, Figures 8–15 shows food security risk assessment indexes of eight kinds of vegetables predicted by four models, respectively. In this paper, the prediction step is 7, so the first seven weeks are a window period, and the prediction is not made in 0 to 6 weeks. The prediction starts at week 7. The 0~46 weeks shown in the figure are the weeks that can be predicted, and the actual 7~53 weeks. In the figure, 0~39 weeks are the training set, and 40–46 weeks are the test set. As it is necessary to predict the evaluation indexes of 20 provinces, RMSE and MAE are used to conduct statistical analysis on the three evaluation indexes of 20 provinces predicted by the four models. As can be seen from the figure, most of the predicted curves are consistent with the actual curves in the process of prediction. However, the predicted curve and the actual curve of some vegetables deviate significantly. This paper conducts research and analysis on such situations, and finds that the serious deviation is mainly due to the change of supply chain caused by prominent events. For example, eight batches of unqualified food were exposed in Shandong, involving vegetables and so on, which flowed into Beijing in November 2019.

Figures 16 and 17, respectively, show RMSE and MAE of three indexes of eight vegetables, predicted by four models. As can be seen from the experimental results, the prediction model proposed in this paper has the minimum RMSE and MAE values for eight kinds of vegetables, which is superior to other models. In terms of the NIPI index, the predicted values of RNN model and LSTM model on four kinds of vegetables deviate greatly from the correct values. In terms of AEA and CDEA indexes, the prediction effect of the four models on solanaceous vegetables is slightly lower, but the index prediction of other vegetables is very close to the actual value. In general, the RNN model has the worst prediction effect on all indexes.

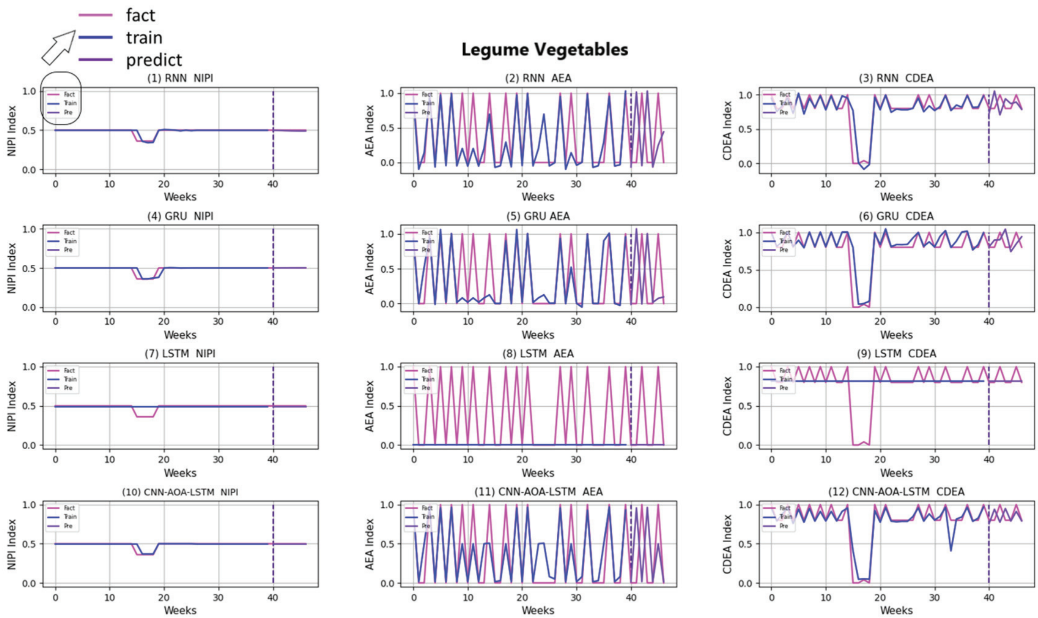

Figure 8. Prediction results of indexes of legume vegetables.

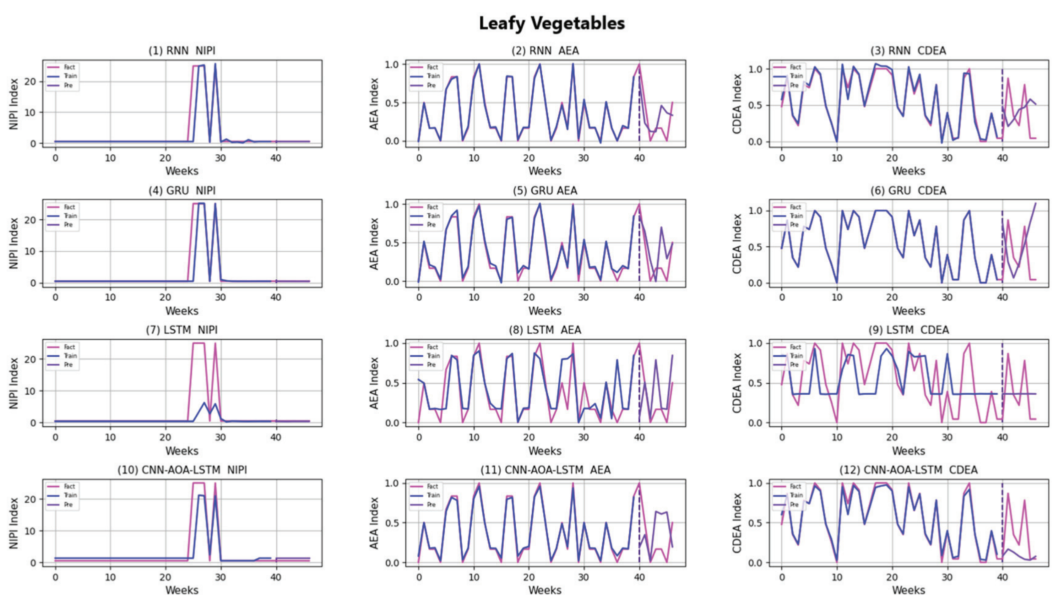

Figure 9. Prediction results of indexes of leafy vegetables.

After predicting NIPI, AEA and CDEA evaluation indexes, the distance between risk evaluation indexes and security risk levels is calculated, and the security risk level is determined. The average accuracy of the prediction results of the four models is statistically analyzed, as shown in Table 2.

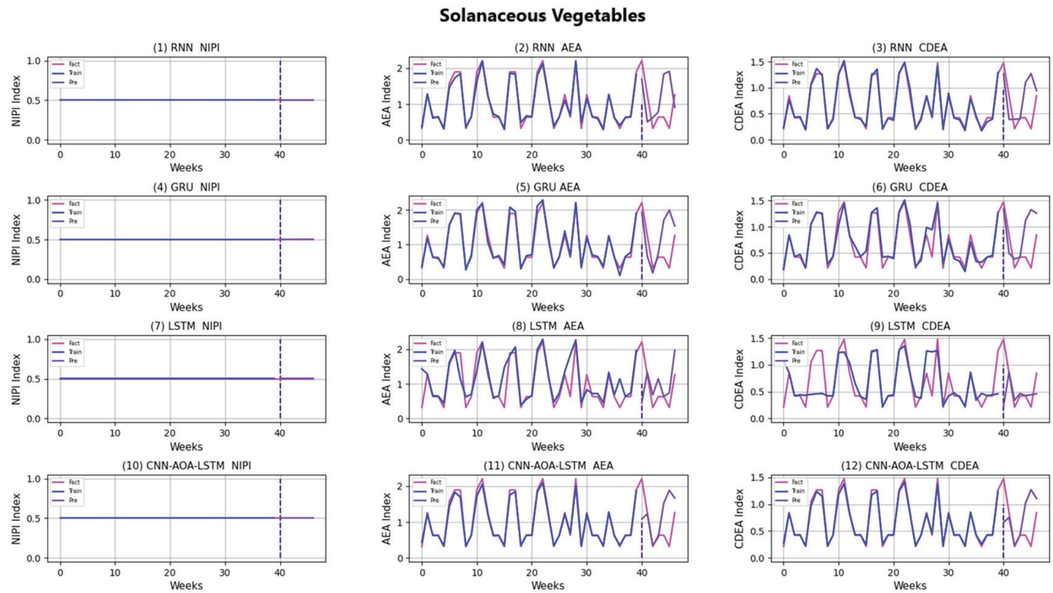

Figure 10. Prediction results of indexes of solanaceous vegetables.

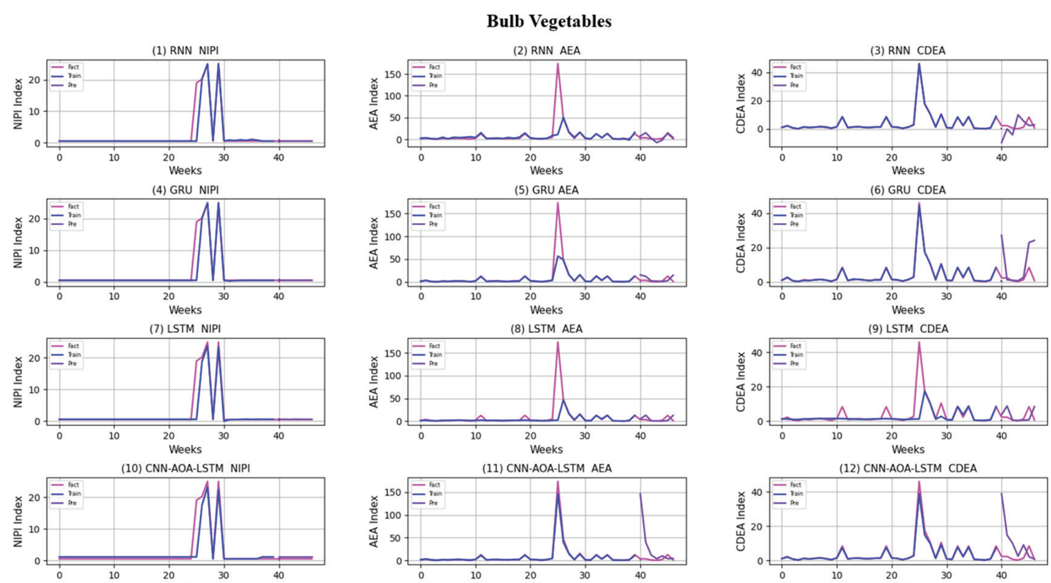

Figure 11. Prediction results of indexes of bulb vegetables.

Experimental results show that the CNN-AOA-LSTM prediction model based on the attention mechanism is significantly better than the other three models in terms of precision and recall rate, and has the best overall performance in F1. Since the small sample data set constructed independently is adopted in this paper, large-scale training cannot be carried out in prediction. Therefore, attention mechanism is introduced when features are extracted through the CNN network model. When the extracted features enter the LSTM network model, the AOA algorithm is introduced to optimize the LSTM model to optimize the model's hyperparameters and improve the prediction accuracy of evaluation indexes.

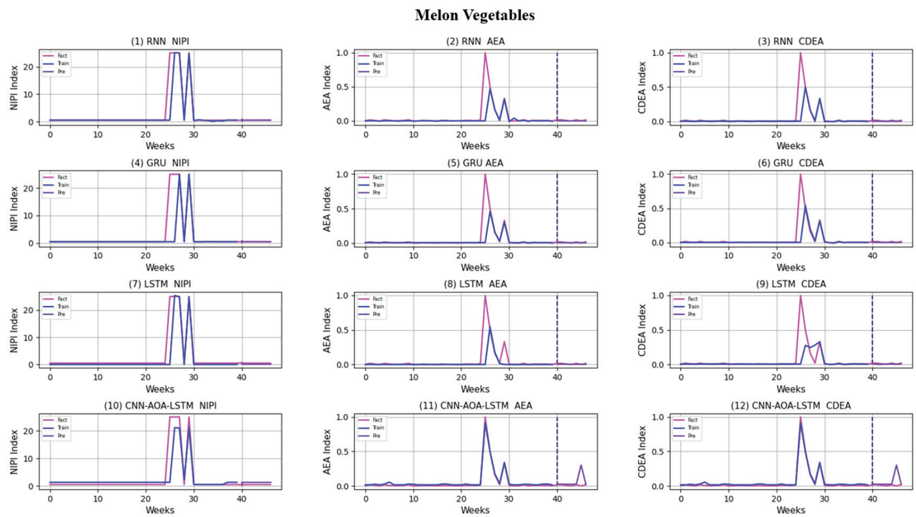

Figure 12. Prediction results of indexes of melon vegetables.

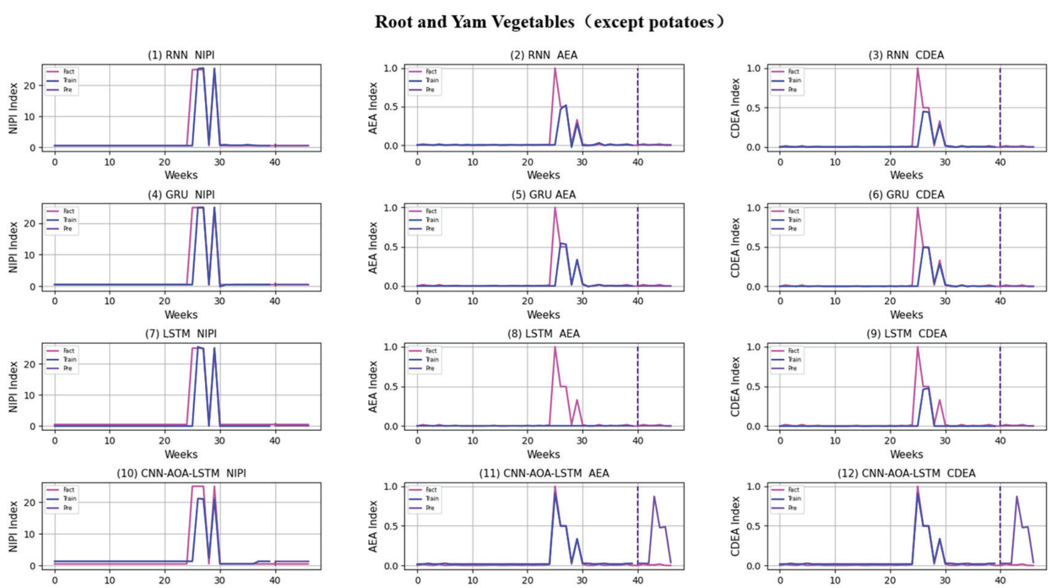

Figure 13. Prediction results of indexes of root and yam vegetables (except potatoes).

In order to verify the reliability of deep learning in pesticide residue prediction, we randomly select the high-risk vegetables in a province, such as leeks in the Zhengzhou Economic Development Zone, Henan province, on 10 December 2019, in which carbofuran was over the standard. Subsequently, we find that the indicators of carbofuran in bulb vegetables in this province were also in the middle and high grades in 43rd week, as shown in Figure 18. It shows that the prediction results of deep learning are reliable when there is no emergency in the supply chain.

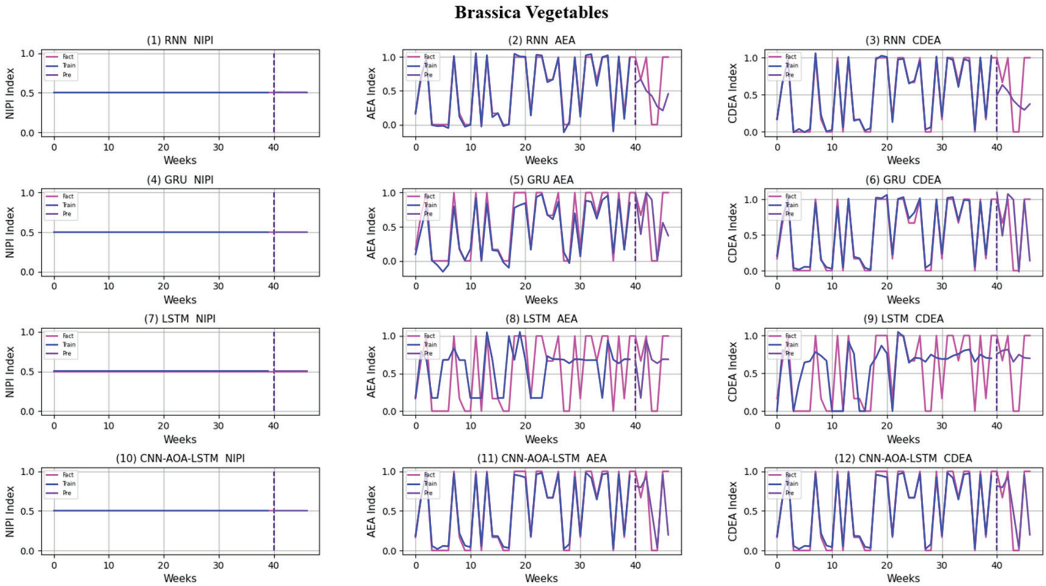

Figure 14. Prediction results of indexes of brassica vegetables.

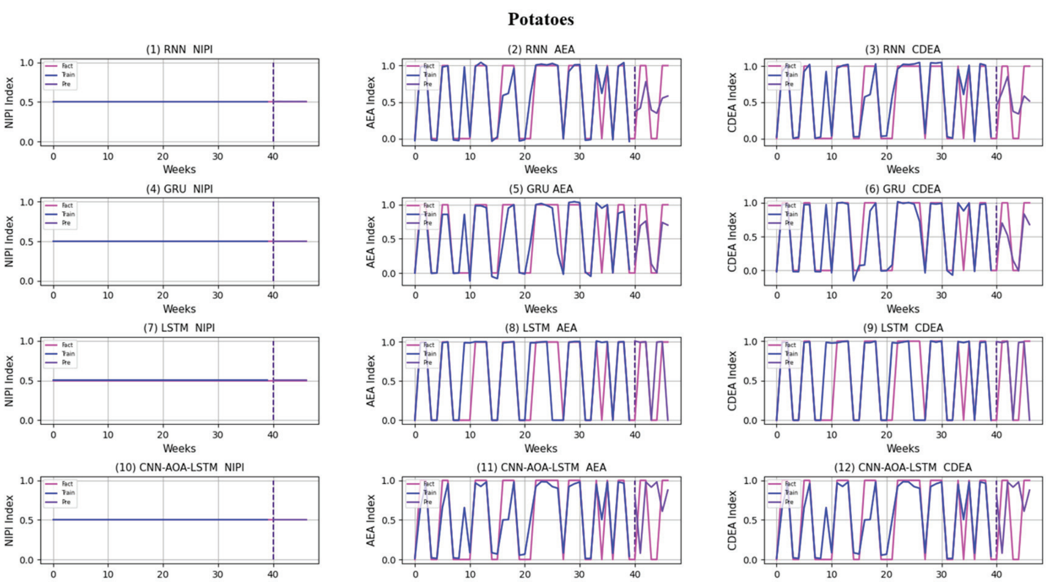

Figure 15. Prediction results of indexes of potatoes.

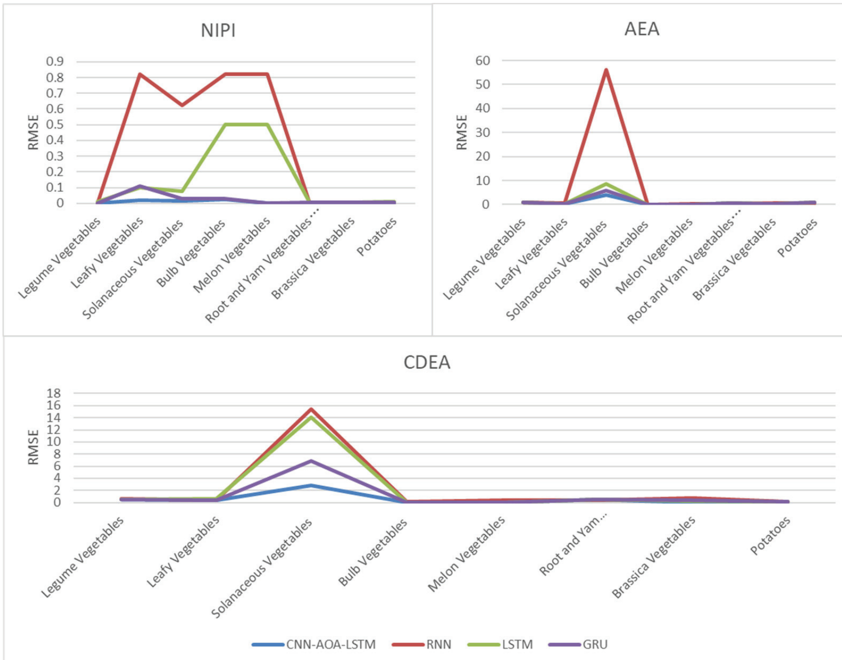

Figure 16. RMSE of NIPI, AEA and CDEA indexes.

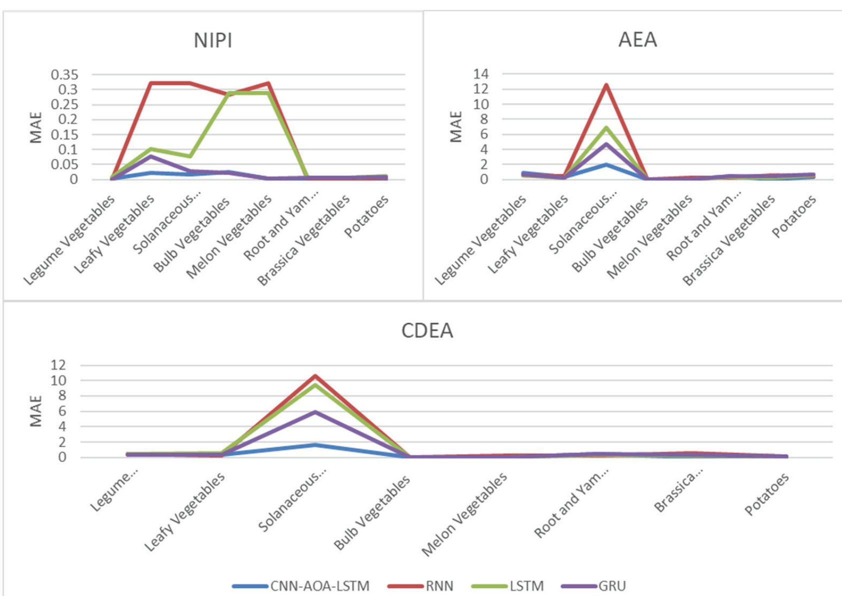

Figure 17. MAE of NIPI, AEA and CDEA indexes.

Table 2. Accuracy evaluation index of security risk level prediction.

Model	Index-Data		
	P%	**R%**	**F1%**
RNN	74.38	73.69	74.03
LSTM	79.37	78.73	79.05
GRU	87.25	86.51	86.88
CNN-AOA-LSTM	93.37	93.12	93.24

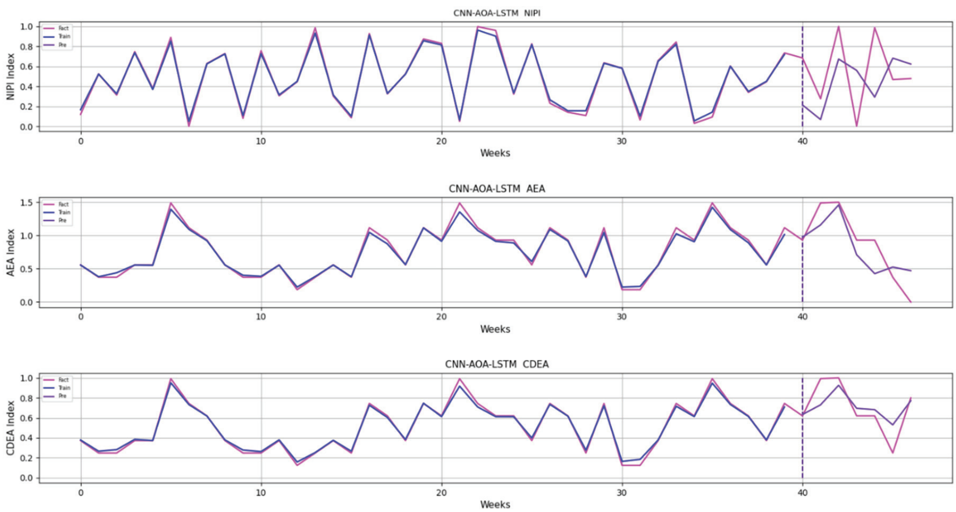

Figure 18. Random sample analysis of predicted results.

4. Discussion

In order to supervise the high-risk areas of dietary intake of carbofuran pesticide residues and effectively guarantee the food quality and security of residents, this paper establishes the prediction model of security risk level of carbofuran pesticide residues in Chinese vegetables based on deep learning. The prediction is carried out based on a small sample data set. The experimental results show that the prediction precision of CNN-AOA-LSTM based on the attention mechanism proposed in this paper reaches 93.37%, which meets the risk management requirements of weekly food sampling reports. At the same time, security risk classification and prediction based on systematic assessment can make the food supervision department objectively determine the key supervision of provinces and vegetable types, so as to strengthen the early control of food security risks, reduce the cost of risk management, provide safe and assured food for consumers, protect the interests of consumers, and maintain public health and security. The proposed approaches in the paper can combine other identification algorithms to study the computer vision problems [38–41] and can be applied to other fields such as prediction processing and engineering application systems [42–46].

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Conflicts of Interest: The authors declare no conflict of interest.

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A Greater Share of Organic Agriculture in Relation to Food Security Resulting from the Energy Demand Obtained from Food—Scenarios for Poland until 2030

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Abstract: In line with the assumptions of the European Green Deal, it is planned to allocate 25% of agricultural land to organic farming by 2030. However, the question arises: what share of organic farming and under what additional conditions is it able to feed the population of a given country? The aim of the article is to try to answer the above question for the example of Poland. In particular, the authors analyze: the problem of satisfying people's nutritional needs, reducing food wastage, and finally the relationship between sustainable consumption and increasing the share of organic farming in Poland. Attention was also paid to possible potential changes in the agricultural land area with the growing share of organic farming. The proposed scenarios for the transition to organic farming concern the year 2030. We propose to increase the share in 20%, 40% and 60%, imposing them on changes in sustainable consumption of +/−25%, +/−50% and +/−75%. The available FAOSTAT (Statistic Data of the Food and Agriculture Organization of the United Nations) and Statistics Poland data from 2008–2018 were used for the analysis. The model scenario analysis showed that the total food demand will be met in most of the scenarios. It has also been shown that with a higher level of transition to organic farming, it becomes necessary to reduce food wastage. Changing the consumption style not only creates opportunities for a wider development of organic farming in Poland but can also generate free areas on arable land (e.g., even more than 26% of free area in the +/−75% scenario). This may create potential opportunities for their use in the production of consumer crops, but also in the protection of the natural and agricultural environment.

Keywords: sustainable food production; sustainable consumption; organic farming; food wastage; model scenarios

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1. Introduction

Agriculture is part of the primary sector of the economy, i.e., one of the greatest importance. Its key function is to provide food, including high-quality food produced with respect for the environment. However, the surging human population poses challenges both to agricultural sustainability and food security [1]. Food security is defined as a situation: "*when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*" [2]. Maintaining it can be a big challenge, while striving to significantly respect the environment in the field of agriculture. Two issues clash here: (1) the required increase in agricultural production resulting from population forecasts, an increase in the consumption of agricultural chemicals and the use of the environment; (2) the need to protect the environment and its resources, the health of consumers, and ensure their access to food of the highest quality.

Various studies emphasize that organic farming is capable of providing food of better quality than conventional agriculture [3–7]. Admittedly, some claim that organic agriculture on a larger scale may pose environmental threats (such as deforestation, due to the need to obtain new space for crops) [8,9]. However, organic farming practices are generally considered more beneficial to the environment and promote animal welfare. These aspects are important, but not the only ones. The availability of sufficient quantities of food of appropriate quality and access to adequate resources for acquiring appropriate foods for a nutritious diet is necessary [10]. They are a derivative of the production capacity of organic farms, the production efficiency of organic farming, but also the prices of organic food. An interesting analysis of the approach to the problem of food security in the context of organic farming is presented by Schreer and Padmanabhan [11]. They point to the important issue in Indonesia that there is a strong need to relax the regulatory control over the organic sector; all this to create space for products without a certificate of organic production but manufactured with respect for the environment. This may be beneficial for small, local agricultural producers, producing food that is safe for the environment and consumer health, but also to broaden an overall market of the so-called natural. In another study [12] also highlighted that organic farming can reduce global food insecurity. However, there is a threshold above which the combination of organic and conventional farming methods is most effective and organic farming alone cannot sustain production that will feed the human population.

Therefore, many of the concerns related to the provision of food security by organic farming are largely due to the possible insufficient supply of organic food. Hence, other important factors should be taken into account that may favor the wider development of organic farming and its importance in providing high-quality food and reducing waste, but also changing the style of consumption.

Thus, a key question in the debate on organic agriculture's share in the future of the entire agricultural sector is whether it is capable, both globally and locally, of feeding a growing the human population, which is expected to reach 8.5 billion by 2030 [13].

There is a general tendency for utilised agricultural area and agricultural output to grow. From 2008 to 2018, total acreage increased globally by over 2% for cereals, nearly 19% for vegetables, 30.5% for leguminous plants, and 9% for oil crops (for oil crops: data for years 2008 to 2014). Global increase in output and yield per 1 hectare were as follows: cereals—output by 17.5%, yield by 15%; vegetables—output by 24%, yield by almost 18%; leguminous plants—output by 46%, yield by 12%; oil plants—output by 27.5%, yield by 9% [14]. Similar relationships are observed in animal production. Milk output for the aforementioned period rose by over 20%, total meat output by over 21%, and table egg output by more than 24% [14].

The role of agriculture is obviously far more substantial, since it supplies products for other sectors of economy, provides workplaces for many people [15–17], and generates environmental pollution [18–20], but may also improve its quality [21–23] or the health of its consumers [24–26].

An increase in global food production is surely a step forward to end world hunger. In the years 1995 to 2018 the supply of food has grown from 2663 to 2929 kcal/cap/day [27]. Those data may indicate an overall improvement in food security, or even suggest that the quantities of food consumed are excessive in proportion to the needs of the human body. Still, food is provided mainly by dominant conventional agriculture, the product quality of which often raises concerns. The fact is emphasised by Pretty [28], who points out that many people worldwide continue to starve. Many million people live on poor diets, i.e., either overeating or consuming poor-quality food. This affects both people and the natural environment.

Is contemporary conventional agriculture therefore sustainable in terms of quantity of food being produced and is the alternative system (organic agriculture in our analysis) capable of feeding the population (e.g., the population of Poland)?

A transition to green farming, including organic agriculture, may potentially contribute to an improvement in the food system. It is generally considered superior to conventional agriculture in terms of environmental, production, and economic sustainability, as well as farmers' welfare [29]. Some researchers claim that organic agriculture is also capable of feeding a substantial part of human population [30,31]. However, on a global scale, this may entail using more space to grow consumer crops, a radical change in consumption styles (e.g., reducing meat intake), reduction in food wastage [9,32] or an implementation of proper cultivation techniques [33,34]. Studies demonstrate the possibility of increasing the share of ecological agriculture globally by maximum 40–60%, due to nitrogen deficiencies affecting organic agriculture [26].

EU environmental policy goals prove the importance of organic agriculture to feeding the population. The implementation of the European Green Deal (EGD) involves allocating 25% agricultural land to organic agriculture by 2030. Emphasis is put on the significant contribution of organic agriculture to environmental equivalence, stimulating demand for ecological food and increasing consumer confidence in this type of production and food [35].

The purpose of this publication is to analyse four problems, attempting to answer the following questions:

(1) is organic agriculture (green farming) capable of feeding the population of Poland (i.e., supply the required amounts of kilocalories and protein), and what share of organic agriculture can guarantee this?
(2) what possibilities for enhanced development of organic food production are created by the potential reduction of food wastage?
(3) what effect can a change in the style of consumption (reduced intake of certain animal and plant products regarded as less healthy) have on a broader growth of organic farming?
(4) what changes in utilized agricultural area may arise from the increasing share of organic agriculture?

For the purpose of analyzing the issues discussed in this article, we defined the so-called base year (mean statistical data for agricultural production in Poland from 2008 to 2018) and outlined possible food production change scenarios for 2030. Main sources of information in the present analyses include statistical data from FAOSTAT, Statistics Poland and previous analysis performed by the authors.

Our analysis refers exclusively to the realities of Polish agriculture. For the purpose of this study, we treat the country as a closed circuit. We assume that the entirety of native agricultural production must serve as potential food supply for the country's residents and satisfy livestock feed requirements.

The present study does not analyze or assess any possible price variations, market effects of the conversion of agriculture to organic production or decisions made by farmers themselves. Such factors constitute a potential new research topic. Nevertheless, we emphasize that both EU and national support is immensely important to a broader development of organic agriculture in Poland.

Reasons why this particular subject has been chosen include:

(a) absence of similar studies for Poland,
(b) noticeable and ongoing changes in consumption patterns among Polish consumers, who increasingly look for organic farming products or products without certificates but naturally grown and sourced directly at the farm gate,
(c) possible use of the results by decision-makers for the purpose of creating a healthier and more environmentally friendly agricultural production policy.

The few available studies on the subject focus mostly on the global scale [9,26,30–32,36,37], alternatively comparing the output of analyzed organic and conventional productions. However, it is worth taking a closer look at a given country's capability to feed its population using food from its own organic production. This aspect is also discussed by Muller et al. [32], who stressed that local and regional statistics are required to gain a full picture of the problem.

2. Organic Farming in Polish Agriculture—General Information, Production, Selected Market Aspects

The history of organic agriculture in Poland goes back to 1930, when count Stanisław Karłowski implemented biodynamic farming on its land in Szalejewo near Gostynin. More recently, a substantial growth of organic farms and the area of their agricultural land (AL) began with Poland's accession to the EU in 2004 and the associated financial support for ecological production. According to data available from Poland's Agricultural and Food Quality Inspection (AFQI), the years 2004–2020 saw nearly a five-fold increase in the number of organic farms in Poland (total: certified and in the process of conversion) (from 3760 to 18,575) and over a six-fold increase in their AL (total: certified and in the process of conversion) (form 82,729.5 to 509,291.27 ha) (Figure 1). In the context of Poland's agriculture, both the number of organic farms and their AL still constitute a small percentage. According to latest data from 2020, the area of land used for organic agriculture [38] corresponds to 3.47% of Poland's total AL. Similar trends are observed worldwide.

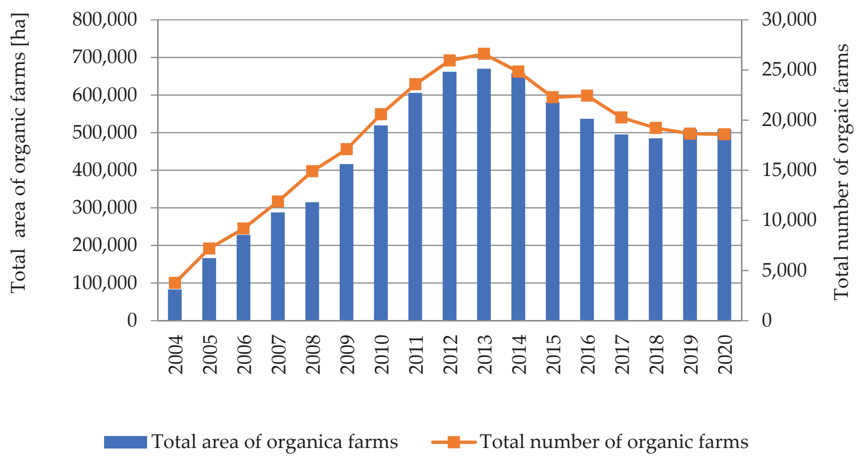


Figure 1. Organic farms number and agricultural land area in Poland in the years 2004–2020. Source: authors' own work based on: [38].

In Poland, the proportion of AL for organic agriculture has evolved and has never been significant. It largely reflected Polish farmers' environmental awareness, food market situation and the impact of the funding system. Since 2014 the area and number of organic farms in Poland have dropped noticeably. A number of them have naturally closed down, since many farmers did not intend to deliver products to the market but rather collect subsidies, and thus they did not meet the criteria of sustaining the production. Other reasons for the decline are stricter regulations applicable to organic agriculture, growing bureaucracy, lack of successors to work on farms and no tangible prospects for the development of a market for organic food grown in Poland. This is a trend of concern in the face of growing interest that Poles take in organic food, particularly in large urban areas [39]. It appears that following a period of fascination with industrially produced food, consumers are increasingly paying attention to the product's origin [40]. Health and healthy diet concerns, as well as environmental or animal rights issues, are important factors in the purchase of ecological food [41]. Studies on consumers' interest in organic food in Poland also suggest a relationship between ecological food consumption and care for health and safety. Of importance to consumers are also sensory aspects and the price of food [42–44].

Organic farms make up over 1.3% of all farms in Poland (as of 2019) [45]). The vast majority of them are small farms, often scattered and situated away from larger urban areas. Data available from AFQI show that in 2018 the share of smallest organic farms (up to 5 ha) in the total number of organic farms was relatively high (21%). Overall, organic farms of area from 1 to 20 ha constituted as much as 64.8%, whereas the largest ones (50 ha and more) only 12.6% of all organic farms in Poland [46]. These proportions are not beneficial in terms of the ability to produce organic food on a larger scale. According to the same body, in the years 2001–2018, agricultural plants (consumer and livestock feed crops) had on average the largest share in organic cultivation, followed by fruits and berries, and vegetables (Figure 2).

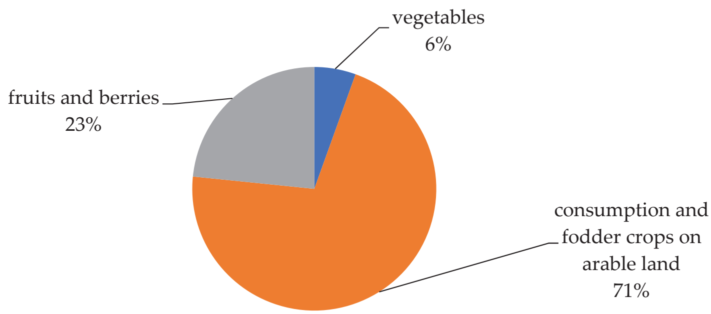


Figure 2. Structure of the categories of potential consumer plants in the years 2001 to 2018. Source: own work based on data: [46–52].

The relatively small percentage of vegetables grown (notwithstanding high subsidies and consumers' interest in organic vegetables) is largely explained by the fact that they are labour-intensive. Higher mean percentage of orchards is a result of high EU subsidies per 1 ha and consumer demand for fruits. Agricultural crops on arable land (ArL) include mainly cereals, legumes, industrial crops, vegetables and a small proportion of herbs. A substantial part of cereals is used as animal feed. Agricultural crops also include animal feed production (green forage, hay).

According to the latest information available from AFQI for years 2017–2018, the structure of all AL was dominated by animal feed on ArL (27.2%), followed by cereals (25.55%), meadows and pastures (22.05%). These proportions clearly indicate the predominance of animal-feed crops in Polish organic agriculture (Figure 3).

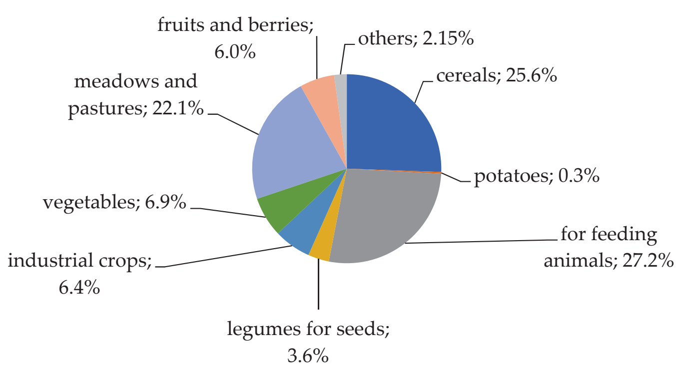


Figure 3. Organic agricultural land structure in Poland in the years 2017–2018. Source: authors' own work based on: [46].

Currently, the quantity of organic farming products in Poland rules out the possibility of feeding the majority of its population. Data available from AFQI for years 2017–2018 show output of selected organic products (Table 1) [46].

Table 1. Mean production output for selected organic farming commodities in Poland from 2017 to 2018 and their supply (cap/year).

Type of Production [1]	Unit	Mean Output in 2017–2018	Supply/Cap/Year [kg, 1]
Cereals	tonne	185,942.32	4.84
Potatoes		17,448.90	0.45
Total vegetables		50,592.22	1.32
Total fruits		84,533.73	2.20
Cow's milk	hL	253,086.76	0.66
Meat processing	tonne	2,370.16	0.06

[1] production declared in certificates issued by the certification body. Source: authors' own work based on: [46,53].

Polish organic output is a subject of many analyses [54–58], and the data presented here suggest output a few to several dozen per cent lower than in the case of conventional production.

De Ponti et al. found organic yields to be 21% lower in developed countries and 20% lower globally [59]. The present study also assumes the 25% difference and intends to demonstrate that the gap may be less significant if we consider a significant reduction in food wastage and the proposed change in Poland's population dietary habits.

A measure of the position and significance or organic farms and organic agriculture is a well-developed organic food market. The global value of organic retail was over EUR 106 billion in 2019, and almost EUR 41.5 billion in EU alone. Taking into account the underdeveloped market, the value of organic food grown in Poland was EUR 314 million in 2019. Unfortunately, in Poland only 8 euros are spent each year per person on organic farming products, in comparison to EU average (84.4 EUR/cap) and global average (14 EUR/cap) [60].

About 32% Polish consumers are regular purchasers of organic food (at least once a month or once a week). 20% eat organic food occasionally and as many as 48% never buy this kind of food [61].

Subsidies play an important role in setting up new organic farms. Financial support promotes farms which supply food to the market. In line with Polish law [62], a subsidy may be obtained if 30% of consumer products is used for processing, for other farms or directly to the market.

Obviously, the above information, albeit providing an overview of the state and condition of Polish organic agriculture, does not offer an answer to the question whether the present system of agriculture is capable of feeding the population of Poland, and what share of organic farms is required.

3. Material and Methods

The analysis and results presented in this study follow up on the author's research on Poles' attempts to work towards a more sustainable production and food consumption. Sustainability is defined here both as use of domestic agricultural output for consumption and attempts to achieve lower food wastage levels and a change in consumption patterns (less meat and plant products of selected types). Sustainable consumption also involves purchasing local, organic products directly from a tried and trusted food supplier.

For the purpose of our analysis, we refer to the results of, and calculation methods and statistical data, applied in Kuczuk and Widera [63]. In that study it was shown, among other things, the method of creating the base year using statistical data, changes for the year adjusted 2030 for the forecast population, but also the type of data used in the calculations. Thus, the following assumptions were made in the aforementioned study:

— the basis for all calculations included data from the so-called "base year" as mean data from the years 2008–2018,

— the extrapolation of data for 2030, referred to as adjusted (or "corrected") data, was performed with the assumption that the changes in the years used to construct the base year were stable; the adjective "adjusted" means that per capita data were adjusted according to the Statistics Poland's population forecast for 2030,
— the scenarios of transition to a more sustainable consumption entailed a reduction in the supply (and production), and consequently consumption, of selected types of meat (pork, beef and chicken poultry), cow's milk, wheat flour and sugar by (−)25%, (−)50% and (−)75%, accompanied by an increase of supply and consumption of duck, goose, turkey, rabbit and sheep meat, as well as honey, by (+)25%, (+)50% and (+)75%, considered healthier for consumers,
— possible change scenarios for agricultural product supply (production) were developed, referred to respectively as $\alpha \epsilon \{25\%, 50\%, 75\%\}$ converted to g per capita/year, kcal per capita/year and g protein per capita/year, which may be supplied to consumers in Poland in 2030,
— food wastage was assumed at the level of 40% of food supply [9,64].

Proposed consumption style change scenarios were maintained in the analysis of current research problems. Our previous analysis has been additionally expanded by an attempt to determine the possible extent of the transition of Polish agriculture to organic farming as well as various food wastage reduction levels. We continue to emphasize the number of kilocalories and protein required by the human body We constantly rely on the volume of agricultural production as well as the number of calories and protein estimated Kuczuk and Widera [63]. For the purpose of the current analysis, we add the following assumptions:

(a) aside from the transition to sustainable consumption, we developed scenarios of a $\beta \epsilon \{20\%, 40\%, 60\%\}$ transition to organic production; due to the fact that conventional farming prevails in Poland, we treat Polish agriculture as a conventional system in its entirety, hence the departure point assuming 0% share of organic farming as a reference,
(b) scenarios of transition to organic production were built allowing for its lower production efficiency, i.e., a 10% drop for animal products [32], and a 25% drop for plant products,
(c) at the same time, we proposed various food wastage reduction scenarios $\epsilon \{10\%, 20\%, 30\%, 40\%\}$, with the initial level of 40% [63] brought down to 30%, 20% and 10%; we assumed that food wastage cannot be completely eliminated,
(d) we simulated changes in the use of utilised agricultural area in 2030, allowing for an increased proportion of area for organic farming scenarios $\beta \epsilon \{20\%, 40\%, 60\%\}$ and for scenarios $\alpha \epsilon \{25\%, 50\%, 75\%\}$; area changes result from changes in plant and animal output as the supply side in order to feed the country's population, but also from changes of area required for growing animal-feed crops.

In the analysis of the current problem, we assume that total food supply (TFS) (kcal/cap/day) is given by Equation (1). This equation only applies to the sustainable consumption part of the analysis:

$$TFS^{\alpha}_{kcal/cap/day} = (1+\alpha)\cdot SSAP + (1-\alpha)\cdot[SUNSAP + SUNSCP] + SSCP \quad (1)$$

where: $\alpha\epsilon\{25\%, 50\%, 75\%\}$—percentage of change assumed in scenarios of sustainable consumption, SSAP—sum of sustainable animal products, the supply of which is to be increased, SSCP—sum of sustainable plant products, the supply of which remains unchanged, SUNSAP—sum of unsustainable animal products, the supply of which is to be reduced, SUNSCP—sum of unsustainable plant products, the supply of which is to be reduced.

Then we use Equation (2) for both sustainable and ecological product consumption:

$$TFS^{\alpha}(\beta)_{kcal/cap/day} = (1-\beta)\cdot TFS^{\alpha} + \beta\cdot TFS^{\alpha}\cdot e \quad (2)$$

where: $\beta \epsilon \{20\%, 40\%, 60\%\}$ are proposed transitions to organic agriculture and the consumption of its products, $e = \begin{cases} 0.90\ for\ animal\ output \\ 0.75\ for\ plant\ output \end{cases}$ are indicators of the decline in production efficiency as a result of the transition to organic agriculture.

Assuming the expected food wastage level, the borderline inequality to satisfy total food demand (TFD) is expressed by Formula (3):

$$TFD^{\alpha}(\beta)_{kcal/cap/day} \geq (1-w) \cdot TFS^{\alpha}(\beta)_{kcal/cap/day} \tag{3}$$

where: $w \epsilon \{10\%, 20\%, 30\%, 40\%\}$ is the assumed percentage of food wastage.

By adopting such a constructed methodology and its assumptions, we relied on actual statistical data for Poland and feasible assumptions regarding, among others, changes in the efficiency of agricultural production after conversion to organic farming, or food waste. In addition, similar assumptions can be found in the works of Schader et al. [9], Muller et al. [32], but also in Alexandratos and Bruinsma [65], where possible scenarios for 2050 were projected.

We propose several scenarios for 2030 taking into account different levels of change for sustainable consumption, waste and the transition to organic farming. The amounts forecasted by us are estimates resulting from the realistic assumptions we have adopted.

4. Results and Discussion

4.1. Base Year vs. 2030—Changes in Population, Utilised Agricultural Area, Availability of Protein and Energy from Domestic Agricultural Products

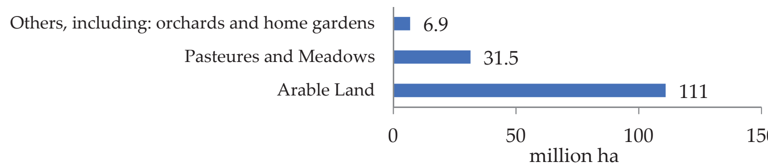
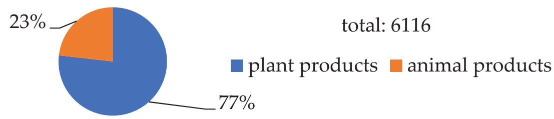
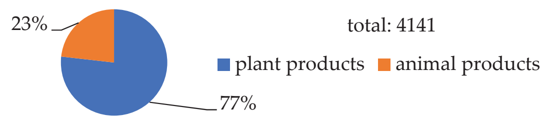
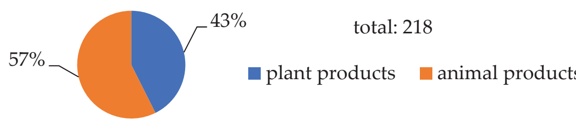
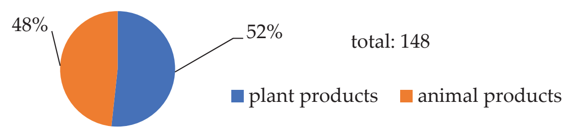
According to global analyses, expected world population growth will make it necessary to increase cultivation area on arable land by 6% by 2050, even without the transition to a more sustainable agriculture. A potential increment in the share of green farming may necessitate utilising even larger areas of land, usually at the cost of forests [8]. For Poland, an inverse demographic trend is at work, which, coupled with a change in consumption styles and food wastage reduction, may create opportunities for the transition to organic farming.

In our calculations for the base year the population of Poland was 38.42 million [53]. We expect this number to drop to approximately 37.62 million by 2030 [66]. This population change trend, combined with a rise in awareness of the need to change consumption patterns, is likely to enable a substantial proportion of Poland's population to be fed with domestic green farming products.

Poland's utilised agricultural area amounts to nearly 150 million hectares (mean value for the base year). This makes for 47% of the country's surface area. Arable land constitutes definitely the largest portion of AL. It accounts for as much as 75% of Poland's agricultural land. Meadows and pastures form 21% of AL area.

According to calculations in [63] for the base year, utilised agricultural area and its related production significantly exceed Poland's population food demand. If we omit $w = 40\%$ food wastage, the country's population would potentially be able to use more than 6000 kcal/cap/day and substantial amounts of available protein while maintaining appropriate proportions of animal as well as plant products. In the year 2030, when the transition to more sustainable food consumption is expected, with a change $\alpha = 75\%$ in the consumption of selected animal and plant products, we anticipate an excess of available kcal/cap (4141) as well as protein (148 g/cap/day). We consider these data as still potentially large quantities supplied by domestic farm production (Table 2).

Table 2. Base year vs. 2030: population, land occupation, energy and protein supply.

Population Base Year:	**38.42 Million**
Population Forecast 2030:	**37.62 Million**
Land occupation base year [ha]:	
Energy supply (with no food wastage) [kcal/cap/day] base year	
Energy supply in 2030 (α = 75% scenario, with no food wastage) [kcal/cap/day] year 2030	
Protein supply (with no food wastage) [g/cap/day] base year	
Protein supply in 2030 (α = 75% scenario with no food wastage) [g/cap/day]	

Source: authors' own work based on [53,63].

4.2. Kilocalories and Protein Supply Change Scenarios Taking into Account the Transition to a Organic Farming System, Food Wastage Reduction and Sustainable Consumption

Statistics for the base year provide valuable information for consumers and food policymakers alike. Polish agriculture was capable of supplying 3670 kcal/cap/day and 131 g protein/cap/day even allowing for food wastage at the level $w = 40\%$ (Table 3). This is a rather high amount of energy considering human body requirements, as reported in Kuczuk and Widera [63] for the base year (2572 kcal/cap/day). Therefore, the data reveal a margin that can be used for enhancing the growth of green farming in Poland and greater consumption of organic products. Lower efficiency associated with organic agriculture may limit current overproduction of food in Poland.

Table 3. Daily total food supply in the base year, adjusted 2030 and scenarios for 2030 including: transition to organic agriculture, food wastage, and sustainable consumption.

Food Wastage Levels		Daily Total Food Supply (TFS)														
w		α	Base Year *	Adjusted 2030 *	**Transition To More Sustainable Food Supply And Consumption**											
					+/−25%				**+/−50%**				**+/−75%**			
		β			**% Transition To Organic Agriculture**											
					0%	**20%**	**40%**	**60%**	**0%**	**20%**	**40%**	**60%**	**0%**	**20%**	**40%**	**60%**
10%		Total [kcal/cap/day]			5741	5494	5247	5001	4734	4526	4318	4111	3727	3558	3389	3221
		total protein [g]			257.45	249.23	241.01	232.79	195.41	188.93	182.46	175.98	133.37	128.64	123.89	119.16
20%		Sum of [kcal/cap/day]			5103	4884	4664	4445	4208	4023	3839	3654	3313	3163	3013	2863
		total protein [g]			228.84	221.54	214.23	206.93	173.70	167.94	162.18	156.42	118.55	114.34	110.13	105.92
30%		Sum of [kcal/cap/day]			4465	4273	4081	3890	3682	3520	3359	3197	2898	2767	2636	2505
		total protein [g]			200.24	193.84	187.45	181.06	151.98	146.94	141.91	136.87	103.73	100.05	96.36	92.68
40%		Sum of [kcal/cap/day]	3670 *	2485 *	3827	3663	3498	3334	3156	3017	2879	2741	2484	2372	2260	2147
		Total protein [g]	131 *	89 *	171.63	166.15	160.67	155.20	130.27	125.95	121.64	117.32	88.91	85.76	82.60	79.44
Data with no food wastage		Sum of [kcal/cap/day]	6116 *	4141 *	6379 *	6104	5830	5557	5260 *	5028	4798	4568	4141 *	3953	3766	3579
		Total protein [g]	218 *	148 *	286.05 *	276.92	267.79	258.66	217.12 *	209.92	202.73	195.53	148.19 *	142.93	137.66	132.40

* Source: authors' own work, taking into account calculations from [63].

The results reveal the effect of a combination of three factors: food wastage reduction, lower consumption of selected products (which are considered non-sustainable in terms of consumption), together with an increased share of organic agriculture and its products, on energy and protein supply for consumers.

The scenarios we developed indicate the point in which the human body's optimum demand for energy and protein may be met. For 2030, it was determined as 2608 kcal/cap/day (TFD) [63]. Our present calculations suggest an optimum scenario, which includes the highest share of organic farming products $\beta = 60\%$ and $\alpha = 75\%$ transition to sustainable consumption, as well as food wastage reduction down to $w = 20\%$. The scenario anticipates 2863 kcal/cap/day and 106 g protein/cap/day (Table 3 and Figure 4), which approximates TFD: 2608 kcal/cap/day. A slight energy shortage is expected at the $w = 30\%$ food wastage scenario: 2505 kcal/cap/day (albeit this quantity may also prove optimal for the human body if functioning in specific conditions). The amount of protein supplied is also within normal limits. If we assume greatest progress in food wastage reduction $w = 10\%$, $\beta = 60\%$ organic share, and $\alpha = 75\%$ changes in consumption style, we may even expect a surplus in the supply of energy and protein (3221 kcal/cap/day and 119 g protein/cap/day) in reference to human body's requirement. Obviously, the last scenario creates further potential for increasing the share of organic farming. However, we should approach this scenario with extreme caution. Muller et al. suggested various degrees (0–100%) of transition to the organic agriculture [32]. Their global analysis takes into account three variants of food wastage reduction (0%/25%/50%), shrinking the food-competitive animal-feed crop area, but also the effect of climate change on crop yield. However, the authors emphasize that a global 100% transition to organic agriculture by 2050 would lead to a substantial rise in the area of utilised agricultural land due to the growing population. In addition, climate change may make it necessary to use more land for organic farming.

Our analyses should also consider a boost in the share of organic farming products by $\beta \in \{20\%, 40\%\}$ with $w = 30\%$ wastage and the $\alpha = 75\%$ scenario. The amount of energy delivered would be 2767 kcal/cap/day, with a protein supply of 100 g/cap/day and 2636 kcal/cap/day, respectively, with a protein supply of 96 g/cap/day. These scenarios seem feasible, considering European Commission's commitment to achieve 25% organic farming in EU member states by 2030 [35].

Both changing consumption patterns and raising awareness of food wastage reduction have a deeply significant role in the process of increasing the share of organic farming and its products. If we wish to obtain $\beta = 60\%$ rise in the share of organic farming in the process of supplying food and the $\alpha = 75\%$ scenario, it is likely that the 2147 kcal/cap/day would not satisfy food standard requirements according to Formula (3). Besides, curbing the $w = 40\%$ wastage level is a priority.

Thus, it seems that the commitment to curbing food wastage is an important step towards a higher proportion of organic farming products in consumption. This, however, requires high consumer awareness, so efforts must be made to raise it. According to Food and Agriculture Organization (FAO) [67], about 1/3 (1.3 billion tons per year) of food made for consumption is wasted. In the EU, around 88 million tons of food waste are generated annually, with costs estimated at 143 billion euros [68]. In Poland, 9 million tons of food are wasted each year, with households being responsible for the majority of food wastage [69]. A change in nutrition patterns is another step in ensuring the supply of high-quality food in optimum quantities.

Table 4 lists selected information on the share of protein supplied and changes in its amount due to the proposed scenarios. The results show that the quantity of protein supplied remain normal in almost all scenarios. Polish standards [70] require that the proportion of energy from protein remains within 10–20%. Nevertheless, certain deficiencies may be observed in the scenario which assumes $w = 40\%$ food wastage. If food wastage remains at the same level, in the $\alpha = 75\%$ scenario we expect a considerable (29–30%) drop in the proportion of animal protein relative to total amount of protein supplied with farming produce. Still, the percentage is natural in many countries due to a low proportion of meat in diet [71]. Results in Table 4 support the finding that food wastage reduction has a positive effect on both the share of animal protein in diet and the availability of energy from animal products.

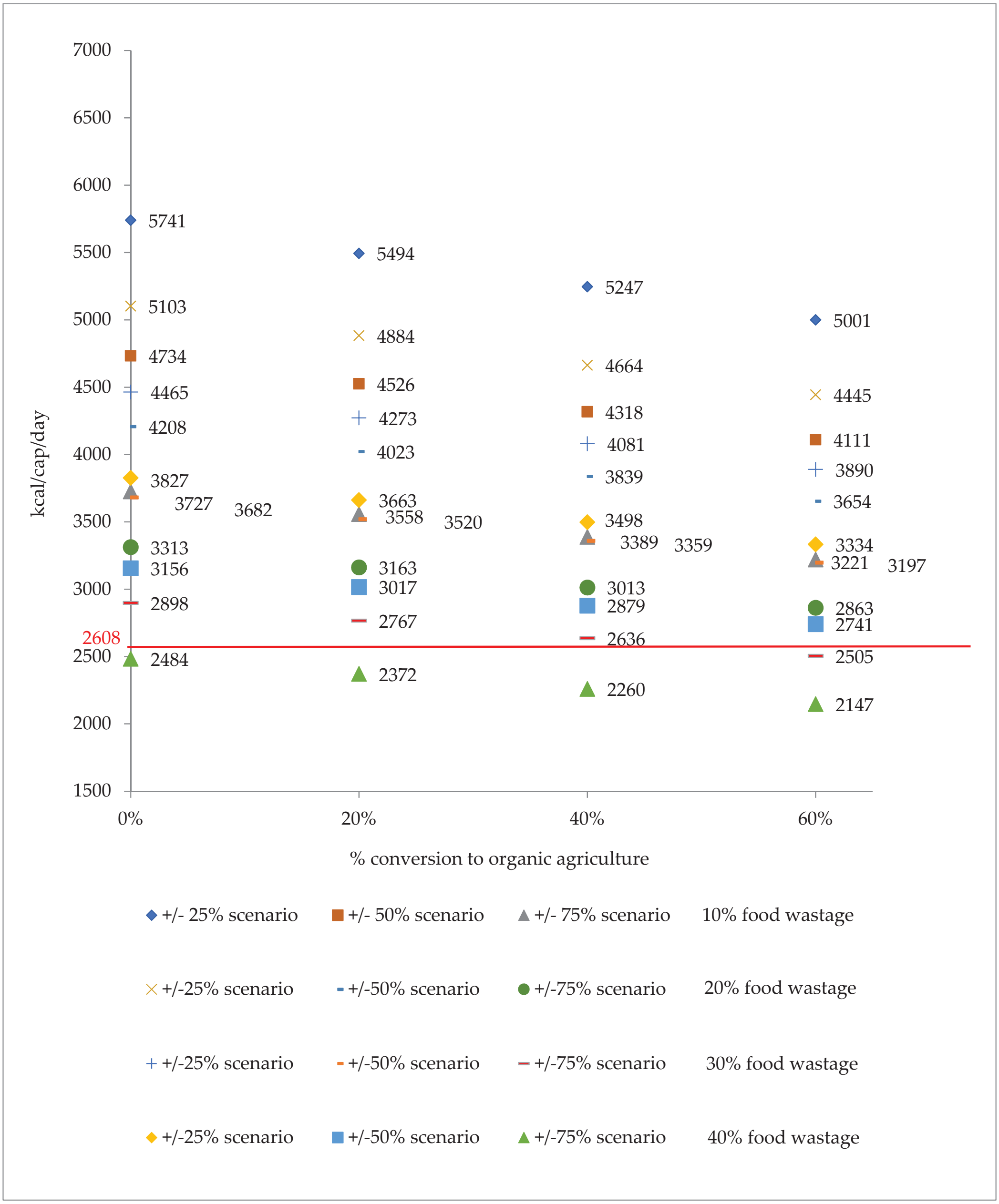


Figure 4. TFD vs. TFS for different variants of organic share $\beta \in \{20\%, 40\%, 60\%\}$, consumption style change scenarios $\alpha \in \{25\%, 50\%, 75\%\}$ and food wastage reduction $w \in \{10\%, 20\%, 30\%, 40\%\}$. Source: authors' own work.

Table 4. Additional information on protein and animal protein supply changes.

			Transition To More Sustainable Food Supply And Consumption											
			+/−25%				+/−50%				+/−75%			
			% Transition To Organic Agriculture											
			0%	**20%**	**40%**	**60%**	**0%**	**20%**	**40%**	**60%**	**0%**	**20%**	**40%**	**60%**
Food Wastage Levels	**10%**	animal protein/total protein	0.54	0.55	0.56	0.56	0.51	0.51	0.52	0.53	0.43	0.44	0.45	0.46
		protein energy/total kcal	0.16	0.17	0.17	0.17	0.15	0.15	0.15	0.16	0.13	0.13	0.13	0.14
		animal protein [g/cap/day]	155.25	152.14	149.04	145.93	109.81	107.61	105.42	103.22	64.38	63.09	61.80	60.51
	20%	animal protein/total protein	0.48	0.49	0.49	0.50	0.45	0.46	0.46	0.47	0.39	0.39	0.40	0.41
		protein energy/total kcal	0.15	0.15	0.15	0.15	0.13	0.14	0.14	0.14	0.12	0.12	0.12	0.12
		animal protein [g/cap/day]	138.00	135.24	132.48	129.72	97.61	95.66	93.71	91.75	57.22	56.08	54.93	53.79
	30%	animal protein/total protein	0.42	0.43	0.43	0.44	0.39	0.40	0.40	0.41	0.34	0.34	0.35	0.36
		protein energy/total kcal	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.10	0.10	0.10	0.11
		animal protein [g/cap/day]	120.75	118.33	115.92	113.50	85.41	83.70	81.99	80.28	50.07	49.07	48.07	47.07
	40%	animal protein/total protein	0.36	0.37	0.37	0.38	0.34	0.34	0.35	0.35	0.29	0.29	0.30	0.30
		protein energy/total energy	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09
		animal protein [g/cap/day]	103.50	101.43	99.36	97.29	73.21	71.74	70.28	68.81	42.92	42.06	41.20	40.34
	Data for no Food Wastage	animal protein/total protein	0.60 *	0.61	0.62	0.63	0.56 *	0.57	0.58	0.59	0.48 *	0.49	0.50	0.51
		protein energy/total energy	0.18 *	0.18	0.19	0.19	0.17 *	0.17	0.17	0.17	0.15 *	0.15	0.15	0.15
		animal protein [g/cap/day]	172.50 *	169.05	165.60	162.15	122.01 *	119.57	117.13	114.69	71.53 *	70.10	68.67	67.24

* Source: authors' own work, taking into account some calculations from [63].

4.3. Required Changes in the Use of Agricultural Land. Does Poland Have Enough Land to Increase Organic Production?

Results presented in Tables 3 and 4 indicate that even the scenario with $\beta = 60\%$ organic agriculture is possible, but only if combined with the $\alpha = 75\%$ scenario and a substantial food wastage reduction. Potential implications of changes in utilised agricultural area due to various degrees of transition to organic agriculture are presented below in (Figures 5 and 6a–d).

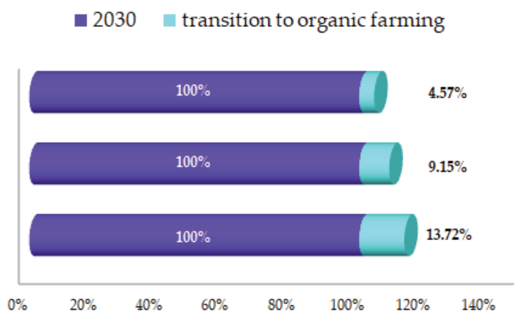


Figure 5. Potential changes in the use of arable land when switching to organic farming (20%/40%/60%). Source: authors' own work.

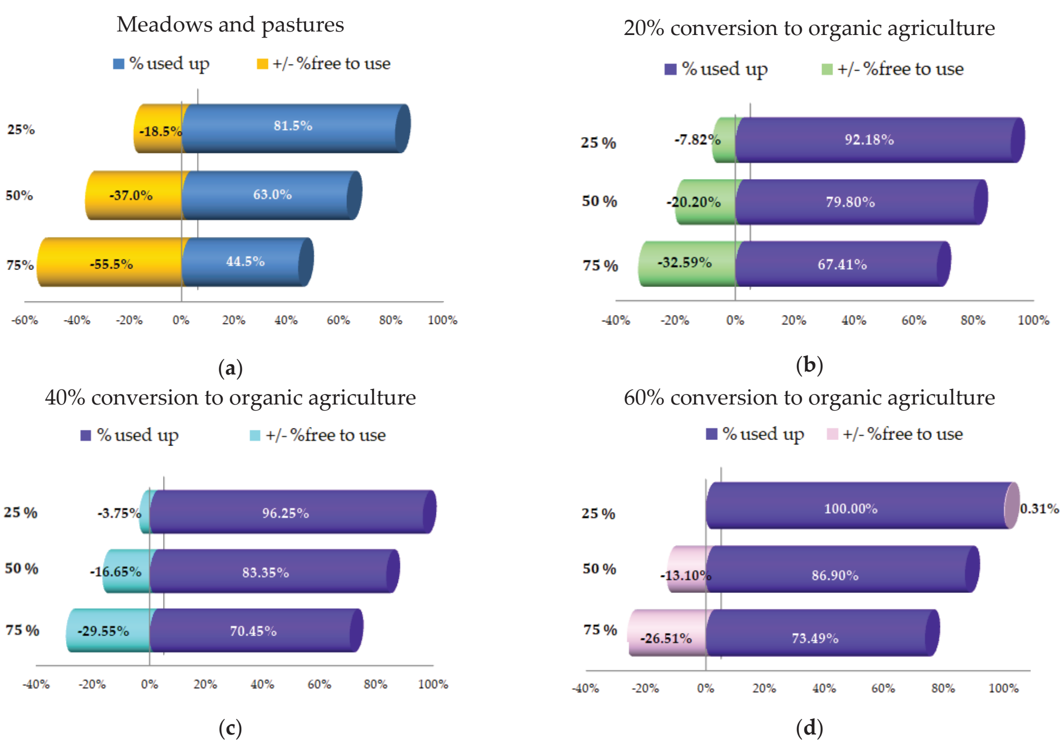


Figure 6. Changes in the use of agricultural land resulting from the transition to organic agriculture and sustainable consumption $\alpha \in \{25\%, 50\%, 75\%\}$; (**a**) meadows and pastures, (**b**) $\beta = 20\%$, (**c**) $\beta = 40\%$, (**d**) $\beta = 60\%$ transition to organic agriculture in 2030. Source: authors' own work.

If we consider a transition to organic agriculture without concurrent changes in consumption patterns, the area of arable land required for farming will likely have to be increased. Figure 5 shows that regardless of changes in organic share $\beta \epsilon \{20\%, 40\%, 60\%\}$ in 2030 it would be necessary to raise the area of utilised agricultural land from 4.5% to nearly 14% (from 0.62 million ha to 1.86 million ha). Only changes in consumption patterns offer the possibility of increasing organic share according to the estimates we have proposed.

Calculated area changes are based on the assumption that the output from meadows and pastures as well as green forage production on arable land do not decrease in spite of the transition to organic agriculture. We treat those crops as extensive, generally grown in an environmentally friendly manner. Productivity declines (by 25%) concern only remaining crops grown on arable land, e.g., allocated to consumption and animal feed.

The calculations performed in this subsection are related to two components of the present analysis: the transition to organic agriculture and the transition to a more sustainable consumption.

Figure 6 a presents potential changes in the use of meadows and pastures. Growing sustainable consumption (lower animal production, meat supply and consumption of selected meat types) is accompanied by an increase in the proportion of unused area for animal-feed crops. In 2030, according to the $\alpha = 75\%$ scenario, there may be as much as 55.5% (2.2 mln ha) of potentially unused area allocated to animal-feed crops (irrespective of the scale of organic agriculture) relative to adjusted 2030 data (without transition to organic agriculture or changes in consumption patterns).

With regard to ArL (Figure 6b–d), we considered changes both in consumer products and animal feed. Note that each of the proposed organic shares ($\beta \epsilon \{20\%, 40\%, 60\%\}$) shows a similar tendency for unoccupied area to grow. We may expect that a 25% decrease in the output of a part of plant production may lead to a shortage of area needed for obtaining the optimum amount of food and animal feed. However, changes in consumption patterns may have a significant impact on this phenomenon. A potential decrease in animal production, and consequently in required feed (mainly concentrate feed), leaves room for other crops. With an organic share of $\beta \epsilon \{20\%, 40\%\}$ and the $\alpha = 75\%$ scenario (with the largest cuts in animal production), there may be even 29.60% or 32.6% (4.0 million and 4.4 million ha) free space for ArL left.

In the most radical $\alpha = 75\%$ scenario and with 60% conversion into organic agriculture, there may be as much as approx. 26.5% (3.6 million ha) unoccupied ArL area. Only with $\beta = 60\%$ organic share and the $\alpha = 25\%$ scenario are considered do we see a slight growth in the area of ArL required for farming. Unused space may offer potential capabilities for consumer commodity production (e.g., more vegetables grown) or for the protection of agricultural and natural environment, soil conservation, etc. Considering that Polish arable land soils are poor in organic matter [72,73], it seems that this option may be advisable, particularly in the context of the transition to sustainable production.

5. Conclusions

The results presented here should be treated as a model and, as such, they required making a number of assumptions. Still, they reveal a certain potential in the Polish agriculture as well as the necessity to raise both consumer and supplier awareness. We believe that they can be used in the activities of decision makers, politicians, agricultural advisors and educators.

The findings allowed us to conclude that various extents of transition to organic agriculture are possible. Our analysis allowed us to answer the questions posed (Introduction section):

1. The paper proposes different shares of organic farming production in Poland, which can provide the necessary amount of energy and proteins per person per day in 2030. We performed the analysis for the share of organic production at the levels $\beta \epsilon \{20\%, 40\%, 60\%\}$. We find that even a 60% share of organic production

($\beta = 60\%$) is potentially feasible. It is able to provide energy at a level similar to TFD (2608 kcal/cap/day), as much as 2863 kcal/cap/day and 106 g of protein/cap/day. However, it will only be possible for the scenario assuming both $\alpha = 75\%$ change in consumption and $w = 20\%$ food waste. Other, perhaps more realistic situations involve a $\beta \epsilon \{20\%, 40\%\}$ share of organic agriculture with $w = 30\%$ food wastage and the $\alpha = 75\%$ scenario. This variant may be in line with the European Commission's commitment to allocate 25% arable land to organic agriculture by 2030. Unfortunately, the 40% level of food waste is typical of many developed countries. If we expect an increase in the share of organic farming production to β = 60%, then such a high level of food wastage may not provide the required TFD.

2. The success of this process (greater share of domestic organic farming products in the consumption of Polish society) will also depends on consumer awareness in terms of the need to curb food wastage and change dietary habits. Both of these issues are important factors that provide space for the development of organic farming. This is shown by the results in Table 3 and Figure 4 A 40% level of food wastage (with zero organic farming and no change in consumption style) gives an effect of 2485 kcal/cap/day in the 2030 adjusted. This is less than TFD. However, when the consumption style $\alpha \epsilon \{25\%,\ 50\%\}$ begins to change, then the scenario of the share of organic farming $\beta = 60\%$ becomes possible. Further gradual reduction of food wastage results in a large surplus of energy per person. Such a situation may provide a basis for considering an even wider development of organic production in Poland. The results of the analysis also demonstrate that the anticipated transition to organic production should not cause protein deficiencies, including animal protein deficiency, in Poles' everyday diet.
3. Our calculations indicate that a reduction in the consumption of selected meat types and selected plant product generates a decrease in production, thus freeing up space on grassland and arable land alike. A transition to even with $\beta = 60\%$ organic share and with $\alpha \epsilon \{50\%, 75\%\}$ scenarios is possible without increasing the area required to supply food for the population of Poland in 2030, although failure to make changes in consumption patterns may necessitate the use of a larger area of land for growing food. With radical changes in consumption style (α = 75%) and a 60% share of organic production, more than 26% of the free arable land is unused space.
4. There is also a question of how to use the potentially unoccupied space previously allocated for animal-feed production. We suggest that grassland be kept in accordance with good farming practices, continuing to provide animal feed, but also protecting the soil's ecosystem and serving as a habitat to many species. As for unused ArL, this would require some concepts with regard to potential use of free space: for commodities, but making it possible to grow more vegetables, or more inclined towards protecting soil ecosystem and accumulating organic matter. Both issues are of interest to the authors of this study.

On a final note, we would like to emphasise that permanent support for organic farmers is necessary, especially those who produce for consumer markets. Current per hectare subsidies, although not insignificant, should be constantly verified in terms of effort related to individual crops, as well as the shifting conditions of the organic products' market.

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Seed Exchange Networks of Native Maize, Beans, and Squash in San Juan Ixtenco and San Luis Huamantla, Tlaxcala, Mexico

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Abstract: Seed exchange networks among farmers favor circulation of crop varieties and have been discussed as an effective means of crop diversity conservation. This study aims to document the processes and structure of seed exchange networks of native maize, beans, and squash among farmers and other participating sectors (local market or seed banks), analyzing their influence on agrobiodiversity conservation in the municipalities of Ixtenco and Huamantla, in the Mexican state of Tlaxcala. Through interviews, questionnaires, and social network analysis, nodal farmers were identified. In the maize network, five nodal farmers were detected, the *blanco* maize being the most commonly exchanged seed. In the bean network, three nodal farmers were identified, with *amarillo* beans as the most exchanged seed. In the squash network, no nodal farmer was identified. For maize and beans, the greater the number of exchanges, the greater the varieties exchanged. The local market of Huamantla and the Vicente Guerrero seed bank are relevant seed sources. The nodal farmers propitiate circulation of a large number of seed varieties in the exchange networks and contribute to maintenance and conservation of agrobiodiversity.

Keywords: native seeds; nodal farmers; seed networks; agrobiodiversity; social network analysis

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1. Introduction

Farmers worldwide continually select native seed varieties for planting, adapting the attributes of the plants they cultivate to particular socio-environmental contexts and local management practices [1–3]. Seed varieties conserved by farmers form part of agrobiodiversity, and represent important reservoirs of genetic diversity [4–7]. Mexico is considered to be one of the nations with the greatest agrobiodiversity, and center of origin and diversification of maize, a variety of species of beans, and some species of squash [2,8,9], which are crucial to the diet of—and a source of income for—rural families [10]. Maintaining native varieties and free exchange of seeds among farmers is key to preserving agrobiodiversity and achieving sustainable agriculture in peasant communities [7,11–13].

Seed exchange involves a variety of strategies carried out by farmers to acquire or renew seeds [6,14] and is undertaken through social relations among family members, friends, and acquaintances [15,16]. Social networks are defined as sets of relationships among social actors which possess a structure through which information, behaviors, attitudes, and values are transmitted [17,18]. Studying the structure of a social network allows for understanding of the influence and significance of the actors in these networks, as well as the manner in which they are connected and form groups with other actors. Social Network Analysis (SNA) is a methodological tool that allows visualizing the structure of social relations (edges) among social actors (nodes), and measuring and analyzing interactions among members of the networks [17].

In recent years, SNA has been employed to evaluate management of agrobiodiversity [19,20]. These studies have allowed analyzing, visualizing, and measuring each node that forms part of a seed network [21–25], as well as identifying nodal farmers, those who are involved in a large number of exchanges of seed varieties [20,22,23,25–27].

Subedi et al. [20,26] and Poudel et al. [28] identified nodal farmers as those who maintain a relatively high seed diversity and are perceived in their communities as having extensive knowledge of plant varieties. They supply other farmers with seeds and maintain links which allow them to acquire new varieties. Authors such as Calvet-Mir et al. [24], Devkota et al. [25], Poudel et al. [22], Rodier and Struik [23] and Song et al. [27] have used SNA to identify nodal farmers, as those with the greatest level of centrality (number of connections a node contains) in a network. Rodier and Struik [23] defined nodal farmers as those with four or more direct connections in a network, while connector farmers are those who have high values of betweenness centrality (measure which indicates that a node may act as a bridge within the network). Nodal and connectors farmers are key actors in seed exchange networks. Nodal farmers have a high crop diversity as well as the capacity to exchange seed varieties with other farmers, thus promoting circulation of seeds [22,25]. Connector farmers may spread certain seed varieties toward other subgroups of the network, facilitating seeds reaching other farmers of distant areas or those who are less connected to the network [22]. In this manner, nodal and connector farmers contribute to the maintenance and conservation of agrobiodiversity [21,25,27]. However, seed networks are dynamic, a nodal or connector farmer may abandon this role after a certain period of time and other farmers may take on these roles. These changes may occur even from one agricultural cycle to another or after a few years [29].

One of the sustainable development goals is the eradication of hunger [30]. It is estimated that by 2050, the global population will reach 9.7 billion, and 10.8 billion by 2080. Therefore, there will be an increase in the demand for food production [31]. The family farming activities produces ~80% of the food worldwide [32,33]. Active participation by small-scale farmers in the conservation of local varieties is essential to achieving food security, as they tend to carry out environmentally sustainable agricultural practices, conserving agricultural land, as well as bearing knowledge and germplasm of native seeds—thereby also enhancing cultural diversity. These practices, together with seed exchanges, favor conservation of agrobiodiversity, which is crucial to achieving food security and sustainable development [12,13]. The seed exchange networks are central to agrobiodiversity conservation since farmers can access local seeds [16]. The farmers of Mexico select and save their seeds year after year to plant [2,9]; however, those who lose seeds, due to environmental factors such as droughts, frosts, floods, or pathogens, or those who seek to renew and acquire new varieties, frequently approach family members and friends within their community [6]. If networks of family members and friends are not able to provide them with seeds, nodal farmers can be an option to achieve the variety [20]. Aside from seed exchange networks, other options for farmers to obtain seeds include community seed banks, seed fairs, and local markets [34].

In order to analyze the functioning of the maize, beans, and squash seeds networks, this study examined the cases of the municipalities of San Juan Ixtenco (Ixtenco) and San Luis Huamantla (Huamantla) in the Mexican state of Tlaxcala. Farmers of these municipalities have maintained and preserved different races of maize (*Zea mays* L.) that belong to the conical racial group, which include the races *Chalqueño*, *Cónico*, *Elotes cónicos*, and *Cacahuacintle* [35]. This racial group is found from 2000 to 2800 m, and they are characterized by the production of conical cobs, with large numbers of grain rows (14–20), 4–8 mm grains and the presence of anthocyanins in the grains. To this racial group belong different native varieties of maize such as *azul*, *amarillo*, *blanco*, *negro*, etc. [35]. Moreover, the farmers of these municipalities maintained beans (*Phaseolus vulgaris* L.) [36], and squash (*Cucurbita pepo* L.) [37,38]. All these varieties of maize, beans and squash have been maintained due to traditions, diet, and economic criteria [39,40]. The municipality of Ixtenco represents a bastion in the conservation of different native varieties. In this municipality, there are maize varieties such as *negro*, *xocoyul* and *ajo* or *tunicado* (*Zea mays* var. tunicata A. St. Hil.) that are only preserved in this region. In the case of Huamantla (and despite being close to Ixtenco), commercial native varieties, such as *blanco* maize, and those used for animals, such as *amarillo* maize, hold greater importance among farmers. This study aims to analyze the structure and processes of interaction among farmers that conform seed exchange networks of native maize, beans, and squash and understand their influence on agrobiodiversity conservation in the municipalities referred to. To reach this goal, the seed exchange network was analyzed to identify the nodal farmers and to characterize the interactions related to seed exchange among farmers. Our main hypothesis was that maize, beans, and squash seed exchange networks can play an important role in maintaining diversity due to favoring of the movement of different seeds among farmers. We expected to find that the maize seed network contains a greater number of seed exchanges of different varieties of seeds and a greater number of nodal farmers than the bean and squash networks, since maize holds a greater dietary and commercial importance for the region's farmers. Finally, we expected to find a greater exchange of varieties that are widely used for subsistence and commerce due to the fact that farmers seek these types of seeds for cultivation.

2. Materials and Methods

2.1. Study Zone

The state of Tlaxcala has a sub-humid temperate climate with an average annual mean temperature of 14 °C and an annual precipitation averaging 800 mm with summer rains [41] (Figure 1). Seasonal agricultural systems are mainly cultivated to provide crops for family consumption. Problems associated with agricultural production include droughts and frosts [42].

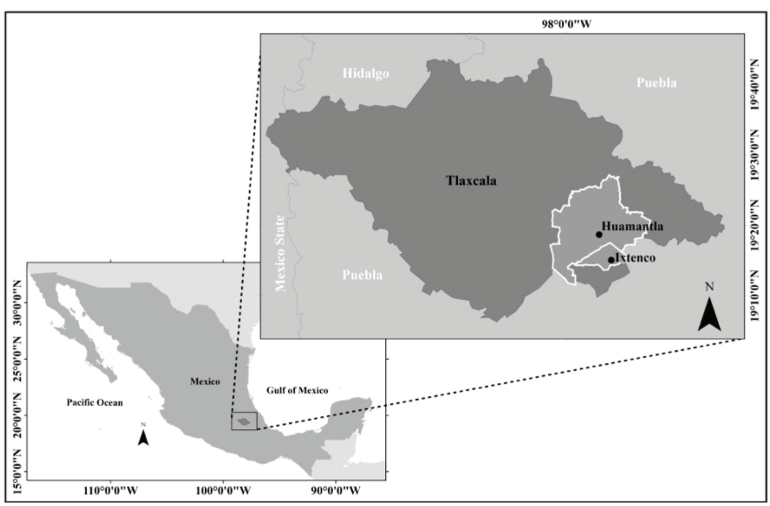

Figure 1. State of Tlaxcala, Mexico and location of the municipalities of Ixtenco and Huamantla.

2.2. Description of Study Sites

The municipalities of Ixtenco and Huamantla, in the western part of the state of Tlaxcala close to La Malinche volcano, are located 9.5 km from each other (Figure 1). In the municipality of Ixtenco, 6791 inhabitants live in 1689 homes, in a single *ejido* with a total area of 5917 hectares and 1777 *ejido* members [41,43]. The annual seed fair called "Fiesta del maíz" has been carried out for the past nine years [44]; in this event farmers of the municipality sell maize, beans, and squash as well their seeds. During the 2019 agricultural cycle, 10,251 tons of maize was reported to have been produced in seasonal crop systems, with an average yield of 3 ton/ha. Total bean production was 1.6 tons, with an average yield of 0.8 ton/ha [45].

The municipality of Huamantla has 84,979 inhabitants who live in 20,870 homes in 24 *ejidos* [41]. In this municipality, two *ejidos* were selected for fieldwork: San Luis Huamantla, with an area of 4826 hectares and 1946 *ejido* members, and Zaragoza, with a surface area of 1022 hectares and 322 *ejido* members [41,43]. During the 2019 agricultural cycle, a production of 19,500 tons of maize was reported in seasonal agricultural systems, with an average yield of 2.6 ton/ha. Total bean production was 39 tons, with an average yield of 0.7 ton/ha [45].

2.3. Interviews with Farmers

During 2018, 40 semi-structured interviews and 100 surveys were carried out in the study sites. A total of 20 interviews were carried out with farmers of Ixtenco (6 women and 14 men) and 20 with farmers of Huamantla (only men were interviewed) (Appendix A). Average age of farmers interviewed was 57.8 (age range 24–89 years). To select farmers, the snowball sampling technique was used. This technique allows for the obtainment of a series of contacts starting with a single informant. The researcher asks this informant for a contact with another person with certain characteristics depending on the research topic, who in turn is asked to name another person [46,47]. The first contact was initiated with key actors, including the coordinator of the seed fair "Fiesta del maíz" and participating farmers. These farmers in turn provided data about other farmers who had at least one variety of maize, beans, or squash. Later, interviews were carried out with farmers who participated in at least one seed exchange. The interview addressed the following topics: (a) conservation of and information regarding seed varieties, (b) seed exchanges, (c) soil preparation for planting, (d) seed sale, (e) knowledge of seed laws, and (f) festivities related to seeds. For the first topic, we recorded the number of varieties of maize, bean, and squash whose seeds were planted by each farmer. The second addressed with whom they exchanged seeds (family members, friends, neighbors, and other acquaintances) and dates of exchanges. The third covered plot description: surface area, location, soil type, and cultivation problems. The fourth addressed seed sale: place, quantity, and varieties sold. The fifth consisted of documenting the farmer's understanding of seed laws at the state and national levels. The final topic addressed farmer's participation in seed-related celebrations. All interviews were transcribed and codified by assigning key words (for example "maize exchange", "beans exchange", "squash exchange") for later analysis.

2.4. Questionnaires Applied to Farmers

Based on information from the interviews, in 2019 a survey was carried out with 100 farmers (50 per municipality): 13 women and 37 men from Ixtenco and 6 women and 44 men from Huamantla (Appendix A). In order to select farmers from the municipality of Ixtenco, for most streets of the village one of every five consecutive houses was selected. Given the difficulty of carrying out this methodology in Huamantla, as it is a city, which makes it complicated to contact the farmers, the local authorities were asked to invite men and women farmers. In the municipality of Ixtenco, approximately 1000 *ejido* members plant and conserve their seeds [48]. In the case of the *ejido* of San Luis Huamantla (the largest of the region) approximately 600 *ejido* members maintain their seeds and the total production of the *ejido* [49]. Based on this information, to expand the sample, 80 farmers of each municipality were invited to be surveyed. Selection of this sample size considered a 93% confidence level with a sampling error of 7%; however, a response was obtained from only 50 farmers per municipality.

2.5. Analysis of the Seed Networks

A graphic representation of the seed exchange network was constructed based on data from the surveys. Variables analyzed were number of maize, beans, and squash varieties that each farmer conserved, whether any of these varieties had been exchanged during the past five years, and if so with whom. These data served to determine the exchange network of each crop and to quantify the crop diversity that each farmer conserved (number of maize, bean, and squash varieties). We maintained in this research the local names of the native maize, beans and squash varieties. The majority of farmers of the two municipalities saved their own seeds every year to plant the following season, and therefore carried out few exchanges. For this reason, and due to the low frequency of exchanges each year mentioned by people interviewed, the decision was made to record the number of exchanges carried out by each farmer within the past five years (2015–2019). In order to provide a visual representation of the network, the open access program Cytoscape 3.7.1 was used [50,51]. The following data were employed for the SNA: farmer's municipality, gender, varieties of maize, beans, and squash exchanged, social relationship with whom the exchange was carried out (family member, friend, neighbor, or acquaintance), and place of origin of the person with whom the exchange was carried out, and place of origin of the seed (e.g., local market, seed bank).

The networks were analyzed as directed networks. Nodes represent farmers, local markets, stores, seed banks and other places, such as different states of Mexico and municipalities, where seeds were exchanged (Puebla, Querétaro, Terrenate, Altzayanca, El Carmen Tepexquitla, and Vicente Guerrero). Edges indicate the direction of a seed exchange between farmers. Outdegree is the number of times that a farmer gave seeds to another, and indegree is the number of times a farmer received seeds from another. Closeness centrality was interpreted as the speed with which a farmer could spread a seed variety. Finally, betweenness centrality was defined as the capacity to spread a variety to other sub-groups in the network, by which the variety may reach farmers of different sites. Nodal farmers were identified as those who carried out four or more seed exchanges (farmers with high outdegree within the network) involving three or more different seed varieties. In the case of squash, nodal farmers were defined as those who carried out four or more seed exchanges, although involving only one variety, due to the fact that in the study region only one local squash variety was cultivated. Connector farmers were identified as those with the highest values of betweenness centrality in the network ($\geq$0.5). In order to detect the nodal and connector farmers of each crop, and due to the fact that some farmers planted only one crop and/or variety, the maize, bean, and squash networks were analyzed separately. To carry out statistical analyses, the R program (R v.1.2.5.033 R Development Core Team) was employed, using the lm () and ggplot2 () functions.

3. Results

3.1. Agricultural Crops Registered in Ixtenco and Huamantla

On average, farmers cultivate 7 ha (range 0.004–60 ha). In Ixtenco, the farmers mainly conserve *blanco* (84%), *azul* (64%), *negro* (44%), *amarillo* (34%), *xocoyul* (28%) and *crema* (26%) maize, and in Huamantla *blanco* (80%), *amarillo* (52%) and *azul* (50%). These maize varieties are important for the market demand, owing to their color, appearance of cobs, their specific use for making traditional food and the quality of their kernels, which are used for handcrafts (Table 1 and Appendix B). In the case of bean crops, the farmers of the two municipalities, mainly conserve *negro*, *amarillo* and *bayo*, varieties used for family consumption and market (Table 1). In Ixtenco, a greater number of farmers conserve the squash crop (82%) than in Huamantla (72%), this crop is used for family consumption and for market (Table 1). In Ixtenco and Huamantla, 21 (42%) of the farmers maintain other crops such as *Vicia faba* (broad bean), *Lathyrus sativus* (pea) and *Avena sativa* (oat) (Table 1).

Table 1. Number of farmers who conserve maize, beans, squash and other crops in the municipalities of Ixtenco and Huamantla, Tlaxcala, Mexico.

Variety	Number of Farmers Who Conserve the Variety in Ixtenco (n = 50)	Number of Farmers Who Conserve the Variety in Huamantla (n = 50)	Benefits and Importance of the Variety to Farmers
		Maize varieties	
Blanco	42 (84%)	40 (80%)	The grain has a high market demand. Used for *tortillas* and flour. Appreciated for the weight, size, and color of cobs.
Amarillo	17 (34%)	26 (52%)	Principally for animal consumption. Appreciated for color and weight of cobs.
Azul	32 (64%)	25 (50%)	Appreciated for color and appearance of cobs. Due to increased demand in recent years, it is sold at a higher price than other varieties.
Crema	13 (26%)	4 (8%)	Appreciated for the weight of cobs.
Negro	22 (44%)	7 (14%)	Highly appreciated by farmers of Ixtenco. Used to make the traditional cooked fermented corn drink "*atole agrio*".
Cacahuacintle	23 (46%)	3 (6%)	Used for making traditional Mexican food such as *pozole*, and maize flour.
Ocho carreras	-	3 (6%)	Appreciated for size and weight of cobs.
Xocoyul	14 (28%)	2 (4%)	Its flour is used for preparing the beverage *atole*, appreciated for its pink color.
Campeón	1 (2%)	2 (4%)	Appreciated for the large size and weight of cobs.
Ajo o tunicado	5 (10%)	-	High cultural value in Ixtenco due to cob characteristics.
Chalqueño	-	3 (6%)	Appreciated for color and size of kernel.
Rojo	18 (36%)	1 (2%)	Used to make maize flour.
Cruza blanco-campeón	-	1 (2%)	Appreciated for color and the cobs.
Sangre de cristo	10 (20%)	-	Its flour is used for *atole* and the kernels for handcrafts.
Arrocillo-palomero	2 (4%)	1 (2%)	Marketed and used for family consumption.
Ancho	-	1 (2%)	Appreciated for short agricultural cycle.
		Bean varieties	
Amarillo	23 (46%)	22 (44%)	It is marketed and used for family consumption.
Negro	25 (50%)	11 (22%)	It cooks rapidly and is marketed and used for family consumption.
Bayo	14 (28%)	18 (36%)	It is marketed and used for family consumption.
Mantequilla	3 (6%)	2 (4%)	It is marketed and used for family consumption.

Table 1. *Cont.*

Variety	Number of Farmers Who Conserve the Variety in Ixtenco (*n* = 50)	Number of Farmers Who Conserve the Variety in Huamantla (*n* = 50)	Benefits and Importance of the Variety to Farmers
Parraleño	3 (6%)	-	It is marketed and used for family consumption.
Pinto	3 (6%)	3 (6%)	It is marketed and used for family consumption.
Ojo de liebre	1 (2%)	2 (4%)	It is marketed and used for family consumption.
Vaquita	-	3 (6%)	It is marketed and used for family consumption.
Morado	-	1 (2%)	It is marketed and used for family consumption.
Flor de mayo	-	1 (2%)	It is marketed and used for family consumption.
		Squash variety	
Squash	41 (82%)	36 (72%)	It is appreciated by farmers for the size of the seeds, its color, and its productivity.
		Other crops	
*	21 (42%)	21 (42%)	These crops are for market and used for family consumption.

* *Vicia faba* (broad bean), *Lathyrus sativus* (pea), *Avena sativa* (oat), *Opuntia* spp. (prickly pear), *Amaranthus* spp. (amaranth), *Triticum aestivum* L. (wheat), *Secale cereal* L. (rye), *Lens* spp. (lentil), *Physalis ixocarpa* (green tomato), *Helianthus* L. (sunflower), *Prunus persica* (peach), *Medicago sativa* (lucerne), *Agave* (maguey) and *Brassica oleracea* var. itálica (broccoli).

3.2. Maize Exchange Network

A total of 18 different maize varieties were exchanged and on average, each farmer carried out 1.93 $\pm$ 1.47 exchanges of 1.62 $\pm$ 0.94 maize varieties in the past five years (Table 2). As shown in Table 2, *blanco* maize had the greatest number of exchanges (52), followed by *amarillo* (26) and *azul* (22) maize. These varieties were the three most exchanged among farmers. Exchanges were carried out among acquaintances from the same locality (73), family members (26) and to a lesser extent friends (20), neighbors (12) and people who the farmers did not know, yet approached to obtain seeds (13). The number of exchanges carried out varies according to the variety of maize (Table 2).

Table 2. Number and percentage of exchanges carried out by variety of maize among farmers of Ixtenco (I) and Huamantla (H), Tlaxcala, Mexico from 2015 to 2019.

Maize Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers Who Exchanged the Variety	Number of Exchanges among Actors in the Maize Network					
						Family Mem-bers (Fa)	Friends (Fr)	Neighbors (N)	Acquaintan (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Location
Blanco	52	36	I	19	14	2 (10.53%)	4 (21.05%)	2 (10.53%)	10 (52.63%)	1 (5.26%)	3
			H	33	22	5 (15.15%)	-	5 (15.15%)	21 (63.64%)	2 (6.06%)	2
Amarillo	26	18	I	11	9	5 (45.45%)	2 (18.18%)	-	3 (27.27%)	1 (9.09%)	-
			H	15	9	2 (13.33%)	1 (6.67%)	1 (6.67%)	10 (66.67%)	1 (6.67%)	1
Azul	22	17	I	10	8	1 (10%)	3 (30%)	-	5 (50%)	1 (10%)	-
			H	12	9	3 (25%)	1 (8.33%)	1 (8.33%)	5 (41.67%)	2 (16.67%)	1
Crema	7	7	I	5	3	1 (20%)	1 (20%)	-	3 (60%)	-	1
			H	2	2	-	-	-	1 (50%)	1 (50%)	1
Negro	7	5	I	3	3	1 (33.33%)	1 (33.33%)	-	-	1 (33.33%)	-
			H	4	2	-	1 (25%)	-	3 (75%)	-	-
Cacahuacintle	5	3	I	3	2	2 (66.67%)	1 (33.33%)	-	-	-	-
			H	2	1	-	1 (50%)	-	1 (50%)	-	-
Ocho carreras	4	2	I	-	-	-	-	-	-	-	-
			H	4	2	-	-	2 (50%)	2 (50%)	-	-

Table 2. *Cont.*

Maize Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers Who Exchanged the Variety	Number of Exchanges among Actors in the Maize Network					
						Family Mem-bers (Fa)	Friends (Fr)	Neighbors (N)	Acquaintan (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Location
Xocoyul	3	3	I	2	2	-	1 (50%)	-	1 (50%)	-	-
			H	1	1	-	-	-	1 (100%)	-	-
Campeón	3	3	I	1	1	1 (100%)	-	-	-	-	1
			H	2	2	1 (50%)	-	-	1 (50%)	-	1
Ajo o tunicado	3	2	I	3	2	2 (66.67%)	-	-	1 (33.33%)	-	1
			H	-	-	-	-	-	-	-	-
Chalqueño	2	2	I	-	-	-	-	-	-	-	-
			H	2	2	-	-	-	1 (50%)	1 (50%)	-
Rojo	2	2	I	1	1	-	-	-	1 (100%)	-	-
			H	1	1	-	1 (100%)	-	-	-	-
Cruza crema-blanco	2	2	I	2	2	-	1 (50%)	-	-	1 (50%)	1
			H	-	-	-	-	-	-	-	-
Cruza blanco-campeón	2	1	I	-	-	-	-	-	-	-	-
			H	2	1	-	-	1 (50%)	1 (50%)	-	-
Sangre de cristo	1	1	I	1	1	-	-	-	1 (100%)	-	-
			H	-	-	-	-	-	-	-	-

Table 2. *Cont.*

Maize Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers Who Exchanged the Variety	Number of Exchanges among Actors in the Maize Network					
						Family Members (Fa)	Friends (Fr)	Neighbors (N)	Acquaintan (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Location
Arrocillo-palomero	1	1	I	1	1	-	1 (100%)	-	-	-	-
			H	-	-	-	-	-	-	-	-
Amealco	1	1	I	1	1	-	-	-	-	1 (100%)	1
			H	-	-	-	-	-	-	-	-
Ancho	1	1	I	1	1	-	-	-	1 (100%)	-	-
			H	-	-	-	-	-	-	-	-
		Total Ixtenco	I	64	51	15	15	2	26	6	8
		Total Huamantla	H	80	54	11	5	10	47	7	6
		Total	I-H	144	105	26	20	12	73	13	14

The directed network of the maize crop consists of 134 nodes with a total of 144 exchanges from 2015 to 2019 (Table 2 and Figure 2).

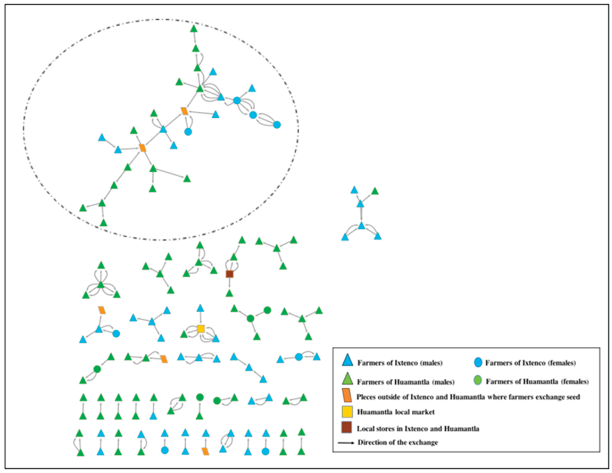

Figure 2. Maize seed network consisting of 134 nodes among farmers of Ixtenco (blue) and Huamantla (green), other places where they exchange seed (orange), local markets (yellow) and local stores (brown). The arrow indicates the direction of the exchange. Note: The dotted circle indicates the principal module of the network.

In Figure 2, the maize network shows a principal module and sub-networks separated from the principal module. Some 22 dyads are observed, in which 31 exchanges were carried out. The *blanco* maize variety was involved in 15 exchanges, the *azul* variety in 5, *amarillo* in 6, and the *chalqueño*, *rojo*, *amealco*, *crema*, and *xocoyul* varieties in only one exchange each. These dyads involved seventeen farmers from Ixtenco (15 men and 2 women) and 26 (24 men and 2 women) from Huamantla. One farmer from Ixtenco exchanged maize seed with a farmer from the state of Queretaro. The greatest number of exchanges (12) were between people who knew each other and lived in the same location. A total of 10 exchanges (one third) took place between family members living in the same location. The exchanges among family members occurred from fathers to sons or sons to fathers, between brothers, or among political family. Exchanges between neighbors (4) and friends (4) occurred between people of the same location, and only one exchange took place between a farmer and a person unknown to them.

A total of 5 triads were identified, involving 16 exchanges. Each variety was involved in the following number of exchanges among triads: *azul* (6), *blanco* (4), *amarillo* (3), *ocho carreras* (2), and *crema* (1). Twelve of these exchanges were among acquaintances of the same location, three among neighbors, and only one among family members. Ten tetrads and one hexad were identified. In the tetrads, 47 exchanges were conducted, many of which involved the local market node of Huamantla, where farmers from Ixtenco and Huamantla buy and sell *blanco*, *azul*, and *amarillo* maize seed. The exchanges in the tetrads were among acquaintances (24), people who did not know each other (12), family members (4), neighbors, (4) and friends (3). In the hexads, eight exchanges were carried out, involving *blanco* maize (5 exchanges) and *crema* maize (3) and these exchanges were among acquaintances (7) and friends (1).

Five nodal farmers were identified in this network (four men and one woman; Table 3). Four of these nodal farmers are from the municipality of Ixtenco and one from Huamantla. Three connector farmers were identified: one from Ixtenco and two from Huamantla.

Table 3. Measures of centrality of the nodes conforming the maize seed exchange network of Ixtenco and Huamantla, Tlaxcala, Mexico.

Node	Location of Farmer/Site Where the Seed Is from	Nodal (N) or Connector Farmer (C)	Outdegree	Indegree	Number of Different Varieties Exchanged	Betweenness Centrality	Closeness Centrality
F84	Huamantla	N	9	0	3	0	1
F121	Ixtenco	N	7	0	5	0	0.444
F33	Ixtenco	N	5	0	3	0	0.571
F44	Ixtenco	N	5	2	5	0.006	0.5
F11	Ixtenco		4	0	2	0	1
F21	Ixtenco		4	0	2	0	1
F34	Ixtenco	N	4	0	4	0	0.666
Agrochemical store	Agrochemical store		4	0	4	0	0.75
F5	Ixtenco		3	1	3	0.333	1
F132	Ixtenco		3	0	3	0	1
F32	Ixtenco		3	0	3	0	1
Huamantla local market	Huamantla local market		3	5	3	0.333	1
F41	Ixtenco		3	0	3	0	1
F71	Huamantla		3	1	2	0.005	0.666
F100	Huamantla		3	7	3	0.0185	0.8
F85	Huamantla		3	0	2	0	1
F1	Ixtenco		2	0	2	0	1
F30	Ixtenco	C	2	1	1	0.5	1
F35	Ixtenco		2	0	2	0	1
F62	Huamantla		2	1	2	0.333	1
F64	Huamantla		2	1	1	0.333	1
F88	Huamantla		2	4	2	0.333	1
F79	Huamantla	C	2	1	2	0.5	1
F96	Huamantla	C	2	2	2	1	1
F98	Huamantla		2	1	1	0.333	1

Nodal (N) and connector farmers (C) are identified. Outdegree indicates the number of times a farmer gave maize seeds to another farmer and indegree the number of times a farmer received seeds from another farmer.

The greater the number of exchanges that a farmer carried out with other farmers, the greater the number of maize varieties exchanged; that is, farmers who carried out more seed exchanges with other farmers also exchanged a greater number of different maize seed varieties (Figure 3).

Figure 4 provides a close-up view of the principal module of the network, which includes 20.1% of the nodes, of which 12 are farmers from Ixtenco and 15 from Huamantla. In this principal module, farmers from Ixtenco and Huamantla had carried out seed exchanges with people from the municipality of Terrenate and the state of Puebla.

The principal module involves a greater number of seed exchanges between farmers of the same municipality. Four women farmers stand out, all of them from Ixtenco. Of these, F121 is considered a woman nodal farmer due to the high outdegree carrying out a large number of exchanges: seven exchanges of a total of five different varieties (*azul*, *cacahuacintle*, *amarillo*, *negro*, and *ajo* maize; Table 3). This nodal farmer has given *cacahuacintle*, *amarillo*, *negro*, and *ajo* maize seeds to a woman farmer from Ixtenco (F29), and *negro* and *azul* maize seeds to another farmer, also from Ixtenco (F44), the latter in turn has shared seeds of these two varieties with a farmer of Huamantla (F100). Another nodal farmer (F33 from Ixtenco) carried out five exchanges of three maize varieties (*amarillo*, *azul*, and *blanco*) with people from Ixtenco, as well with people from the municipalities of Huamantla and Terrenate, and other areas of the state of Puebla (Table 3).

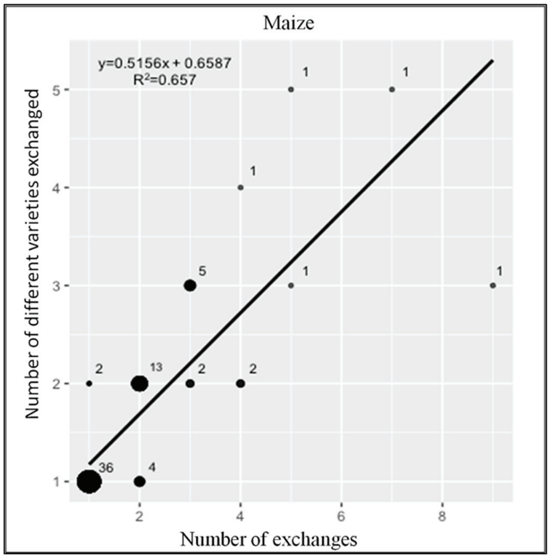

Figure 3. Relationship between number of exchanges and number of maize varieties exchanged by each farmer of Ixtenco and Huamantla participating in the maize seed exchange network ($n = 69$). Note: This graph employed outdegree of each node of the network, without considering local markets and stores.

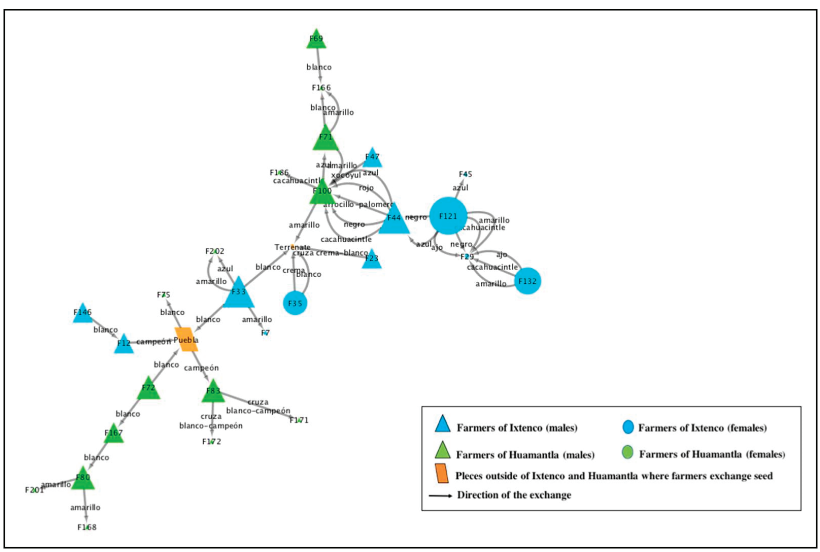

Figure 4. Principal module of the maize network with respect to outdegree. The greater the node size, the greater the number of exchanges carried out. Farmers of Ixtenco (blue) and Huamantla (green), other places where they exchange seeds (orange), local markets (yellow) and local stores (brown). The arrow indicates the direction of the exchange.

3.3. Bean Exchange Network

A total of nine different bean varieties were exchanged in the two municipalities (Table 4). On average, each farmer carried out 2.3 ± 1.84 exchanges of 1.93 ± 1.08 varieties of beans from 2015 to 2019. As shown in Table 4, *amarillo* and *negro* beans were involved in the greatest number of exchanges (28), followed by *bayo* (19). The bean exchanges were principally carried out between acquaintances from the same location (43), followed by people who did not know each other but approached these farmers to obtain seeds (22), and to a lesser extent between family members (17) and friends (10).

The directed network for exchange of bean seeds consists of 79 nodes, with a total of 92 exchanges from 2015 to 2019 (Figure 5).

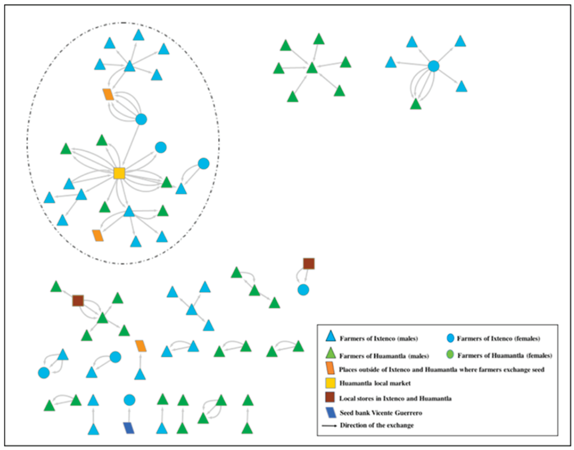

Figure 5. Bean seed network consisting of 79 nodes among farmers of Ixtenco (blue) and Huamantla (green), other places where they exchange seeds (orange), local markets (yellow), local stores (brown) and local seed bank (dark blue). The arrow indicates the direction of the exchange. Note: The dotted circle indicates the principal module of the network.

In Figure 5, the network shows a principal module which includes different municipalities of Tlaxcala to which farmers have spread seeds, including Terrenate and El Carmen Tequexquitla. This network includes 14 dyads, in which 24 exchanges were carried out, involving 12 nodes of Ixtenco and 13 nodes of Huamantla. In these dyads, farmers from Ixtenco obtained seeds through a local store, and one farmer gave seeds to a person from Puebla. The majority of the dyads involved family members and acquaintances of the same location exchanging *amarillo* bean seeds. *Amarillo* beans were involved in eight exchanges, the *bayo* variety in seven, *negro* beans in six, and *parraleño*, *morado*, and *pinto* beans in one exchange each. Twelve farmers from Ixtenco (eight men and four women) were involved in these dyads, and 13 (all men) from Huamantla. One farmer from Ixtenco exchanged *parraleño* beans with a farmer from the state of Puebla, and a woman farmer from Ixtenco acquired *amarillo* bean seed in a local store. Most exchanges (15) were carried out between people who knew each other and lived in the same location. Six exchanges were recorded between family members and three between friends. In one triad, *amarillo* and *mantequilla* bean seeds were exchanged between farmers from Huamantla. One woman farmer from Ixtenco received *morado* bean seeds from the Vicente Guerrero seed bank. This fragmented part of the network is composed of a tetrad, two hexads and a heptad.

In this network, three nodal farmers (two women and one man) were detected, all from the municipality of Ixtenco (Table 5). Only one connector farmer was detected in the municipality of Huamantla.

Table 4. Number and percentage of exchanges carried out by variety of bean among farmers of Ixtenco (I) and Huamantla (H), Tlaxcala, Mexico from 2015 to 2019.

Bean Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers who Exchanged the Variety	Number of Exchanges among Actors in the Bean Network					
						Family Members (Fa)	Friends (Fr)	Neighbors (N)	Acquaintances (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Location
Amarillo	28	21	I	18	11	2 (11.11%)	4 (22.22%)	-	8 (44.44%)	4 (22.22%)	3
			H	10	10	1 (10%)	-	-	6 (60%)	3 (30%)	-
Negro	28	28	I	19	13	3 (15.79%)	5 (26.32%)	-	8 (42.11%)	3 (15.79%)	3
			H	9	8	2 (22.22%)	-	-	3 (33.33%)	4 (44.44%)	-
Bayo	19	19	I	7	6	3 (42.86%)	1 (14.29%)	-	3 (42.86%)		1
			H	12	11	1 (8.33%)	-	-	6 (50%)	5 (41.67%)	-
Mantequilla	6	6	I	4	3	2 (50%)	-	-	1 (25%)	1 (25%)	1
			H	2	2	1 (50%)	-	-	1 (50%)	-	-
Parraleño	3	3	I	3	2	1 (33.33%)	-	-	2 (66.67%)	-	1
			H	-	-	-	-	-	-	-	-
Pinto	3	3	I	1	1	1 (100%)	-	-	-	-	1
			H	2	2	-	-	-	1 (50%)	1 (50%)	-
Ojo de liebre	2	2	I	1	1	-	-	-	1 (100%)	-	-
			H	1	1	-	-	-	1 (100%)	-	-

Table 4. *Cont.*

Bean Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers who Exchanged the Variety	Number of Exchanges among Actors in the Bean Network					
						Family Mem-bers (Fa)	Friends (Fr)	Neighbors (N)	Acquaintances (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Location
Vaquita	2	2	I	1	1	-	-	-		1 (100%)	-
			H	1	1	-	-	-	1 (100%)	-	-
Morado	1	1	I	1	1	-	-	-	1 (100%)	-	-
			H	-	-	-	-	-	-	-	-
		Total Ixtenco	I	55	39	12	10	-	24	9	20
		Total Huamantla	H	37	35	5	-	-	19	13	-
		Total	I-H	92	74	17	10	-	43	22	20

Table 5. Measures of centrality of the nodes conforming the bean seed exchange network of Ixtenco and Huamantla, Tlaxcala, Mexico.

Node	Locality of Farmer/Site Where the Seed Is from	Nodal (N) or Connector Farmer (C)	Outdegree	Indegree	Number of Different Varieties Exchanged	Betweenness Centrality	Closeness Centrality
Huamantla local market	Huamantla local market		16	3	7	0.050	0.7
F14	Ixtenco	N	8	0	4	0	1
F32	Ixtenco		6	2	2	0.021	1
F33	Ixtenco	N	6	1	4	0.009	1
F35	Ixtenco	N	6	0	5	0	0.444
Huamantla local store	Huamantla local store		4	0	3	0	0.625
F22	Ixtenco		3	0	3	0	1
F70	Huamantla		3	3	3	0.15	1
F15	Ixtenco		2	0	2	0	1
F25	Ixtenco		2	1	2	0.010	1
Ixtenco local store	Ixtenco local store		2	0	1	0	1
F34	Ixtenco		2	0	2	0	0.428
F121	Ixtenco		2	0	2	0	1
F48	Ixtenco		2	0	2	0	1
F61	Huamantla		2	0	2	0	1
F84	Huamantla	C	2	1	2	0.5	1
F1	Ixtenco		1	0	1	0	1
Vicente Guerrero seed bank	Vicente Guerrero seed bank		1	0	1	0	1
F12	Ixtenco		1	0	1	0	1
F2	Ixtenco		0	1	1	0	0
F40	Ixtenco		0	3	2	0	0
F27	Ixtenco		0	2	2	0	0
F29	Ixtenco		0	2	1	0	0
F43	Ixtenco		0	3	3	0	0
F45	Ixtenco		0	2	2	0	0

Nodal (N) and connector farmers (C) are identified. Outdegree indicates the number of times a farmer gave bean seeds to another farmer, and indegree the number of times a farmer received seeds from another farmer.

As with maize, the greater the number of bean seed exchanges carried out among farmers, the greater the number of varieties exchanged (Figure 6).

The principal module of the network included 31.6% of nodes, of which 17 were farmers from Ixtenco and five from Huamantla (Figure 7). This module includes the node of the Huamantla local market, in which farmers of the municipalities studied obtain and sell seeds. In this local market, *amarillo*, *bayo*, *mantequilla*, *negro*, *pinto*, and *vaquita* bean seeds may be acquired. Two farmers of the module gave seeds to people of Terrenate and El Carmen Tequexquitla, municipalities close to Huamantla.

The principal module included two nodal farmers (F33 and F35); F33 gave seeds of four varieties (*amarillo* bean, *bayo*, *negro*, and *ojo de liebre*) to six people, two of whom were from Terrenate. Meanwhile, F35 carries *amarillo* bean seeds to sell in the Huamantla local market and provides *amarillo*, *negro*, *bayo*, *pinto*, and *mantequilla* bean seeds to people of Terrenate.

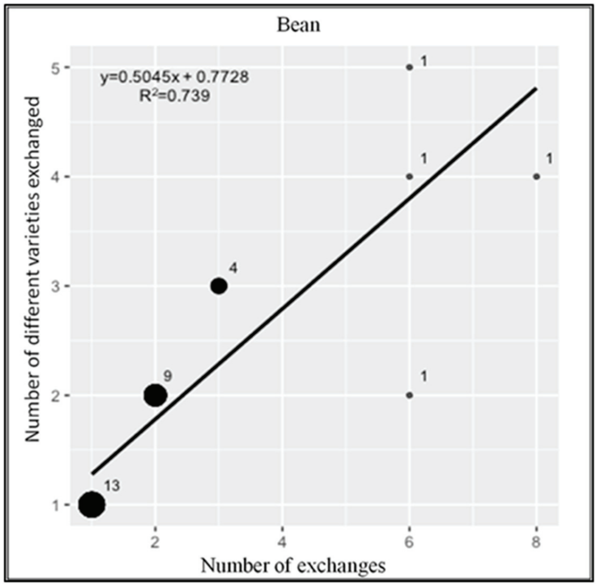

Figure 6. Relationship between number of exchanges and number of bean varieties exchanged by each farmer of Ixtenco and Huamantla participating in the bean seed exchange network (n = 30). Note: This graph employed outdegree of each node of the network, without considering local markets and stores.

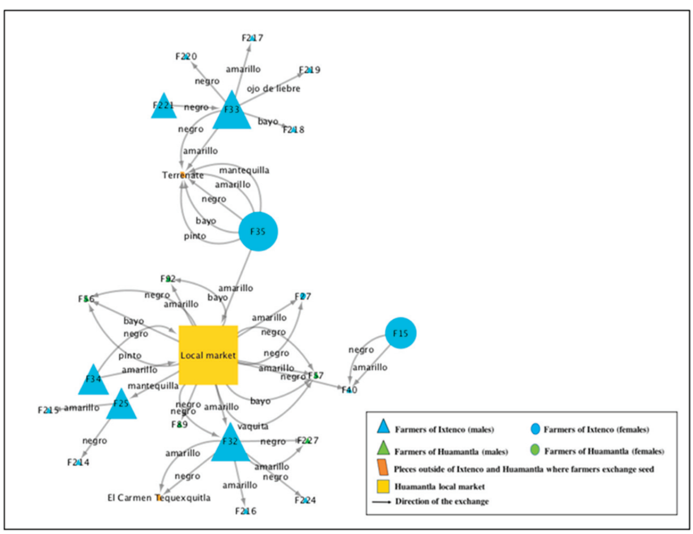

Figure 7. Principal module of the bean network with respect to outdegree. The greater the node size, the greater the number of exchanges carried out. Farmers of Ixtenco (blue) and Huamantla (green), other places where they exchange seed (orange), local markets (yellow) and local stores (brown). The arrow indicates the direction of the exchange.

3.4. Squash Exchange Network

Only one native variety of squash is cultivated in the study area. Farmers call it "creole squash". The farmers involved in this network carried out 1.17 ± 0.51 exchanges of this variety. Squash was involved in a total of 41 exchanges, approximately half of which were between acquaintances of the same locality (20). The others were with people who the farmers did not know, but approached to obtain seeds (8), others were friends (6), family members (5), and neighbors (2) (Table 6).

The directed network of this crop consists of 64 nodes, with a total of 41 exchanges from 2015 to 2019 (Figure 8). This network involves a series of segmented subnetworks.

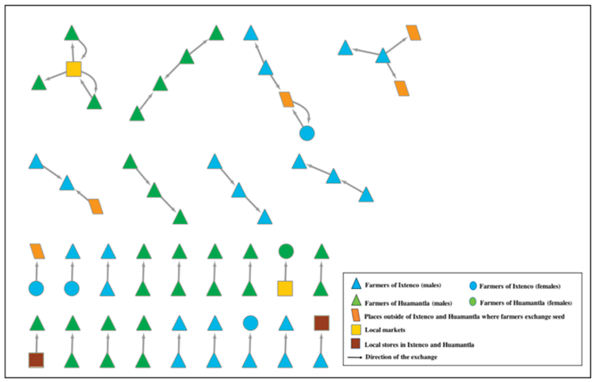

Figure 8. Squash seed network consisting of 64 nodes among farmers of Ixtenco (blue) and Huamantla (green), other places where they exchange seed (orange), local markets (yellow) and local stores (brown). The arrow indicates the direction of the exchange.

The squash network consists of 18 dyads in which 18 exchanges were carried out (Figure 8). The exchanges in these dyads were between farmers of the same locality—principally acquaintances, and three farmers obtained squash seeds through local stores and local markets. A total of 14 farmers of Ixtenco (11 men and three women) and 18 from Huamantla (17 men and one woman) were involved in these dyads. One female farmer from Ixtenco carried out an exchange with a male farmer from the nearby municipality of Terrenate. In these dyads, seeds were also acquired at the Ixtenco local market and local stores in Ixtenco and Huamantla. Nine exchanges between acquaintances of the same locality were recorded, including, four exchanges between family members—from parents to sons and among political family. Three exchanges were carried out between people who did not know each other, one between friends, and one between neighbors. Four triads were identified, involving a total of eight exchanges between farmers of the same location and one with a person from Querétaro. Four tetrads were identified, with a total of 15 exchanges, one of which involved the Huamantla local market, where three farmers from Huamantla went to obtain or sell squash seeds. Some farmers had given squash seeds to people of sites close to the study municipalities, including Vicente Guerrero, Apizaco, and Terrenate, and some farmers had given seeds to people of other states such as Puebla.

In this network, no nodal farmer and only three connector farmers were found (two from Ixtenco and one from Huamantla) (Table 7).

Table 6. Number and percentages of exchanges carried out of squash seeds among farmers of Ixtenco (I) and Huamantla (H), Tlaxcala, Mexico from 2015 to 2019.

Squash Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers Who Exchanged the Variety	Number of Exchanges among Actors in the Squash Network					
						Family Members (Fa)	Friends (Fr)	Neighbors (N)	Acquaintan (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Locality
Squash	41	41	I	21	15	4 (19.05%)	4 (19.05%)	2 (9.52%)	10 (47.62%)	1 (4.76%)	5
			H	20	16	1 (5%)	2 (10%)	-	10 (50%)	7 (35%)	-
		Total Ixtenco	I	21	15	4	4	2	10	1	10
		Total Huamantla	H	20	16	1	2	-	10	7	-
		Total	I-H	41	31	5	6	2	20	8	10

Table 7. Measurements of centrality of the nodes conforming the squash seed exchange network of Ixtenco and Huamantla, Tlaxcala, Mexico.

Node	Location of the Farmer/Site Where the Seed Is from	Nodal (N) or Connector Farmer (C)	Outdegree	Indegree	Number of Different Varieties Exchanged	Betweenness Centrality	Closeness Centrality
F32	Ixtenco		3	0	1	0	1
Huamantla local market	Huamantla local market		3	2	1	0.666	1
F5	Ixtenco		2	0	1	0	0.75
F63	Huamantla		2	0	1	0	1
F1	Ixtenco		1	0	1	0	1
F2	Ixtenco		1	1	1	0	1
Vicente Guerrero	Vicente Guerrero		1	2	1	0.166	1
F4	Ixtenco		1	0	1	0	1
F6	Ixtenco		1	0	1	0	1
F16	Ixtenco	C	1	1	1	0.5	1
F17	Ixtenco		1	0	1	0	1
F26	Ixtenco	C	1	1	1	0.5	1
F28	Ixtenco		1	0	1	0	0.666
FI2	Ixtenco		1	0	1	0	1
F35	Ixtenco		1	0	1	0	1
F49	Ixtenco		1	0	1	0	1
F61	Huamantla		1	0	1	0	1
F60	Huamantla		1	1	1	0	0.6
Ixtenco local market	Ixtenco local market		1	0	1	0	1
F82	Huamantla		1	0	1	0	1
Huamantla local store	Huamantla local store		1	0	1	0	1
F53	Huamantla		1	1	1	0	0.6
F77	Huamantla		1	0	1	0	1
F70	Huamantla		1	0	1	0	1
F58	Huamantla	C	1	1	1	0.5	1

Nodal (N) and connector farmers (C) are indicated. Outdegree indicates the number of times a farmer gave squash seeds to another farmer, and indegree the number of times farmer received seeds of another farmer.

3.5. Seed Exchange among Farmers from Ixtenco and Huamantla

Of all farmers interviewed (n = 40), in the past five years, 42.5% of those from Ixtenco and 22.5% of those from Huamantla carried out at least one seed exchange. Farmers named several reasons for exchanging seeds: recovering seeds, increasing varieties, making handcrafts, replacement, lending seeds, planting the crop for the first time, and experimenting (Table 8). Twenty percent of farmers interviewed actively participate in the "Fiesta del maíz", all of whom live in the municipality of Ixtenco.

One of the principal reasons farmers interviewed seek seeds is to recover from loss due to frost:

> "*We've been very careful about caring for[seeds], although on some occasions the weather hasn't favored us. For example, in 2011, due to frost, seed was lost out in the entire region. In 2012 we had planted, but also it came to frost when we'd reestablished [the crops of] 90% of the entire region of Huamantla and its 39 communities. So we were in need of going to bring creole seeds from near [the volcano] the Malinche and on the other side of Puebla, and we again recovered creole seeds*". Farmer from Huamantla, 26 April 2019

For some farmers who are also artisans, it is important to obtain new varieties of different colors:

"[Seeds] of colors we plant practically for mosaic made seed grains to exchange among each other, because some dedicate themselves to making figures, well more than figures, necklaces, earrings, some things with cornhusk, so for this, [we need] colored maize". Farmer from Ixtenco, 12 November 2018

Table 8. Reasons farmers exchange maize, bean, and squash seeds (n = 40).

	Reasons Farmers Exchange Seed	Percentage of Farmers Who Carry out Each Reason
Recover seed	To recover seeds they lost due to frost, pests during storage, or low crop yield	42.5%
Increase varieties	To obtain seeds with a variety of colors to plant, and conserve	12.5%
Make handcrafts from seeds	To obtain different colored seeds to plant and harvest for use in handcrafts, such as mosaic made of seed grains and jewelry	12.5%
Seed replacement	To replace "old" seeds or that with low productivity	7.5%
Lend seed	To lend seed of the same or different varieties, of the same quantity or different quantities	2.5%
Plant the crop	To plant the crop for the first time	2.5%
Experiment	To experiment with new varieties in their plots	2.5%

3.6. Maize, Bean, and Squash Exchange Networks and Conservation of Crop Diversity

On average, each farmer conserves 3.17 ± 2.22 varieties of maize and 1.34 ± 1.46 varieties of beans. However, not all the maize, bean, and squash varieties a farmer conserves are exchanged; in other words, farmers are conserving more varieties than those they are exchanging for the maize, bean, and squash crops (Figure 9 and Table 9).

Farmers who exchange seeds do so on average with 1.93 ± 1.47 varieties of maize and 2.3 ± 1.84 varieties of beans. In the case of squash, each farmer exchanges on average 1.17 ± 0.51 of the only native variety present in the region.

Of the 99 farmers who plant maize, 58 carried out at least one exchange during the past five years. In the case of beans, 33 farmers carried out at least one exchange, and 31 farmers carried out one exchange of squash seeds (Table 9).

The five nodal farmers for maize conserve on average 6.4 ± 2.70 varieties of maize, and the three nodal farmers for beans conserve on average 4.33 ± 0.57 bean varieties (Tables 3 and 5).

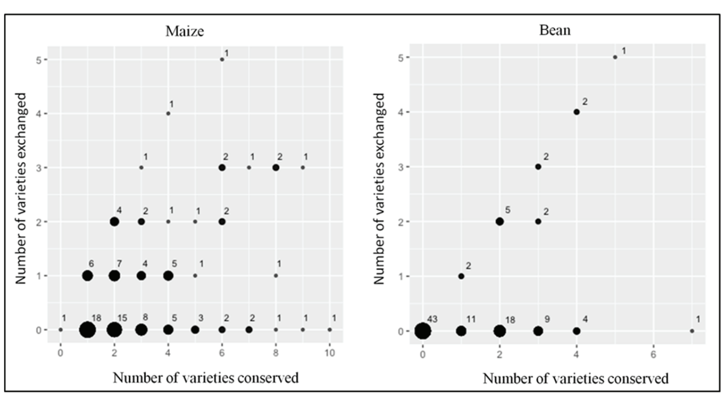

Figure 9. Relationship between the number of varieties of maize and beans conserved per farmer to the number of varieties exchanged in the municipalities of Ixtenco and Huamantla (n = 100).

Table 9. Number of farmers who plant and exchange maize, beans, and squash seeds in the municipalities of Ixtenco and Huamantla, Tlaxcala, Mexico (n = 100).

Number of Farmers Who Plant and Exchange Maize, Beans, and Squash			
Number of farmers who plant the crop			
Locality	Maize	Beans	Squash
Ixtenco	49	28	41
Huamantla	50	29	36
Total	99	57	77
Number of farmers who exchange the seed			
Locality	Maize	Beans	Squash
Ixtenco	27	17	15
Huamantla	31	16	16
Total	58	33	31

4. Discussion

4.1. Structure of Seed Exchange Networks

In the seed exchange networks of maize, beans, and squash, nodal farmers identified exhibited a high outdegree that is, they carried out the greatest number of exchanges and shared a greater number of seed varieties. Connector farmers exchanged seeds with people from sites close to the municipalities studied. Nodal farmers as well as connectors are key to the seed exchange network due to their role in conservation and circulation of seeds.

Previous studies regarding exchange networks have detected a different number of nodal farmers, depending on the seeds exchanged [21,23,25,27]. In this study, from 2015 to 2019 which corresponds to the past five years of seed exchanges analyzed, a total of eight nodal farmers were identified: five for the maize network, three for the bean network, and none for the squash network. These nodal farmers conserve 6.4 ± 2.70 varieties of maize and 4.33 ± 0.57 of bean varieties, and carried out six exchanges, which directly contribute to the maintenance of local genetic flow and diversity. On average, farmers cultivate 7 ha (range 0.004–60 ha), while nodal farmers cultivate 5.9 ha (range 1.5–20 ha), and two of them participate in the seed fair of Ixtenco.

Nodal farmers play a central role in seed exchanges as they maintain a connection to a network of farmers over several years. They conserve a diversity of seeds with agricultural and commercial interest for the farmers, seeds which contribute to farmers' income as well as their family's consumption. These nodal farmers hold knowledge and represent a source of knowledge regarding seed maintenance, and obtain new varieties through gradual selection over the years or by acquiring new seeds [20,26]. Farmers of the maize and bean seed exchange network (e.g., F121 and F33; Figure 4), directly promote movement of seed varieties (upon giving seeds to other farmers) as well as indirectly (upon giving seeds to farmers who in turn pass it on to other actors of the network). In the absence of these nodal farmers who interconnect several farmers, several varieties could be lost, and the structures of the seed exchange network would be modified.

Nearly 63% of the nodal farmers identified in this study are men, although women also participate in a variety of farm-related activities, such as planting, harvesting, fertilization, weeding, and seed selection. Previous studies, such as those by Devkota et al. [25], Rodier and Struik [23], and Song et al. [27], identified women nodal farmers who conserve a large diversity of seeds. In this study, a female nodal farmer from Ixtenco carried out seven maize exchanges, involving five varieties. Through this farmer, *negro* maize seeds reached farmers of the municipality of Huamantla.

Previous studies have reported nodal farmers to be of an advanced age [25]. In this study, the average age of nodal farmers was 46 years and that of all participating farmers was 58. Therefore, it is important to involve the nodal farmers in strategies focused on maintaining agrobiodiversity [20], and to invite more farmers to participate [52], principally youth from their communities. Furthermore, through the nodal and connector farmers, they could distribute seeds that are being lost or important crops for the region that have disappeared, such as lentils.

In each agricultural cycle, farmers save their own seeds to plant [27]. They select their own seeds based on size and color for replanting, and only given the situations listed in Table 8, do they carry out exchanges. One of the principal reasons for exchanging seeds is its loss due to frost and drought that affect the study area year after year, with crops planted at lower altitudes being the most affected by these phenomena (Table 8).

Comparing the networks of the three types of crops, the maize network contains the greatest number of nodes (134), while the bean network has 79 nodes, and the squash network 64 nodes. Maize is the principal crop of the region and year after year farmers plant for family consumption and for sale as grain, above all white varieties, which have a greater market demand. Furthermore, maize crops cover a greater surface area than beans or squash, which are principally planted for family consumption. In the past years, many farmers have stopped planting these two crops due to use of agrochemicals to cultivate maize. In the case of squash, upon planting only one local variety and as the crop is principally used for family consumption, the frequency of exchange is less than that of maize and beans.

In the municipalities of Ixtenco and Huamantla, a great diversity of varieties is exchanged (18). Nevertheless, the *blanco* maize is the most exchanged among farmers given its high commercial value in the region in comparison to other varieties. The price of maize grain in the region varies due to the supply and demand price that intermediaries offer, which ranges from USD 0.15 to USD 0.25 per kilogram, while the price of seeds range from USD 0.30 to USD 0.69 per kilogram. Furthermore, this maize is used to produce a variety of foods such as tortillas and *atole* (a thick hot drink made of boiled ground corn). To obtain it, farmers of sites near the state of Tlaxcala travel to Ixtenco and Huamantla in search of the *blanco* maize. Nevertheless, in recent years, other varieties, such as the *azul* maize, have increased in commercial value, and therefore farmers seek it for planting.

4.2. Fragmented Exchange Networks

Most exchanges of maize, beans, and squash seeds occurred in the dyads of the networks, and these exchanges were principally between people of the same community who knew each other, and between family members (parents, siblings, aunts and uncles, and political family). In this manner, the seeds are maintained and remain among farmers of each community and are preserved in the family. Furthermore, farmers who seek a specific variety know which of their family members or close contacts could provide it. Of all maize varieties, white maize was involved in the greatest number of exchanges between acquaintances (Table 2). As this variety bears a high commercial value, farmers seek it most often to renew it and obtain higher crop yields.

Differences were observed in the structuring of the networks of Huamantla and Ixtenco; as Huamantla is a city, seed exchanges are facilitated between acquaintances, not only between family members or friends. As beans and squash represent crops that are being lost in the region, it is difficult to acquire seeds, including through nearby networks and, therefore, farmers may need to approach their networks of acquaintances or even local markets to acquire the variety desired. Carrying out exchanges among relatives reduces the probability of losing different seed varieties; if a close family member conserves the seeds in question, a farmer may be able to quickly obtain them; the search time of the variety is reduced, the quality of the seeds are guaranteed, and there is certainty that the seeds are adapted to local conditions. Furthermore, a farmer who does not have the seeds they desire may know who, in their community or among other acquaintances, may have them. Acquiring seeds from family members and acquaintances may reduce the cost of obtaining them. In some cases, seeds exchanged among family members are lent or given away [25]. Among friends and acquaintances, seeds may be lent or sold at a price lower than the market price. Furthermore, exchanges among family members and acquaintances reinforce trust [53]. When a seed is acquired, a farmer trusts the information provided to maintain and conserve the variety. Upon acquiring new seeds with family members or others of the same location, the seeds tend to remain in the region, and they are already adapted to local conditions [27,54]. In the study municipalities, networks among friends, family members, and acquaintances were a source for acquiring seeds. As previously mentioned, within these networks, the *blanco* maize is mainly exchanged, and to a lesser extent the other varieties recorded in Table 2. In the case of bean seeds, the most frequently exchanged varieties are the *amarillo*, *bayo*, and *negro* beans (Table 4).

4.3. Local Market and Seed Bank in the Exchange Networks

Farmers who have lost seeds to frost or pests attend the Huamantla local market to acquire bean seeds, and to a lesser extent maize and squash seeds. Some rotate maize with beans in their plot after some years with the aim of increasing the yield. Since few farmers still plant beans, it is difficult to obtain the seeds from people of the locality; however, the Huamantla local market presents an option for obtaining bean seeds. As those who sell seeds in the Huamantla market are from Ixtenco, Huamantla, and other nearby areas, the seeds they sell are adapted to the environmental conditions of the region, which improves the chance of a good harvest.

Aside from the local markets, community seed banks are an important source of seed varieties [55,56]. One such source involved in the bean seed exchange network is the seed bank of the municipality of Vicente Guerrero. This seed bank provided *morado* bean seeds to a farmer of Ixtenco, who currently maintains the variety. Farmers from Ixtenco and Vicente Guerrero maintain contact through seed fairs carried out in both municipalities. The Ixtenco seed fair has allowed farmers of this municipality to display and sell grains for consumption, as well as seeds [44,57]. Two nodal farmers actively participate in this fair, which provides them with the opportunity to access and exchange new seed varieties. Previous studies show that seed fairs play an important role in the flow of seeds, and may contribute to conservation of native varieties [58,59]. Leyte et al. [60] found that in the Philippines and Vietnam livestock exchanges networks, the government agencies were a primary source of high quality seeds, with Philippines dairy case being dominated by actors in active cooperatives, while in the Vietnamese beef networks, farmer to farmer exchanges were more important, indicating that formal and informal seed systems play essential roles in access to forage seeds. By contrast, government agencies are not an important source of seeds for farmers of the municipalities of Ixtenco and Huamantla; rather, they save their own seeds. Nonetheless, the dynamics of the network could change and the seed fairs, local markets, seed banks or government agencies could become more relevant in the seed supply.

Limitations of this study include (a) sample size. Our small sample size (n = 100) did not allow us to detect more nodal farmers nor carry out statistical analyzes to detect differences between nodal and non-nodal farmers, (b) limited study area. Carrying out fieldwork in a greater number of municipalities would allow for determination of the distance of movement of the seeds, (c) lack of monitoring exchanges in good and bad cycles. Violon et al. [61] emphasize the need to carry out studies throughout several agricultural cycles to identify changes in farmers' strategies for acquiring seeds. As frosts and droughts affect the study area, it would be important to document how farmers acquire seeds under contrasting climatic conditions, (d) lack of genetic studies. As we did not carry out genetic analyses of native varieties, it is possible that we over or underestimated the number of native maize and bean varieties, (e) multiple factors operate in conservation. It would be convenient to measure additional factors that come into play in conservation of agrobiodiversity, such as the commercial networks that encourage farmers to plant native varieties. Furthermore, the importance of understanding the cultural impact on seed exchange has been pointed out [27]. In Ixtenco, farmers maintain and exchange varieties that are of biocultural importance to the community, such as *negro*, *xocoyul*, and *ajo* maize, and it would be important to have a better understanding of why they select these varieties, and (f) it is necessary to identify in greater detail the role of nodal women in the seed exchange networks [62].

5. Conclusions

Social network analysis allows for identification of the structure and processes of interaction within the seed exchange network of maize, beans, and squash among farmers from the municipalities of Ixtenco and Huamantla, Tlaxcala, Mexico. This analysis allowed for the detection of nodal farmers for seeds of these crops—those involved in the greatest number of exchanges of different varieties. It was found that the nodal farmers of the maize and bean seed networks, upon carrying out more exchanges, also exchanged a greater number of varieties. Thus, these farmers promote circulation of a large number of seeds within the network, thereby contributing to the maintenance and conservation of agrobiodiversity. Farmers involved in the maize and bean seed exchange networks of the two study municipalities attend the Huamantla market to obtain seeds, and it is important to further identify the seed varieties sold in this market. Given the large number of exchanges undertaken by the nodal farmers, as well as their capacity to conserve, acquire new varieties and their knowledge regarding maintenance of seed varieties, these farmers are important for the conservation of local agrobiodiversity and key actors in the seed exchange networks.

There is a need for future studies to address the dynamics of seed exchange networks over time. For example, it would be important to determine whether nodal farmers maintain their role over many years or for a limited time and to understand how their presence or absence affects the number of seed exchanges conducted. Furthermore, there is a need to determine the relative importance of other actors of the network, such as markets, government agencies, and seed banks, in seed provisioning over time. The exchange between farmers represents the possibility of recovering lost seeds immediately and therefore of recovering crops. Understanding the functioning of exchange networks offers the opportunity to change the weaknesses of the system and to carry out actions which guarantee exchanges between farmers. Studying seed exchange networks in broader spatial, ecological and cultural contexts is particularly important in countries such as Mexico with high biocultural diversity. The regional and case studies such as this one provides methodological tools and experiences useful for conducting studies at larger scales. Understanding the dynamics of the networks allows for appreciation of the restrictions and the ability to take action in improving the network's efficiency, thereby promoting conservation of agrobiodiversity.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

Appendix A

Guide to interview of farmers of the communities of Ixtenco and Huamantla
State:
Municipality: Date:
Interviewer name:
Interviewee name:
Gender: M F Age:

Native seed networks

1. How many plots do you have and what do you grow in each of them?
2. What is the total surface area of your plots?
3. Describe each plot (surface area, location, soil type, climate).
4. Why do you cultivate these plots?
5. Are the plots you cultivate your own or do you rent them?
6. [If rented:] How much do you pay for rent?

Maize

7. Where do you obtain the seed for each variety of maize you plant (friend, neighbor, family member, market, save own seeds, etc.)?
8. Do you always obtain seed from this source/these sources? Why?
9. How long have you been conserving these seeds?
10. Why do you like cultivate each variety?
11. Why do you prefer to plant these varieties and not others?
12. What do you use each variety for?
13. Would you try planting other varieties? Why?

Beans and Squash

14. Do you plant squash and beans?
15. Where do you obtain squash and bean seeds?
16. Since when do you have the seeds?
17. What varieties of squash and beans do you have? Name of the squash and beans varieties
18. Do you plant beans and squash the same time as maize?
19. Is the maize, bean, and squash seed you produce for self-consumption, sale, or both?
20. How many months does the maize you harvest for your family last?
21. How many months do the beans and squash last your family?
22. Can you tell us the names of all the people you have ever given maize, bean, and squash seed?
23. Can you name the people that have given you maize, bean, and squash seed?
24. Last season, did anyone give you seeds to plant? Why?

Preparing the land for planting

25. How do you prepare the land for planting?
26. When does maize planting begin (for each variety)?
27. How long does it take for the cob to fully form (for each variety)?
28. When do you begin to plant beans (each variety)?
29. When do you begin to plant squash (each variety)?

30. How many harvests of maize do you have per year?
31. In the first, how much do you harvest? In the second?
32. How do you control weeds?
33. Do you use fertilizer/herbicide?
34. How much does the herbicide cost?
35. How much does the fertilizer cost?
36. Which family members plant?
37. Do women participate in agriculture? What do they help with? When you are not there, do they help with agriculture?
38. Do women select seeds? Do they exchange seeds?
39. When women marry, do they inherit seed?
40. Within the community, are there people who leave seed as inheritance? Have you received seed as inheritance?
41. What crops do you plant besides maize, beans, and squash?
42. Do you have animals? How many cattle? What do you give them to eat?
43. Do you carry out any income generating activities aside from agriculture?

Seed loss, storage, and pests

44. Have you ever lost your maize, bean, or squash seed? If so, how (frost, poor harvest, etc.)? What variety?
45. How do you recover lost seed? Who do you ask for seed? Do you purchase it? Does someone lend it to you? Who?
46. Do you return borrowed seed? The same seed and the same quantity? Or do you return the favor by giving another variety of seed that they lent to you?
47. Do you or have you had problems with any maize, bean, or squash pest? Which pests? How do you control them?

Seed sale

48. Do you sell seed?
49. If so, to whom? What price?
50. Do you know the destination of this seed?

Organization and seed laws

51. Do you belong to any farmers' organization?
52. Do you know of the Law to foment and protect maize as original heritage, in constant food diversification for the State of Tlaxcala?
53. Do you know of the Law of Production, Certification, and Commerce of Seeds or the Law of Plant Varieties?

Festivities related to seeds

54. What do maize, beans, and squash mean to you?
55. Do you participate in any festivity of maize, beans, and squash?
56. In this municipality, the people carry out maize, beans, and squash fairs? When?

Hybrid seed

57. Do you plant any hybrid seeds? Why?
58. Which hybrid seeds do you purchase?
59. Where do you purchase them?
60. What amount of hybrid seed do you purchase? By kilo, bag, or sack?
61. Are the seeds certified?
62. How much do you pay for hybrid seed?
63. Do you receive any subsidy for seed purchase? If so, how much?
64. What characteristics do these seeds have? What do you consider their advantages to be?
65. Do you use fertilizer to cultivate these seeds?

66. Do you sell the crops cultivated with these seeds? Do you conserve some seed for the following planting?
67. If you sell seed, to whom? At what price?
68. Do you know the destination of these seeds?
69. Do you replant these seeds for harvest?
70. In what cases do you replant these seeds for harvest?

Questionnaire on seed networks

Date: State: Municipality:
Farmer name:
Gender: Male Female Age:
Notes:
How many plots do you have?
For each plot:
Surface area:
Type (irrigated/seasonal):
Elevation (high, medium, low):
What quantity of seed do you need to plant the plot?
MAIZE
How many varieties of maize do you have? Which varieties?
For each variety
How long have you had it?
Who gave it to you (family member, friend, neighbor, acquaintance? Other:
What do you like about this variety?
Have you ever lost it? YES/NO How? Frost Drought Hail Pests Other:
How did you recover it and when? By purchase or gift? If gift, who gave it to you? Was it lent to you? If borrowed, from whom?
Which of these varieties is the most important to you and why?
During the past 5 years
Have you exchanged/sold/gifted/lent any of your maize varieties during the past 5 years? YES/NO
Which ones?
With whom have you exchanged/sold/gifted/lent it/them? Friend ( ) Neighbor ( ) Family member ( ) Other:
What amount of seed did you exchange/sell/gift/lend?
Since when have you exchanged/sold/gifted/lent this seed?
BEAN
How many bean varieties do you have? Which varieties?
For each variety:
How long have you had it?
Who gave it to you (family member, friend, neighbor, acquaintance? Other:
What do you like about this variety?
Have you ever lost it? YES/NO How? Frost Drought Hail Pest Other:
How did you recover it and when? By purchase or gift? If gift, who gave it to you? Was it lent to you? If borrowed, from whom?
Which of these varieties is the most important to you and why?
During the past 5 years
Have you exchanged/sold/gifted/lent any of your maize varieties during the past 5 years? YES/NO
Which ones?
With whom did you exchange/sold/gifted/lent it/them? Friend ( ) Neighbor ( ) Family member ( ) Other:
What amount of seed did you exchange/sell/gift/lend?
Since when have you exchanged/sold/gifted/lent this seed?

SQUASH
How many varieties of squash do you have? Which varieties? **For each variety:** How long have you had it? Who gave it to you (family member, friend, neighbor, acquaintance? Other: What do you like about this variety? Have you ever lost it? YES/NO How? Frost Drought Hail Pest Other: How did you recover it and when? By purchase or gift? If gift, who gave it to you? Was it lent to you? If borrowed, from whom? Which of these varieties is the most important to you and why? **During the past 5 years** Have you exchanged/sold/gifted/lent any of your squash varieties during the past 5 years? YES/NO Which ones? With whom did you exchange/sold/gifted/lent it/them? Friend ( ) Neighbor ( ) Family member ( ) Other: What amount of seed did you exchange/sell/gift/lend? Since when have you exchanged/sold/gifted/lent this seed?
SEED SELECTION
What characteristics do you focus on upon selecting maize seed? What characteristics do you focus on upon selecting bean seed? What characteristics do you focus on upon selecting squash seed? Would you try planting another variety of maize? YES/NO Why? Would you try planting another variety of beans? YES/NO Why? Would you try planting another variety of squash? YES/NO Why?
OTHER CROPS
Do you plant anything aside from maize, beans, and squash? YES/NO What?
GRAIN
Do you plant anything aside from maize, beans, and squash? YES/NO What? Sale of grain Is the grain you produce for: Family -consumption ( ) Sale ( ) Both ( )? Do you know the destination of your grain? YES/NO Do you always sell in the same place/to the same person? YES/NO How much do you sell? What is the destination of your grain? How much do you sell your grain for?
PARTICIPATION OF WOMEN IN SEED SELECTION/SEED FAIRS
Do women participate in agricultural activities? YES/NO In what activities do they participate? Do women select seed? YES/NO The women, where does seed selection begin? At home/In plot Other: Do they exchange seed? YES/NO Do you living only from agriculture? YES/NO Do you participate in the seed fairl of Ixtenco? YES/NO Why do you participate? Why don't you participate? Farmer from other municipality: Do you know or have you heard of the seed fair in Ixtenco? YES/NO

HYBRID SEEDS
Have you planted any hybrid maize seed? YES/NO
Which varieties? of which brand?
Where do you purchase or obtain it?
How much do you purchase?
Do you replant, sell, or exchange this seed?
Why do you like hybrid seed? Or Why do you not like hybrid seed?
Have you ever planted hybrid varieties? YES/NO
Why or why not?
Would you be interested in trying hybrid seed? YES/NO Why?
If you already plant some hybrid maize, would you be interested in trying other hybrid maize varieties? YES/NO Why?
Do you receive any subsidy for seed purchase? YES/NO
How much?
Do you receive any subsidy to purchase fertilizer or herbicide? YES/NO How much?
Have any government programs given away/exchanged seeds? YES/NO
Which programs? When?
Have you participated? YES/NO Why or why not?
Do you belong to any farmers' organization? YES/NO Which one?
What are the advantages of belonging to this organization?

Appendix B

Varieties of Maize, Beans, and Squash of Ixtenco and Huamantla, Tlaxcala, Mexico

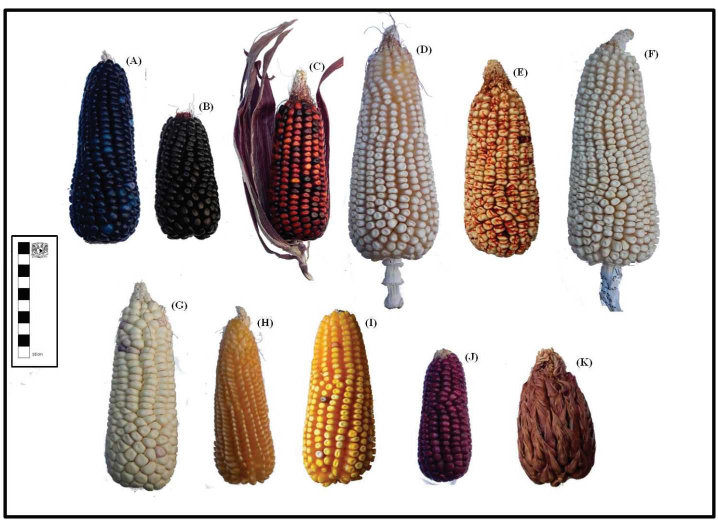

Figure A1. Different varieties of maize of Ixtenco and Huamantla, Tlaxcala, Mexico. *Azul* (**A**), *negro* (**B**), *rojo* (**C**), *blanco* (**D**), *sangre de cristo* (**E**), *crema* (**F**), *cacahuacintle* (**G**), *arrocillo-palomero* (**H**), *amarillo* (**I**), *xocoyul* (**J**) and *ajo/tunicado* (**K**).

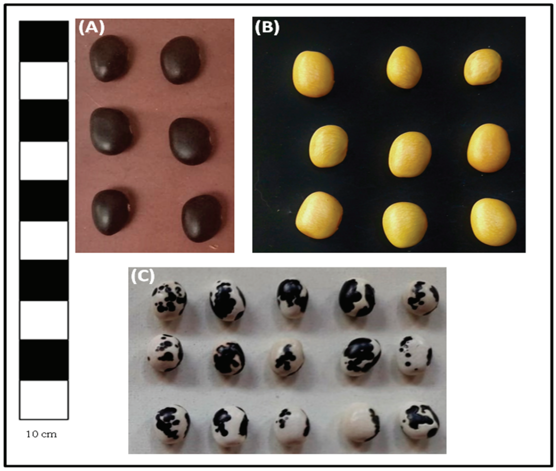

Figure A2. Bean varieties of Ixtenco and Huamantla, Tlaxcala, Mexico. *Negro* (**A**), *mantequilla* (**B**) and *vaquita* (**C**).

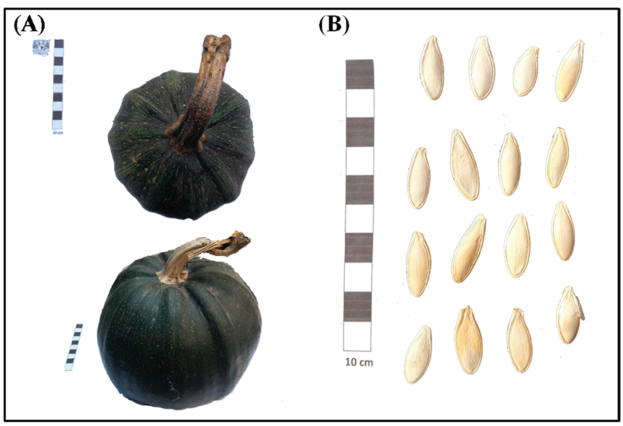

Figure A3. Squash variety of Ixtenco and Huamantla, Tlaxcala, Mexico. Squash fruit (**A**) and squash seeds (**B**).

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Article

Plate Waste in School Catering in Rezekne, Latvia

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Abstract: This research was conducted within the framework of a research project aimed at detecting patterns of plate waste and developing recommendations for improving catering in seven schools in Rezekne city (Latvia) by a combination of observation, physical weighing, semi-structured interview approaches and statistical analysis of variance (ANOVA). We identified plate waste (including wasted beverages), which remains after the lunch of schoolchildren in grades 1–7, examining a total of 7064 lunch samples. The originality of the research is due to the fact that a unified menu was designed for the field study, which ensured the same field study conditions in all the schools. The results of the research revealed that the average weight of plate waste per schoolchild reached 178 g, and the total weight of plate waste accounted for 28.75% of the total weight of food served. No significant differences in plate waste weight between various age groups and grades of schoolchildren were found, which was also confirmed by a one-way ANOVA test. An analysis of plate waste by food category showed that beverages accounted for the largest share of total plate waste (42.24%), followed by staple food (28.38%) and meat (11.77%). An analysis of plate waste shares of food served (%) by food category revealed a similar situation: the largest share of food served was made up of beverages (37.56%), followed by staple food (36.48%) and meat (28.77%). An analysis of the monetary value of food waste showed that the average cost of plate waste (excluding beverage) per schoolchild was EUR 0.236, which represented 16.6% of the national and municipal funding of EUR 1.42 per portion. Given the research results, the authors have concluded that in order to reduce the amount of plate waste generated by Rezekne city schools, school menus should be based not only on the requirements prescribed by relevant legal acts but also on cooking processes that meet the requirements of modern consumers (learners), e.g., by following trends in cooking practices in society to make the learners interested in consuming school food.

Keywords: food waste; plate waste; school menu; eating habits; eating behavior; school catering

1. Introduction

1.1. Food Waste and Sustainability

Every year, significant amounts of food are lost or discarded throughout the food supply chain, from primary production to final consumption. Over the last 10 years, food loss (FL) and food waste (FW) have become a global problem with a negative impact on sustainable resource consumption, nature and the environment as well as on the development of society [1–4].

Reducing FW is an important prerequisite for achieving the Sustainable Development Goals set in 2015, namely SDG 2 (ending hunger) and SDG 12 (ensuring responsible consumption and production patterns) by 2030 [5]. In 2019, according to the Food and Agriculture Organization of the United Nations (FAO), 690 million people or 8.9% of the world's population suffered from malnutrition, and this figure is projected to increase significantly due to the negative impacts of the COVID-19 pandemic [6].

1.2. Theoretical Framework

Although there is no general definition of food loss and waste, the FAO [7] states that food loss and waste are "the masses of food lost or wasted in the part of food chains leading to edible products going to human consumption". Therefore, food originally intended for human consumption but later addressed to other non-food uses (e.g., animal feed, energy recovery) must be considered as lost or wasted [8].

Kaur et al. (2021) distinguish FL from FW and refer to "food loss" as the food that leaves the food supply chain at its initial stages, while "food waste" refers to the food that is not consumed at the places of consumption [9].

Ishangulyyev et al. (2019) conclude that FL represents a decrease in the weight of edible food at the first three stages of the food supply chain due to infrastructure constraints, environmental factors and quality or safety standards. In contrast, FW is food that was originally produced or processed for human consumption but was not consumed. FW also includes food that is edible or spoiled at the time of disposal. FW occurs at the distribution and marketing and consumption stages of the food supply chain (see Figure 1) [10].

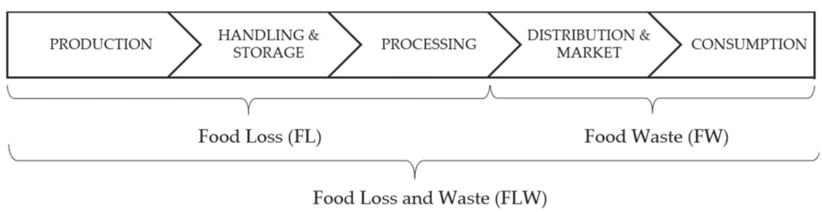

Figure 1. Framework of Food Loss and Food Waste definitions [10].

Falasconi et al. (2015) define FW as all foods that are removed from the food supply chain but still retain their nutritional value and meet safety standards [11].

Papargyropoulou et al., (2014), developing a food waste prevention strategy, recommend distinguishing avoidable food waste (foods or components of food that are generally considered edible) from unavoidable food waste (includes foods that are not normally edible, e.g., bones, fruit peel, etc.) [12].

FW at the consumption stage of the food supply chain could also be categorized according to when the waste occurs. For example, FW produced during the purchase and storage of food is considered to be "spoilage food waste" (or "storage waste" [13]); "preparation food waste" occurs during cooking, i.e., due to peeling, cutting, as well as overproduction or food surplus; "leftover waste" occurs when the prepared food is not served to the consumer (unserved food); "plate waste" pertains to the food served to the consumer but not eaten [14].

García-Herrero et al., (2019), conducting a study on FW in Italian schools, divided FW into the following categories: (1) preparation waste: the FW that occurs during cooking (might be both avoidable and unavoidable); (2) serving waste: the food left on the serving dishes and not served to the students in the canteen (avoidable FW); (3) plate waste: the food left by students on their plates in the canteen (avoidable FW) [15].

Clarke et al. (2015) distinguish the following kinds of FW: (1) waste generated during preparation and cooking, (2) discards due to preparation of too much food, (3) discards due to expired use-by or open dates, (4) spoilage food waste and (5) plate waste [16].

A summary of the opinions available in the scientific literature on the kinds of FW at the consumption stage of the food supply chain is presented in Figure 2.

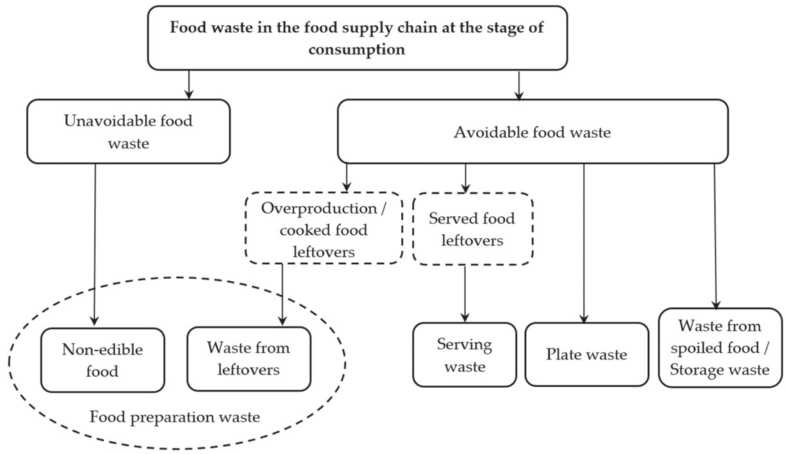

Figure 2. Kinds of FW at the consumption stage of the food supply chain. Source: authors' construction based on [11–16].

As shown in Figure 2, FW generated at the final stage of the food supply chain, i.e., the consumption stage, can be both avoidable and unavoidable. Most of the FW generated at the food consumption stage is avoidable food waste, which in turn consists of waste from spoiled food (it is discarded due to changes in quality that make it undesirable and unfit for human or animal consumption, as evidenced by signs of deterioration such as unpleasant odor, changes in texture and appearance), plate waste (food served to consumers that remains uneaten on the plate and is discarded), served food leftovers (food served but not eaten (intact) and discarded) and waste from leftovers (food prepared in excess of what was needed (overproduction) and not served go to waste). It should be noted that waste from leftovers comprises food preparation waste together with non-edible food (unavoidable food waste), which usually are not edible, e.g., peel of fruit or vegetables, bones, seeds, etc.

It should be mentioned that in 2019, at the distribution and marketing as well as consumption stages of the food supply chain, approximately 931 million tons of FW were generated, of which 61% were by the household sector, 26% by the catering sector and 13% by the retail sector. This means that around the world, 17% of the total food production was wasted (11% by the household sector, 5% by the catering sector and 2% by the retail sector), thereby increasing environmental pollution and unnecessary pressure on nature [17].

In this research field, researchers have a common understanding of the term plate waste, which refers to the amount of food served to consumers that remains uneaten on their plates and is subsequently discarded.

Plate waste is the largest source of food waste in schools [18], followed by food waste from serving lines [19]. It should be noted that most of the researchers working on food waste analysis focus specifically on plate waste analysis [11,12,15,16,18,20–25]. Derqui and Fernandez (2017) have found that approximately 80% of research in this field directly relates to plate waste analysis, without auditing FW at the entire stage of food consumption, i.e., not considering the FW generated during cooking in the kitchen or the FW from serving lines [19].

1.3. Literature Review

The plate waste generated in schools is influenced by multiple factors. The authors of the present paper have analyzed a number of research papers focusing on this field with the aim of summarizing the factors contributing to plate waste in schools (see Table 1).

Table 1. Factors contributing to plate waste in schools referred to in the scientific literature.

Factor	Explanation	Source
	Exogenous (objective) factors	
School administration position	The restrained position of the school administration and a lack of interest in the implementation of a sustainable management policy, a lack of responsible personnel, a lack of attention to the amount of food waste in the school canteen, etc., increase the irrational consumption of food, which also indirectly affects schoolchildren's eating behavior	[26,27]
Class schedule at school	A poorly planned schedule of classes leads to a lack of time for lunch; due to the short lunch break, schoolchildren do not have enough time to eat a full meal	[13,20,28–32]
Atmosphere and environment in the dining hall	A lot of noise in the canteen, a large number of schoolchildren and crowding put psychological pressure on the schoolchildren to finish their meals faster	[18,26,33–39]
Cooking techniques	The incompatibility of the cooking technique with the kind of food can adversely affect the appearance and sensory properties of the food	[23,30,34,40]
Way of serving food	The way food is served (e.g., peeled and sliced fruit, etc.) is an essential prerequisite for reducing plate waste: "The easier the food is to eat, the less plate waste is generated"	[27]
Cooking skills of kitchen personnel and kitchen equipment	Poor cooking skills of kitchen personnel and insufficient kitchen equipment can adversely affect the appearance and sensory properties of food	[27,41]
Competitive foods	Availability of competitive food from other sources (i.e., sweet/savory snacks and beverages), including food brought from home, can also reduce schoolchildren's appetite	[20,25,34,42,43]
Catering service management and coordination policy	The way catering is managed (e.g., portioned or buffet-style catering, on-site cooking in the school kitchen or an outsourced service), a lack of flexibility to adapt the centrally planned menu to schoolchildren's needs, a lack of timely information on changes in the number of schoolchildren and other organizational aspects can lead to an inadequate amount of food prepared, thereby creating leftovers	[11,23,26,27,30,44]
Non-involvement of supervisory or support personnel in the catering process	The non-involvement of supervisory or support personnel (e.g., a teacher or kitchen worker) in the catering process, which could otherwise promote the schoolchildren's healthy attitudes towards food and new tastes and help to reduce food waste	[13,34,39]
Inadequacy of food portions to schoolchildren's age, appetite and nutritional needs	The portion size of food served is not differentiated according to the age of schoolchildren (including their nutritional needs); consequently, the schoolchildren are simply unable to eat the whole portion	[20,26,41,45–49]
	Endogenous (subjective) factors	
Schoolchildren preferences	Schoolchildren may refuse to eat or not eat all the food served to them because they might not like the particular food or kind of food	[20,24,26,30,39,50–54]
Schoolchildren's appetite level, total daily nutritional energy requirements and body mass index	Schoolchildren might or might not eat the food served to them due to a reduced appetite and/or need for nutritional energy	[20]
Appearance and sensory properties of food	Schoolchildren might refuse to eat or not eat all the food served to them if they are not satisfied with the appearance, taste, texture, color and temperature of the food. This factor is partly subjective, as the appearance and sensory properties of food also depend on the cooking skills of kitchen personnel and kitchen equipment	[26,30,33,39,41,43,46,49,50,55–57]
Schoolchildren's desire to socialize during free time	Schoolchildren might refuse to eat or not eat all the food served to them because they communicate with others at the table, or they might leave the dining hall to meet their fellow students during the lunch break	[28,38]
Schoolchildren's unhealthy eating habits	Schoolchildren might refuse to eat or not eat all the food served to them due to their unhealthy eating habits, which often come from their families	[11,58]
Schoolchildren's knowledge and understanding of and attitude towards food	Schoolchildren might refuse to eat or not eat all the food served to them due to a lack of understanding of the negative effects of food waste on the environment and the associated ethical and socio-economic consequences, as well as of the sources and production of food	[27,37,58–60]

The summary of factors influencing plate waste shown in Table 1 reveals that the authors have divided the factors into exogenous or objective ones that do not depend on schoolchildren's (consumers') subjective preferences and physiological condition, but tend to influence their eating behavior externally, and endogenous or subjective factors arising from the schoolchildren's (consumers') psychological and/or physiological condition.

Derqui et al. [27] point out that the catering sector is one of the largest sources of FW generated by schools, which also provides an opportunity to improve the dietary habits of the population and educate the public about sustainable resource consumption and development, thereby affecting the food system in the future. According to a delegated decision of the European Commission [61], from 2020 onwards, the measurement of FW and leftovers needs to be carried out at each stage of the food supply chain. This also applies to the FW generated by educational institutions, which has been little researched in Latvia to date. Research on waste generated by an educational institution have been conducted by some enthusiasts, whereas larger-scale research that would allow for drawing overall conclusions and continuous science-based, qualitative research, has not been carried out in Latvia yet.

1.4. Scope of Research

The purpose of this pilot study was to identify the patterns of plate waste in seven schools of Rezekne city (Latvia) and to develop recommendations for stakeholders on how to reduce the amount of plate waste by a combination of observation (the design of the dining hall, the placement of food on a plate, the way food was served and the process and time of enjoying the meal were observed), physical weighing and semi-structured interview approaches, as well as statistical analysis of variance.

The novelty of the research stems from the fact that no research studies have been conducted in Latvia that placed a focus on zero-waste food consumption, including plate waste in schools, and although there are publicly available reports on this problem by individual researchers, the reports are not considered scientifically relevant for further research. The present pilot study provides a first sign of examining the normally ignored amount of plate waste in Latvian schools. The authors believe that the results of this study are a good basis for further analysis in this field, and can help to inform stakeholders and policy makers in the field of education about the current situation in catering in Latvian educational institutions. This study also aims to promote the implementation of the recommendations developed (supported by the fact that the preliminary survey results were discussed with the head of the Education Department of the Rezekne State City and the observed schools' representatives, as well as the fact that the research report was submitted to the Ministry of Education and Science of Latvia).

The fact that we performed an analysis of plate waste instead of an analysis of all food waste generated by school canteens could be considered to be a research limitation. This was due to the insufficient capacity of human resources involved in the present research. Otherwise, a comprehensive analysis of food waste would provide comprehensive information on the amount of food wasted.

2. Materials and Methods

2.1. Sample Selection

A field study was conducted in schools of Rezekne city in the Latgale region of the Republic of Latvia. Rezekne is the seventh largest city in the Republic of Latvia and the largest eastern border city of the European Union, with a total population not exceeding 30 thousand (Figure 3). The field study was performed in 7 publicly funded schools (one primary school, one gymnasium and 5 secondary schools). In all the schools, catering was provided on-site and funded from the Rezekne city municipality budget and the state budget. The selection of the surveyed schools was based on the fact that there were only 8 schools in the city, one school that was not surveyed was a school for children with special needs, and catering was managed differently in this school, therefore, it was excluded from the analysis.

During the observations, emphasis was put on quantitative measurements of plate waste by examining 7064 school lunch plates.

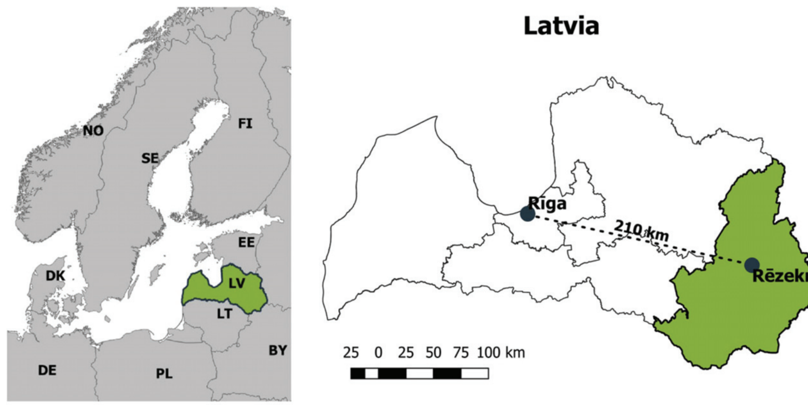

Figure 3. Map with the observation location; authors' construction.

Regarding the research methodology, the following plate-waste parameters were identified by the field study:

- number and grades of schoolchildren;
- work organization in school canteens or opportunities for a caterer to prepare food, the way of serving food, the capacity of the dining hall and other factors;
- free lunches for schoolchildren (grades entitled to free lunches funded jointly by the national and local governments were selected for the field study in Rezekne city schools: grades 1–7).

During the research, the authors, based on a number of legal acts [62–64], as well as after getting acquainted with the public food procurement situation in Latvia [65] and requests for tenders to procure food and catering services placed on the website of the Procurement Monitoring Bureau [66] and the Electronic Procurement System [67], concluded that in Latvia, catering in educational institutions was organized in the following ways:

- Type 1. The municipality in whose territory the schools are located organizes catering for schoolchildren on its own, equipping canteens in the schools in accordance with the requirements of safe food handling and creating special workplaces for canteen personnel;
- Type 2. Catering for schoolchildren is provided on an outsourced basis, i.e., the entire service is purchased from catering companies, delivering the food to the schools and serving it in accordance with the requirements stipulated in the procurement contract;
- Type 3. Catering for schoolchildren is provided as an outsourced service, provided that the catering provider prepares the food on-site in the schools.

In all the schools covered by the field study, the catering process was organized in closed-type canteens (hereinafter referred to as school canteens), which were provided by the local government of Rezekne city (Type 1). This means that catering services are supplied only to certain social groups—only to those who study, work or stay in the institutions that have an operating catering facility. The local government of Rezekne city covers the maintenance costs of school canteens, salaries of school canteen personnel, purchases of food and other functions related to catering services (control of compliance with hygiene requirements, monitoring of compliance with healthy nutrition requirements, etc.).

In accordance with the provisions of legal acts, including Cabinet Regulation No. 614 "Procedures for Calculating, Allocating and Using Funding Provided from the

State Budget for Catering to Learners" [68] and the Rezekne City Council's Education Board's Order No. 197 of 3 September 2020 "On Catering for Learners" [69], in the schools of Rezekne city, catering is provided free of charge for the following schoolchildren:

- grades 1–4, free lunches are funded by the national government;
- grades 5–7, free lunches are funded by the local government of Rezekne city.

Only schoolchildren in grades 1–7 were included in the field study sample, i.e., those who were entitled to free lunch, and in this case, the schoolchildren had a specific lunch menu (Table 2). It should be noted that school S1 was a state gymnasium that starts from grade 7; therefore, only the schoolchildren in grade 7 were included in the sample of the field study.

Table 2. Unified menu designed for the field study.

	Placed/Portion/Planned Weight in Grams	Weight of Food Served on a Plate in Grams		Placed/Portion/Planned Weight in Grams	Weight of Food Served on a Plate in Grams
Monday			**Thursday**		
Pasta	150	150	Stewed rice with carrots and corn	150	150
Pork goulash	50/50	100	Chicken cutlet	80	80
Fresh cabbage salad	50	50	Fresh tomato	30	30
Glazed curd cheese	1 piece	46	Lemon drink	200	200
Bread	25	25	Bread	25	25
Tea with sugar	200/10 *	200	Apple	1 piece	95
Tuesday			**Friday**		
Pickled cucumber	25	25	Milk soup with pasta	125	125
Pork cutlet	75	75	Mashed potatoes	130	130
Mashed potatoes	130	130	Fish in breadcrumbs	60–65	63
Juice drink	200	200	Carrot salad with sunflower seeds	50	50
Bread (optional)	25	25	Juice drink	200	200
Banana	1 piece	160	Bread	25	25
Wednesday					
Borscht (beet soup) with fresh cabbage, sour cream	250/5 **	250			
Mashed potatoes	130	130			
Stewed liver in cream sauce	50/45	95			
Fresh cucumber	30	30			
Juice drink	200	200			
Bread	25	25			

* Note: 10 g of sugar per 200 g of tea. ** Note: 5 g of sour cream is put in a common pot of soup, providing 5 g per 1 child. The weight of soup in each plate is 250 g. Source: menu calculations performed by the Rezekne City Council's Education Board based on the research conducted by the authors.

2.2. Description of the Unified Menu and Catering Processes

Before performing plate-waste quantification, it was necessary to design a unified menu for the field study week that would eliminate differences in food availability and ensure laboratory conditions, thereby minimizing the impact of gastronomic distraction on the study. In Rezekne city schools, menus are designed by the canteen employees of each school together with the school nurse in accordance with Cabinet Regulation No. 610 "Hygiene Requirements for Educational Institutions Implementing General Primary Education, General Secondary Education, Professional Basic Education, Vocational Education or Professional Secondary Education Programmes" [70] and Cabinet Regulation No. 172 "Regulations regarding Nutritional Requirements for Learners of Educational Institutions, Clients of Social Care and Social Rehabilitation Institutions and Patients of Medical Institutions" [62], which set dietary requirements and require that the lunch menu include a second course and a soup or dessert. Cabinet Regulation No. 172 restricts the use of salt, sugar and other flavor enhancers in school meals, bans unhealthy foods (e.g., French fries and other foods cooked in oil, mayonnaise, ketchup, tomato sauce, sausages with a meat content of less than 90%, dried, smoked and salted meat and fish). Processed foods such as dumplings and fish fingers may be included in the diet of schoolchildren no more than once a week and only if meeting certain requirements (i.e., contain at least 70% meat or 60% fish; do not contain flavorings (E620–E650) and dyes, do not contain mechanically separated meat, do not contain raw foods produced from genetically modified organisms, contain less than 1.25 g of salt per 100 g of meat and 1.5 g per 100 g of fish) [62]. The menu is agreed and approved by the head of the educational institution or an authorized person.

It should be noted that in the autumn of 2021, in order to reduce the spread of COVID-19 in schools, legislative amendments were made to reduce the number of learners staying in the dining hall for a long time (i.e., food delivery and consumption time was reduced), allowing for one main course instead of two dishes, while at the same time ensuring that it complied with the nutritional requirements stipulated by Cabinet Regulation No. 172.

To design a unified menu, individual structured interviews were conducted with the canteen managers and specialists of the Rezekne city schools with the aim of obtaining information about school menus, schoolchildren's preferences regarding the food served in each school, the frequency of serving particular foods, the factors influencing whether schoolchildren eat or do not eat the free lunch provided by school canteens, as well as food-waste management. A total of 11 individuals took part in the interviews: 7 canteen managers, 3 canteen specialists and a nurse who was also responsible for designing the school menu. All the interviewed canteen managers and canteen specialists had the professional qualification of a cook, they had at least 5–10 years working experience in school canteen service and had a good understanding of children's food preferences.

The Interview provided experiential, semi-subjective opinions of the personnel of educational institutions and school canteens about the categories of food that children liked, did not like or were indifferent to. During the interviews, the researchers identified five foods that children preferred (i.e., more than 90% children ate them), five that they ate reluctantly (i.e., only up to 20% preferred them) and five foods that children were indifferent to (i.e., at least 65% preferred them). Based on the information obtained, the responsible employee of the Rezekne City Education Board (a chief specialist in nutrition who knew all the requirements for designing menus) prepared a unified menu for the field study for all the schools, considering the nutrition requirements stipulated by Cabinet Regulation No. 172 (Table 2).

The method for analysis of strengths, neutrals and weaknesses (SNW) was employed to evaluate the dishes prepared at the Rezekne city schools and a typological group index was calculated for the menu according to the equation [71]:

$$I = \frac{1*S + 0,5*N - 1*W}{n} \quad (1)$$

where

I—typological group index (ranging from 1 to −1);
S, N, W—number of respective indicators;
N—number of respondent replies.

The typological group index calculated for the dishes prepared at the Rezekne city schools, which showed the rating of 7 dishes prepared at the schools, was 0.47, i.e., moderately high and positive. An analysis of the Rezekne city school menus showed that schoolchildren were indifferent to a total of 351 dishes prepared at the schools, 82 dishes they ate reluctantly, and 209 dishes they enjoyed (Table 3).

In all the Rezekne city school canteens, serving of the food partly takes the form of self-service, and the food is partly served, i.e., shortly before the lunch break, the school canteen personnel set a table reserved for each class. Only at school S1 is the food served at the canteen distribution point (at the distribution counter) where the schoolchild is given a tray with portioned food plates (except for fruit and glazed curd cheese), which are available in shared dishes on the tables). At the other schools, canteen personnel serve portions of a set meal on the tables (staple food and meats on a single plate), at some schools, vegetables with a set meal could be served on a single plate (e.g., schools S1, S4, S5 and S6), while at schools S2, S3 and S7 vegetables are served in shared dishes on the tables for each class separately. Except for school S1, where soup is served on separate plates for each schoolchild, at schools S2–S7 the soup is served in shared soup pans on the tables for each class (the amount of soup to be served is calculated according to the number of schoolchildren in each class by applying standardized measures and serving cups). A beverage is served in separate glasses for each schoolchild. Except for school S1, where a piece of bread is given to each schoolchild individually on the tray, in schools S2–S7 the slices of bread are placed on tables in shared containers according to the number of schoolchildren in each class. At all the schools, fruits (whole unpeeled apples or bananas) are placed on tables in shared containers according to the number of schoolchildren in each class; the way of serving glazed curd cheese, which is served in packaging in shared containers according to the number of schoolchildren in each class, is similar.

Table 3. Schoolchildren's attitudes to the dishes prepared at the Rezekne city schools analyzed by the SNW method.

School	Number of Dishes Enjoyed by More Than 90% Children, or the Strength (S)	Number of Dishes Eaten by at Least 65% Children, or the Neutral (N)	Number of Dishes Eaten by Less Than 20% Children, or the Weakness (W)	Typological Group Index
S1	46	36	13	0.54
S2	21	70	5	0.53
S3	21	75	10	0.46
S4	12	62	5	0.48
S5	27	54	12	0.45
S6	53	30	22	0.44
S7	29	24	15	0.38
Total	209	351	82	0.47

Source: authors' calculations based on the results of an interview with canteen personnel.

2.3. Data Collection

In the present research, the authors have considered plate waste as the amount of food served to schoolchildren that remains uneaten on their plates and is subsequently discarded. The total measured weight of plate waste includes uneaten food and beverages that remain on plates and in glasses, bowls, etc., after free lunches for schoolchildren in grades 1–7 in Rezekne city schools.

The field study was conducted in late September 2021. The field study was first tested at school S1 from 13 to 17 September 2021, evaluating the process of catering management in accordance with the unified menu, which was designed for the needs of the project, including plate-waste weighing. In the period from 20 to 24 September 2021, the field study was conducted simultaneously at schools S2, S3, S4, S5, S6 and S7. At each school, the field study lasted for 5 working days, from Monday to Friday, except for school S1 (grade 7) and school S7 (grades 5–7), where the field study lasted only for 4 days (from Monday to Thursday) because on Friday all the schoolchildren went on study tours and did not have lunch at school.

Each school had a different lunch break schedule. The average lunch time for schoolchildren in grades 1–4 was from 9:30 to 11:30, and for schoolchildren in grades 5–7 it was from 11:30 to 13:00. The researchers arrived at the schools at about 9:00 in the morning and finished their work at about 14:00 (depending on the school) for 5 consecutive days of the field study. Before the meal, the researchers identified the expected number of schoolchildren, considering the number of schoolchildren in the classes examined, and during the lunch they noted the number of schoolchildren who actually participated in the meal.

The research employed the following methods: observation, photography and direct manual weighing of plate waste by food category and by grade of schoolchildren [15,38,41,72,73]. The authors of the paper observed the design of the dining hall, the interior, the ergonomics, the table setting, the placement of food on a plate, the way food was served and the process and time of enjoying the meal. During the field study, the schoolchildren were asked to leave their dirty dishes on the tables (usually the schoolchildren had to bring their own dirty dishes to a special place). When the schoolchildren had finished their lunch, the researchers measured the plate waste by dividing the plate waste into the following food categories: soup, staple food, meat/fish, salad/vegetables, beverage, bread, fruit, curd products (glazed curd cheese). Later, each bucket was weighed, and the data on the weight of the waste were entered into a waste registration protocol. The following measurement tools were used to quantify the plate waste: two kinds of high-density polymer buckets (a large bucket with a capacity of 2 L, weight 61 g, and a small bucket with a capacity of 1 L, weight 35 g; each bucket was marked with the food category and the number of the class for which it was intended) and electronic kitchen scales (model—Clatronic KW3412, art. No. 271680, measuring range—up to 5 kg, units of measurement—grams).

2.4. Data Analysis

All the survey data were analyzed using the data-processing program IBM SPSS (version 26) and MS Excel.

The research employed a statistical analysis method—one-way ANOVA—to identify the effect of an independent variable on the dependent variable, i.e., whether the average plate waste, measured in grams per schoolchild, differed significantly across grades. The independent variable was a qualitative variable representing several, at least three, categories; therefore, for the analysis of variance, the grades were divided into three groups: grades 1–2, grades 3–4 and grades 5–7. An appropriate sample was selected for each of the grade groups, and the metric values of dependent variables were recorded for the sample.

To determine the cost of plate waste, the research also calculated the monetary value of waste (see equation No. 3) [19]. However, given that most of the waste consisted of liquid waste (beverages), as well as the fact that the most important component of this food category was water, the weight of plate waste excluding beverage waste per schoolchild and the cost of plate waste excluding beverages were also calculated (see equations No. 4 and No. 5).

3. Results

In total, 7064 schoolchildren were involved in the field study; of the total, 4105 or 58.11% were in grades 1–4, and 2959 or 41.89% were in grades 5–7. The total number of schoolchildren who actually ate lunch was equivalent to the number of portions of food served (Table 4).

Table 4. Basic information on the 7 sample schools.

School	Grade Group	Age Range	Number of Children in Grades	Number of Field Study Days (per Week)	Actual Number of Lunch Participants (Number of Samples) *	
S1	Grade 7	13 (14)	76	4	234	234
S2	Grades 1–4	(6) 7–10	176	5	677	1127
	Grades 5–7	11–13 (14)	126	5	450	
S3	Grades 1–4	(6) 7–10	150	5	603	1024
	Grades 5–7	11–13 (14)	126	5	421	
S4	Grades 1–4	(6) 7–10	184	5	663	1110
	Grades 5–7	11–13 (14)	130	5	447	
S5	Grades 1–4	(6) 7–10	206	5	94	493
	Grades 5–7	11–13 (14)	147	5	399	
S6	Grades 1–4	(6) 7–10	314	5	1239	1813
	Grades 5–7	11–13 (14)	165	5	574	
S7	Grades 1–4	(6) 7–10	202	5	829	1263
	Grades 5–7	11–13 (14)	174	4	434	
Total:		-	2176	-	7064	

* Note: the sample of the field study included only the number of schoolchildren who actually ate lunch, which might not correspond to the actual number of schoolchildren at school, as some schoolchildren did not eat lunch during the field study due to illness or self-isolation because of COVID-19.

It should be noted that the number of participants in the field study was significantly affected by COVID-19. For example, in school S4, grade 3 (24 schoolchildren) was in self-isolation throughout the week, and grade 7 (28) was in self-isolation from Tuesday. In school S7, grade 6 (25) was in self-isolation throughout the week. The number of participants in the field study was most significantly affected by COVID-19 in school S5: from Monday to Wednesday, 9 classes with a total of 212 schoolchildren, on Thursday 8 classes with a total of 201 schoolchildren and on Friday 7 classes with a total of 177 schoolchildren were in self-isolation.

The results of the interview with the personnel of the schools and their canteens showed that no food waste sorting nor food waste inventory were performed in any of the schools included in the field study. However, school S6 sorted food waste into fractions, i.e., solid and liquid food waste. At school S5, however, waste from vegetable preprocessing was partially sorted.

This is because the local government of Rezekne city has not entered into contracts with any waste-management company to dispose of FW generated by schools and pre-school educational institutions, as Rezekne waste management companies do not provide biodegradable waste-disposal services. Currently, such services are available only in the regions of Riga and Pieriga. Sorting biodegradable waste needs to be introduced throughout Latvia by the end of 2023. According to the principles of a circular economy, disposing of food waste is the least desirable option. However, if this cannot be avoided, food waste needs to be collected separately from other municipal waste. It should be noted that the management of biodegradable waste, including the management and control of food waste, is very poorly implemented in Latvia, which still makes the population overpay for the service received and hinders the fulfillment of national commitments to achieve the goals of the EU economy [74].

In the schools examined, some of the solid FW, e.g., cereals, potato, meat, etc., were often used informally for pet food. If there was no one to give such FW to, it was disposed of into general waste containers. However, beverage and soup waste were discharged into sewerage.

The field study revealed that the average weight of plate waste per schoolchild per day ranged from 142 g (school S6) to 268 g (school S4) (Table 5).

Table 5. Weights of plate waste identified by the field study at the Rezekne city school canteens (by school and by grade group).

School	Total Weight of Plate Waste (g/Week)	Average Plate Waste per Schoolchild (g) *	Grade Group	Total Weight of Plate Waste (g/Week)	Actual Number of Lunch Participants (Number of Samples)	Average Plate Waste per Schoolchild (g)
S1	52,578	225	Grade 7	52,578	234	225
S2	163,750	145	Grades 1–4	99,397	677	147
			Grades 5–7	64,353	450	143
S3	197,674	193	Grades 1–4	109,544	603	182
			Grades 5–7	88,130	421	209
S4	297,603	268	Grades 1–4	180,518	663	272
			Grades 5–7	117,085	447	262
S5	71,131	144	Grades 1–4	15,416	94	164
			Grades 5–7	55,715	399	140
S6	256,933	142	Grades 1–4	190,644	1239	154
			Grades 5–7	66,289	574	115
S7	216,630	172	Grades 1–4	152,566	829	184
			Grades 5–7	64,064	434	148
Total:	1,256,299	178	Total for grades 1–4	748,085	4105	182
			Total for grades 5–7	508,214	2959	172

* Note: the average weight of plate weight per schoolchild (g) was calculated as the total weight of plate waste divided by the actual number of schoolchildren [19]. Source: authors' calculations based on the results of the field study.

As shown in Table 5, the field study identified differences in the average weight of plate waste per schoolchild between the youngest schoolchildren (i.e., grades 1–4) and older ones (i.e., grades 5–7) (except for school S1 that starts from grade 7). Higher weights of plate waste were found for grades 1–4 in 5 out of the 6 schools (S2, S4, S5, S5 and S7). The average weight of plate waste per schoolchild registered in grades 1–4 exceeded that registered in grades 5–7 by 10 g, or 5.81%.

To perform a one-way ANOVA test, the schoolchildren of the seven Rezekne city schools were divided into three grade groups: grades 1–2, grades 3–4 and grades 5–7. The analysis of variance showed that the average weight of plate waste per schoolchild, in grams, was not affected by the grade which the schoolchildren were in (Table 6).

Table 6. Results of the ANOVA test for the average weights of plate waste per schoolchild, in grams, identified at the Rezekne city school canteens.

Grade Group	Count	Sum	Average	Variance		
Grades 1–2	22	4147.681	188.531	3670.868		
Grades 3–4	27	4754.659	176.0985	2988.212		
Grades 5–7	39	6830.969	175.1531	3965.215		
One-way ANOVA						
Source of variation	**SS**	**df**	**MS**	**F**	***p*-value**	**F crit**
Between groups	2798.964	2	1399.482	0.389432	0.678644	3.103838661
Within groups	305,459.9	85	3593.646			
Total	308,258.9	87				

F < Fcrit, = grades do not statistically significantly affect the amount of plate waste. Source: authors' calculations based on the results of the field study.

The share of plate waste (%) in the total weight of food served was calculated to identify the share of the food served that went to waste.

The share of plate waste at the schools examined was on average 28.75% of the total weight of food served, which means that on average almost one-third of the served food went to waste (Table 7).

Table 7. Shares of plate waste (%) in the total weight of food served at the Rezekne city school canteens (by school).

School	Total Weight of Plate Waste (g/Week)	Total Weight of Food Served, g/Week *	Share of Plate Waste, % **
S1	52,578	145,970	36.02
S2	163,750	696,962	23.49
S3	197,674	629,858	31.38
S4	297,603	684,707	43.46
S5	71,131	305,503	23.28
S6	256,933	1,122,945	22.88
S7	216,630	783,191	27.66
Total:	1,256,299	4,369,136	28.75

* Note: the total weight of food served (g/week) was calculated based on the weight of food indicated by the menu (see Table 3), multiplying the weight of food served each day by the number of samples examined that day and adding up the results for all the days and all the schools. ** Note: the share of plate waste (%) in the total weight of food served was calculated as the ratio of the total weight of plate waste (g) to the total weight of food served (g) × 100% [19]. Source: authors' calculations based on the results of the field study.

As shown in Table 7, a lower share of plate waste than the average was identified in schools S2, S5, S6 and S7, while a higher share than the average was found in schools S1, S3 and S4.

The shares of plate waste in the total weight of food served were analyzed also by grade group, revealing a 1.68%-point difference between grades 1–4 and 5–7: the average for grades 1–4 was 29.46%, while the average for grades 5–7 was 27.78% (Figure 4).

Figure 4 shows that a higher share of plate waste in the total weight of food served than the average for grades 1–4 (i.e., 29.46%) was found in two out of the six schools, i.e., school S4—44.08% and school S7—29.72%; in school S3 this coincided with the average of

29.46%; however, in three schools the figure was below the average, i.e., school S2—23.73%, school S5—26.97%, school S6—24.79%. In the group of grades 5–7, a higher figure than the average (i.e., 27.78%) was found in three out of the seven schools, i.e., school S1—34.89%, school S3—34.16% and school S4—42.55%, whereas in four schools it was below the average: school S2—23.14%, school S5—22.43%, school S6—18.72% and school S7—23.73%. It should be noted that the largest share of plate waste in the total weight of food served among grades 1–4 (44.08%) and grades 5–7 (42.55%) was found in school S4.

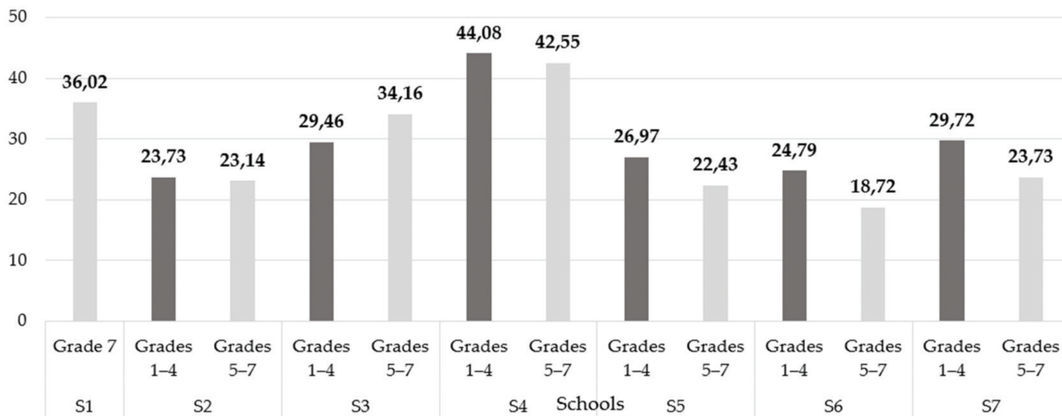

Figure 4. Share of plate waste (%) in the total weight of food served at the Rezekne city school canteens (by school and by grade group). Source: authors' construction based on the results of the field study.

The food served during the field study at the Rezekne city school canteens consisted of the following food categories: soup, staple food, fish or meat, beverages, fruit, vegetables, bread and curd products (glazed curd cheese). An analysis of the data obtained during the field study on the weight of plate waste by food waste category revealed that in all the schools, the largest share of plate waste in the total weight of plate waste was made up of beverages at 42.24%, followed by staple food (potato, pasta)—28.38% and meats—11.77% (Table 8). The authors of the paper note that in the present research, the plate waste analysis involved beverages (because all of them contain calories), as this method was suggested as the most comprehensive accounting of plate waste [75]. In some research studies, this method is called tray waste measurement, as all foods and beverages on schoolchildren trays are included in the total amount of food wasted [76].

Table 8. Breakdown of plate waste by food waste category at the Rezekne city school canteens, as a % of the total weight of plate waste (by school).

Plate Waste by Food Category, Share of Total Plate Waste	School							Total
	S1	S2	S3	S4	S5	S6	S7	
Soup	2.66	4.45	5.48	12.09	6.17	12.94	5.56	8.37
Staple food	19.21	29.90	22.25	29.72	40.77	34.19	22.24	28.38
Fish	0.00	1.71	0.75	1.33	0.96	1.97	1.00	1.28
Meat	12.55	13.25	12.97	10.03	16.22	14.53	7.00	11.77
Beverage	45.89	43.18	53.31	37.92	22.33	31.49	55.76	42.24
Fruit *	14.24	1.66	2.30	1.63	0.00	3.15	0.57	2.30
Vegetables	5.14	5.03	1.41	6.98	13.33	1.07	6.82	4.89
Bread	0.32	0.75	1.53	0.26	0.22	0.65	1.05	0.74
Glazed curd cheese	0.00	0.07	0.00	0.05	0.00	0.01	0.01	0.03
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Note: regarding fruit waste, it is difficult to draw any conclusion because the schoolchildren were given whole bananas and whole apples during the field study, which they often took with them. For example, in school S5, fruits were served in a box, which was usually taken to the classroom where the fruits were later consumed. Source: authors' calculations based on the results of the field study.

As shown in Table 8, an analysis of plate waste shares by food waste category revealed a similar situation, as the largest share of plate waste was represented by beverages, followed by staple food and meat, which was found in three out of the seven schools: S2 (43.18%, 29.90% and 13.25%, respectively), S3 (53.31%, 22.25% and 12.97%) and S7 (55.76%, 22.24% and 7.00%). In two out of the seven schools, i.e., S5 and S6, the largest share of plate waste was found for staple food (S5—40.77% and S6—34.19%), followed by beverages (S5—22.33% and S6—31.49%) and meat (S5—16.22% and S6—14.53%). In school S4, however, the largest share of plate waste was found for beverages (37.92%), followed by staple food (29.72%) and soup (12.09%). In school S1, the largest share of plate waste was found for beverages (45.89%), followed by staple food (19.21%) and fruit (14.24%). Such shares of plate waste by food category were directly related to the weight of food served by food category, as beverages, staple food and meat had the largest share in the total weight of food served. Therefore, it would be more correct to analyze the shares of plate waste by food category by considering the weight of each food category served, using Equation (2):

$$\text{Share of Plate Waste by Food Category, } \% = \frac{\text{Weight of Plate Waste by Food Category, g}}{\text{Weight of Served Meal by Food Category, g}} \times 100 \quad (2)$$

At the same time, the calculations also showed which categories of food served the schoolchildren consumed the most and the least (Table 9).

Table 9. Plate waste shares of food served (%) at the Rezekne city school canteens by food category (by school).

School	Soup	Staple Food	Fish	Meat	Beverage	Fruit	Vegetables	Bread	Glazed Curd Cheese
S1	7.99	30.84	0.00	32.52	51.56	50.18	34.32	2.85	0.00
S2	8.63	31.47	20.81	27.10	31.37	4.74	19.79	4.34	1.00
S3	14.76	31.07	10.93	36.32	51.46	8.59	7.30	11.83	0.00
S4	44.56	57.62	29.64	37.87	50.83	8.62	50.38	2.75	1.33
S5	12.40	42.44	15.29	31.32	16.11	0.00	53.62	1.25	0.00
S6	24.65	35.05	25.77	28.44	22.31	8.43	4.15	3.70	0.20
S7	13.67	27.53	21.29	15.80	47.82	1.68	32.94	7.23	0.25
Total	20.45	36.48	21.64	28.77	37.56	7.65	23.90	5.26	0.49

Source: authors' calculations based on the results of the field study.

As shown in Table 9, the largest share of plate waste in the total weight of food served was represented by beverages at 37.56%, followed by staple food—36.48% and meat—28.77% (see Figure 5). An analysis of the data by school revealed that there were categories of food that the schoolchildren consumed less than 50% of, i.e., the share of plate waste exceeded half of the total weight of food served, for example, in school S4, the share of plate waste for the category of staple food reached 57.62%, in schools S4 and S5, the shares of plate waste for the category of vegetables were 50.38% and 53.62%, respectively, and for the category of beverages, the figures were the highest in schools S1 (51.56%) and S3 (51.46%), followed by school S4—50.83%.

The authors of the paper point out that in Latvia, the planning and management of menus in educational institutions is conducted strictly in accordance with the dietary guidelines stipulated by various legal acts. After analyzing the menus used in the Rezekne city schools, the authors concluded that the menus were based on the government's recommendations on nutrition for children; however, given the large share of meat and staple food in the total weight of food served during the field study, in this case compliance with the dietary guidelines did not guarantee a balanced diet for children. The large number of wasted beverages also indicated that the beverages given to the schoolchildren did not taste good. In the Rezekne city schools, beverages were poured into glasses and served on tables for each schoolchild individually. The observations during the field study showed that the schoolchildren often did not even taste their beverages. Due to COVID-19 restrictions, the intact beverages could not be given to other schoolchildren; therefore, they went to waste.

The monetary value of plate waste [19] was calculated using Equation (3); the weight of plate waste excluding beverage waste per schoolchild (see Equation (4)) and the cost of plate waste excluding beverages (see Equation (5)) were also calculated:

$$\text{Cost of Plate Waste, EUR} = \frac{\text{Average Weight of Plate Waste per Schoolchild, g}}{\text{Average Weight of Served Meal , g}} \times 1.42 \tag{3}$$

$$\text{Average Weight of Plate Waste excluding Beverage Waste per Schoolchild, g} = \text{Average Weight of Plate Waste per Schoolchild, g} - \text{Average Weight of Beverage Waste per Schoolchild, g} \tag{4}$$

$$\text{Cost of Plate Waste excl. Beverage Waste, EUR} = \frac{\text{Average Weight of Plate Waste excl. Beverage Waste per Schoolchild,g}}{\text{Average Weight of Served Meal , g}} \times 1.42 \tag{5}$$

where EUR 1.42 is the cost of free lunch per schoolchild that is provided for learners in grades 1–7 in Rezekne city schools and funded from the state and local government budgets in accordance with the requirements of legal acts [68].

The calculation results by school and by grade group, as well as for the entire period of the field study, are presented in Table 10.

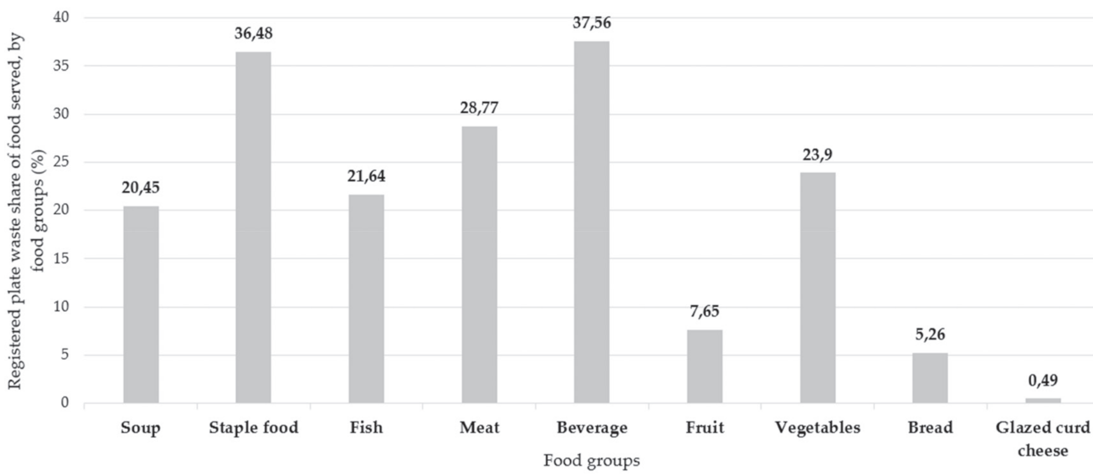

Figure 5. Shares of plate waste in the total weight of food served at the Rezekne city school canteens (%). Source: authors' construction based on the results of the field study.

After analyzing the costs of plate waste (excluding beverage waste) per schoolchild, shown in Table 10, it could be concluded that the average cost of plate waste (excluding beverage waste) per schoolchild was EUR 0.236 (EUR 1666.88/7064 samples). An analysis by grade revealed that except for schools S3 and S4, the figure was higher in all the other schools in the group of grades 1–4; in school S4, this figure was the same for both groups of grades, while in school S3, the cost of plate waste (excluding beverage waste) per schoolchild was lower in grades 1–4 than in grades 5–7. It should be noted that the highest cost of plate waste (excluding beverage waste) per schoolchild was found in school S4 at EUR 0.38. The average cost of plate waste (excluding beverage waste) per schoolchild found in the group of grades 1–4 was EUR 0.243 (EUR 997.06/4105 samples), and in the group of grades 5–7 it was EUR 0.226 (EUR 669.82/2959 samples), which made up a difference of EUR 0.017, or 7.5%. Given that the cost of plate waste for the period of the field study, i.e., for 5 working days (in some schools for 4 working days), totaled EUR 1666.88, per day it was about EUR 333.38, per month or on average 21 working days it was about EUR 7000.00.

Table 10. Weights (g) and costs (EUR) of plate waste at the Rezekne city school canteens (by school and by grade group).

Schools	Groups of Grades	Average Weight of Served Meal, g	Average Weight of Plate Waste Per Schoolchild, g	Cost of Plate Waste per Served Meal, EUR	Average Weight of Beverage Waste Per Schoolchild, g	Average Weight of Plate Waste Excluding Weight of Beverage Waste Per Schoolchild, g	Cost of Plate Waste Excluding Beverage Waste Per Schoolchild, EUR	Actual Number of Lunch Participants (Number of Samples)	Total Cost of Plate Waste Excluding Beverage Waste, EUR
S1	Grade 7	613	225	0.52	103	122	0.28	234	66.13
S2	Grades 1–4	618	147	0.34	58	89	0.20	677	138.45
	Grades 5–7	618	143	0.33	69	74	0.17	450	76.51
S3	Grades 1–4	618	182	0.42	94	88	0.20	603	121.93
	Grades 5–7	618	209	0.48	116	93	0.21	421	89.96
S4	Grades 1–4	618	272	0.62	105	167	0.38	663	254.41
	Grades 5–7	618	262	0.60	97	165	0.38	447	169.47
S5	Grades 1–4	618	164	0.38	34	130	0.30	94	28.08
	Grades 5–7	618	140	0.32	32	108	0.25	399	99.01
S6	Grades 1–4	618	154	0.35	52	102	0.23	1239	290.38
	Grades 5–7	618	115	0.26	29	86	0.20	574	113.43
S7	Grades 1–4	618	184	0.42	98	86	0.20	829	163.81
	Grades 5–7	624	148	0.34	92	56	0.13	434	55.31
Total for grades 1–4								4105	997.06
Total for grades 5–7								2959	669.82
Total									1666.88

Source: authors' calculations based on the results of the field study.

4. Discussion

4.1. Comparison with Other Studies

The management of catering in the schools of Rezekne city differs significantly from the approach applied in several European countries and the USA, where it mostly takes the form of buffet-type catering. In Rezekne city schools, before each lunch break, tables reserved for individual classes are set by placing portions of a set meal (staple food and meats on a single plate) according to the expected number of lunch participants, while vegetables can be served together with a set meal on a single plate or served in shared dishes on tables for each class individually, while soup is usually served in shared dishes on each table. The menus are designed based on government recommendations on child nutrition and are agreed and approved by the head of each educational institution.

The results of the quantification of plate waste that was performed at the canteens of the Rezekne city schools, examining the plate waste of 7064 school lunches for schoolchildren in grades 1–7, showed that the average weight of plate waste per schoolchild reached 178 g: in the group of grades 1–4 it was 182 g, in the group of grades 5–7 it was 172 g. The share of the total weight of plate waste in the total weight of food served was 28.75%: in the group of grades 1–4 the figure was 29.46%, while in the group of grades 5–7 it was 27.78%.

It could be concluded that the share of plate waste calculated by the field study exceeded that identified by previous research studies conducted in other European countries and the USA. This could be due to the fact that in the present field study, the beverages that were not consumed were also included in the weight of plate waste. Many plate waste measurement studies considered only solid plate waste (excluding beverage waste), and often the components of plate waste were not discussed in detail at all. Eriksson et al. identified that 23% of food served in Swedish school canteens went to waste. Waste from beverages was not recorded or quantified in this study [35]. A research study on Italian schools by Garcia-Herrero et al. found that the average weight of food waste (excluding beverage waste) per primary school pupil was 136 g, of which about 95% was plate waste and about 5% was served food waste [15]. In an audit of food waste (excluding beverage waste) in Spanish schools, Derqui and Fernandez (2017) found that the largest amount of food waste came from plate waste, i.e., ranging from 21 g to 47 g per pupil per day in primary schools and from 23.7 g to 88.0 g per student per day in secondary schools, concluding that the plate waste tended to increase with the age of students [19]. This observation showed the importance of taking measurements for the quantification of food waste by age group. Conducting food waste research at three U.S. schools in Florida, Wilkie et al. found that school A had the highest average food waste per pupil among all the three schools, even though the kitchen did not generate a measurable amount of food waste. This was due to the higher number of school-provided meals in school A and the number of primary schoolchildren who were more selective, or the fact that they were served larger portions than they could eat. In this research, the amount of wasted milk was measured separately [37]. Buzby and Guthrie, and Niaki et al. also concluded that food waste tended to decrease with the age of schoolchildren [20,48]. Steen et al., in contrast, found that the amount of plate waste tended to increase with the age of schoolchildren [38]. The results of our field study showed that no significant differences in the share of plate waste in the total weight of food served were observed between the groups of grades; it was found that there was a difference of 1.68 percentage points between the groups of grades 1–4 and 5–7: the average for grades 1–4 was 29.46%, while for grades 5–7 it was 27.78%.

An analysis of plate waste by food category showed that beverages accounted for the largest share of total plate waste (42.24%), followed by staple food (28.38%) and meat (11.77%). An analysis of plate waste shares of food served (%) by food category revealed a similar situation: the largest share of food served was made up of beverages (37.56%), followed by staple food (36.48%) and meat (28.77%). The results of the present field study, broken down by plate-waste food category, differed from the results of other research studies conducted worldwide, which were as follows: in Italian schools, analyzing plate waste by food category, it was found that about 22.4% pasta or rice, 31% livestock food products and 43.6% vegetables were wasted [73]; in a research study conducted in Boston schools, Cohen et al. (2013) found that students discarded about 19% of their food, including 47% fruit, 25% milk and 73% vegetables [24]; a research study of students in grades 3 to 8 in four U.S. schools found that the share of vegetable waste reached 58.9% [77]; research studies conducted in China found that vegetables accounted for the largest share of plate waste, i.e., 42% [78] and 31% to 53% [41]. It could be concluded that vegetables were wasted the most, and this was a very common situation all over the world [20,23].

The results of the present field study on vegetable plate waste were as follows: the share of vegetables in the total amount of plate waste was only 4.89%, while the share of discarded vegetables in the total amount of vegetables served was 23.90%, which was the fourth largest plate waste food category. The authors of the paper attribute this to the relatively small share of vegetables in the school menu (only fresh vegetables such as fresh cucumbers, tomatoes, carrots and cabbage), which accounted for only 4–8% of the total weight of food included in the school menu. This mostly depended on the insufficient funding for free lunches (i.e., only EUR 1.42), which limited the possibility to introduce different kinds of vegetables to the menu. It is also necessary to consider the fact that Latvia is located in Northern Europe, where fresh vegetables such as cucumbers, tomatoes, peppers, etc. are mostly available at the end of summer when their prices are the lowest, yet during the school year their prices increase significantly, which does not encourage the diversification of the menu.

4.2. Monetary Value of Plate Waste

Regarding the monetary value of food waste, as noted by Derqui and Fernandez, such a measurement was very seldom taken by researchers due to the fact that the research objectives rarely related to costs [19].

The aim of the present research was not to perform a detailed analysis of the monetary value of food waste. However, given the fact that in Rezekne city, lunches for schoolchildren in grades 1–7 are funded by the national or local governments whose main source of revenue is personal taxes, in this case it was worth calculating the monetary value of food waste. To make the calculation of plate-waste costs as correct as possible, the weight of beverages was deducted from the total weight of plate waste, as the authors of the paper believed that the most significant component of any beverage was water, which was cheaper than, for example, meat or vegetables. The calculations showed that the average cost of plate waste (excluding beverage waste) per schoolchild was estimated at EUR 0.236 (or 16.6% of the cost of a portion of free lunch at EUR 1.42).

Given that the cost of plate waste for the period of the field study, i.e., for 5 working days (in some schools for 4 working days) totaled EUR 1666.88, per day it was about EUR 333.38, and per month or on average 21 working days it was about EUR 7000.00. Due to the different price levels across various countries, it is difficult to compare our figures in terms of whether they are high or low. However, given that the cost of one free lunch portion is EUR 1.42, almost 5000 schoolchildren a month could be provided with free lunch for this funding. Additionally, this is a significant figure, considering that the number of schoolchildren in grades 1–7 in Rezekne city schools was 2176: the monetary value of plate waste would be enough to provide free lunch for schoolchildren in the grades for about 2 days a month.

4.3. Policy Recommendations

One of the research methods was observation. The researchers observed the atmosphere in the dining halls of the school canteens, the interior, the table setting, the way the food was placed on the plate, the way the food was served for lunch and the process and time for enjoying the food. The plate-waste analysis was only one of the activities of the research project that developed recommendations for several areas of school catering management: designing of school menus, organization of the catering process, assessment of catering infrastructure and equipment, school canteen personnel, food waste management, etc.; for example, one of the recommendations developed was as follows *(1) designing and implementing an education and communication strategy in schools, which is focused on sustainable and healthy food consumption.* This recommendation is based on the idea of education and communication as the most effective approach to changing learners' food-consumption behavior [79]. Food waste in school canteens could be reduced by educating learners and school personnel, thereby changing their behaviors [37,80,81], especially given that childhood food consumption behaviors and habits tend to continue into adulthood [20]. An awareness of food waste, healthy eating and waste needs to be raised among both learners and school personnel (teachers, administrators, kitchen personnel) [27,82–84]. Often it is one-way communication, through posters or table talkers, which conveys messages such as "Eat as much as you can—but throw away as little as you can" [85]. In addition, schools were recommended to integrate nutrition education and healthy food awareness into the school canteen environment, using a competency approach to the curriculum.

The use of various digital tools to track plate waste also allows the responsible personnel to gain an understanding of why the meal is wasted, as well as providing food planning, which could have a positive effect on the amount of waste in the long term [85]. One of the results of our research project was the development of a prototype of an e-mentor tool that is able to predict the quantity of food required for educational institutions with the aim of reducing food waste. The mathematical calculations for the prototype of the e-mentor tool showed that if the lunch break was less than 20 min (considering also the time it takes for schoolchildren to get to the canteen and go back to the classroom after the lunch), the weight of plate waste increased exponentially. By means of the prototype of the e-mentor tool, it is possible to predict not only the effect of the lunch break duration on the amount of plate waste but also to identify the effects of other parameters such as schoolchildren's attitudes to certain categories of food and competitive food consumption (e.g., food brought from home) [86]. The authors of the paper plan to develop the e-mentor tool within future research projects so that it would be practically applicable in Rezekne city schools.

The other recommendations developed pertain to:

(2) the focus of school administration on the sustainability of food resources, which means that the more school administrators and teachers focus on sustainability, the larger the potential for waste-reduction initiatives [27,87];

(3) diversification of school menus, including identifying learners' wishes for designing a menu [11,27], as well as the revision of and improvement in nutritional guidelines considering the changing demand for food by learners in today's conditions, but based on the consumption of healthy food. It is highly recommended to review the menu periodically and to not include dishes that are not preferred by the learners [88];

(4) careful planning of the quantity of food to be prepared. Forecasting canteen attendance can help canteens to identify the number of learners they need to provide catering for, i.e., plan the demand [89]. Derqui et al. (2018) point out that timely and fast communication between the school administration and the kitchen about the actual number of learners is needed in order to be able to adjust the quantity of food prepared [27]. Previous research studies have shown that canteen attendance forecasting can reduce food waste and save financial resources [82,89–91]. The authors of the paper concluded that in the Rezekne city schools, due to external circumstances (mainly because of sick schoolchildren or the COVID-19 pandemic), the number of schoolchildren participating in lunch on a given day was variable. This is one of the risk factors in food waste, as from the organizational perspective, the educational institution does not always have a system in place that allows the catering provider to receive timely information on the actual number of schoolchildren on a given day to avoid unnecessary food production;

(5) prudent planning of lunch breaks and dining hall environment adaptation. Several research studies have examined the impacts of changes in the dining hall on food waste, e.g., the implementation of the Smarter Lunchrooms Movement (SLM) strategy [92] and its impact on the consumption of fruit, vegetables and dairy products by learners [31,93,94]. Research studies show that the implementation of fruit and vegetable-oriented marketing activities in schools significantly increase the consumption of the foods [95–97]. However, an extensive research study by Cohen et al. on school food promotion strategies conducted in 2021 showed that in the long term, the interventions yielded conflicting results, meaning that not all school food promotion methods included in the SLM strategy actually worked. The best results could be achieved by applying the holistic approach, e.g., giving students an opportunity to choose meal components (especially fruit and vegetables), improving the taste of food, offering cut fruit, allowing more time for lunch breaks (~30 min), limiting access to competitive foods, etc. [98].

(6) the way the food is served. Liu et al. (2016) have concluded that it is buffet-type catering that is more effective in serving food in schools, as it makes students more flexible in relation to the food choice, taste and weight (compared with a way of serving food that is of an oppressive nature) [78]. However, Simanovska points out that in some schools in Latvia, the Food and Veterinary Service inspectors objected to the possibility for schoolchildren to choose the components and size of the portion themselves, stating that this could

be contrary to strict legal requirements concerning a certain amount of nutrients to be provided to every schoolchild. Nevertheless, the official opinion of the National Food and Veterinary Service states that it is acceptable for schoolchildren to choose their own food and portion size if the average nutritional requirements for every child are met [99]. Methods of serving foods that make it practically difficult for schoolchildren to consume them should be avoided [26]. The supply of unpeeled and uncut fruit to schoolchildren significantly increases the amount of plate waste [100]. The size of plates also plays an important role in placing the food in an attractive way for schoolchildren. The field study found that in most of the schools examined, the plate size was too small, often the food on the plate was placed in such a way that the components of each food were not visible, which made a negative impact on the schoolchildren's attitudes to the food;

(7) modern kitchen equipment and professional kitchen personnel. The amount of food waste generated by schools is influenced by the diverse resources of their canteens, both physical (facilities and infrastructure) and human (school and canteen personnel). Some of the resources are structural, e.g., the size and equipment of the kitchen or canteen, while human resources are more closely linked to the school administration's focus on sustainability [19,27]. The appearance and taste of food are influenced by factors such as the cooking skills of kitchen personnel, the quality of the food, cooking equipment and the storage of foods [27,41]. Despite the fact that 70.91% of school canteen personnel involved in the field study had the required qualifications to perform the responsibilities of a cook, it was recommended to develop a training plan for the school canteen personnel to acquire or improve the skills and knowledge required for the job. Regarding improvements in school canteen infrastructure, the schools were recommended to purchase modern technological equipment to prepare food by applying newer, more food-friendly methods, e.g., convection ovens or combination ovens. It is also necessary to consider the fact that the Rezekne school canteens mainly used manual work; therefore, equipment was needed that could automate many processes, e.g., a machine for portioning semi-finished foods, etc.

The authors of the paper believe that within the research project, significant work was conducted and basic information about the management of catering in Rezekne schools was obtained on which to build on future research. This future research would relate to the implementation of individual recommendations for the management of catering, as well as the improvement of the e-mentor tool with the aim of applying it in practice at school canteens.

5. Conclusions

Within the research project "E-mentor as a Transformation tool for Ensuring Zero-Waste Food Consumption in Educational Institutions" No. lzp-2020/2-0115, funded by the Latvian Council of Science, an analysis of plate waste was performed in seven schools of Rezekne city, and recommendations for stakeholders on how to reduce the amount of plate waste were developed. It should be noted that, to date, no research studies have been conducted in Latvia placing a focus on zero-waste food consumption, including plate waste generated by educational institutions.

The distinguishing feature of the present research was that during the week of the field study, a unified menu was introduced into all the schools examined, which eliminated differences in food availability and ensured the same research conditions, thereby reducing the impact of factors influencing gastronomic choices on the study.

The research results showed that in Rezekne city schools, the average weight of plate waste per schoolchild reached 178 g. The weight of plate waste accounted for 28.75% of the total weight of food served. The figures were higher than those obtained by earlier research studies conducted worldwide, and the authors of the paper explain this by a different methodology for measuring plate waste—the present field study also took into account beverages because all of them contain calories, and this method is considered to be the most comprehensive accounting of plate waste. The field study did not find significant differences in the average weight of plate waste between different age groups of schoolchildren: in the group of grades 1–4 it was 182 g, in the group of grades 5–7 it was 172 g. Regarding the share of plate waste in the total weight of food served, in the group of grades 1–4 the figure was 29.46%, while in the group of grades 5–7 it was 27.78%. A one-way analysis of variance showed that the average weight of plate waste per schoolchild, in grams, was not affected by the grade which the schoolchildren were in.

After analyzing the amounts of plate waste by food category, the authors of the paper found that the results obtained differed from those of previous research studies conducted worldwide, which found that vegetables were wasted the most. In the schools of Rezekne city, the largest share of plate waste in the total weight of plate waste was made up of beverages (42.24%), followed by staple food (28.38%) and meat (11.77%). An analysis of plate waste shares of food served (%) by food category revealed a similar situation: the largest share of food served was made up of beverages (37.56%), followed by staple food (36.48%) and meat (28.77%). The authors of the paper explain this via the relatively small share of fresh vegetables in the school menu, which, in the opinion of the authors, depends on insufficient national and municipal funding for school lunches, which does not allow the schools to diversify their menus with a variety of fresh vegetables.

The aim of the present research was not to perform a detailed analysis of the monetary value of food waste. However, given the fact that in Rezekne city, lunches for schoolchildren in grades 1–7 are funded by the national or local governments whose main source of revenue is personal taxes, in this case it was worth calculating the monetary value of food waste. To make the calculation of plate waste costs as correct as possible, the weight of beverages was deducted from the total weight of plate waste. The calculations showed that the average cost of plate waste (excluding beverage waste) per schoolchild was estimated at EUR 0.236, or 16.6% of the cost of a portion of free lunch at EUR 1.42.

Given the research results, the authors conclude that in order to reduce the amount of plate waste generated by Rezekne city schools, school menus should be based not only on the requirements prescribed by relevant legal acts but also on modern learners' understanding of nutrition, their perception of food consumption and whether it is in line with their understanding of a "modern" and self-evident process. It is necessary to ensure that the schools' cooking processes meet the requirements of modern consumers (learners) by introducing cooking techniques that are understandable and familiar to them (e.g., offering smoothies). By following the trends in cooking practices in society, it is possible not only to increase the consumption of school food but also to make the learners interested in consuming school food.

Nowadays, children's eating habits have changed significantly. Many dishes that are preferred by school menu makers and children's parents are not aligned with children's understanding of a delicious and healthy diet. The observations made by the authors of the paper revealed that in relation to competitive foods, children often chose a food that they consider healthy, and its physical volume was smaller than the volume of free lunch food. Most often, a competitive food chosen by learners did not meet the requirements of a healthy diet. The authors of the paper believe that serving school food in a modern way could change learners' attitude to the food offered. For example, packed small carrots, chopped peppers or cucumbers placed in disposable snack dishes allows schoolchildren to take the vegetables with them and eat them later. Expanding schoolchildren's choices of the kinds of free lunch dishes could reduce the amount of plate waste. The authors recommend that schoolchildren be provided with food choices (e.g., pre-ordering or organizing buffet meals). The authors further recommend reviewing and improving the dietary guidelines by considering changes in the demand for food by learners in today's world, while also ensuring the guidelines remain based on healthy food consumption.

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Article

Do Village Allocation Funds Contribute towards Alleviating Hunger among the Local Community (SDG#2)? An Insight from Indonesia

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Abstract: Using an exclusive data set from Indonesia in 2018–2020, this study aims to prove whether there is a relationship between the allocation of village funds and the level of hunger in the community. In particular, this study tries to find out whether the Village Fund allocation policy has an effect on the achievement of the United Nations Sustainable Development Goal 2 (SDG#2). Using a quantitative method with regression analysis, this study found that the allocation of village funds by the Indonesian government supported hunger and poverty alleviation in all areas of Indonesia's villages. This research result has implications for policymaking on sustainable food inclusion, especially in Indonesian villages.

Keywords: village funds; level of hunger; SDG#2; poverty and hunger pattern; zero hunger

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1. Introduction

Hunger has been a worldwide problem for centuries. Those who suffer from chronic hunger do not have the option and ability to buy food. Hence, they do not get enough calories and essential nutrients. When this primary need is not met, people do not have the energy for anything else that is normal in human life, for instance going to school, having a job, and so on. Hunger is an ongoing problem that is closely related to poverty.

Poverty is the powerlessness to gain access to basic resources, whether it is food, clothes, education, or anything else of that nature. As poverty increases, as does hunger. Hunger is the worst consequence of poverty. In turn, poverty increases when people are silent and indifferent toward social injustice. In rural areas, injustice may include a lack of access to energy as well as an inability or difficulty in using modern information and communication technology (Acharya and Chakraborty 2018; van Gevelt et al. 2018; Zavratnik et al. 2018; Samarakoon 2019).

World hunger is still the biggest challenge faced by humanity today. In 2018, around 857 million people in the world were still suffering from chronic hunger. Many kinds of research have been conducted to find solutions. Some believe that sustainability is considered a key driver for food innovation and that it can solve the problem. Transgenic food and gen-engineering technologies (Garcia et al. 2019; Ahmad et al. 2021), for instance, have been offered as one of the solutions, but such ideas are still controversial and debatable. Many approaches, whether one-dimensional or covering multi-dimensional aspects, have been conducted to test and see how the problem can be solved. Yet, up to the present time, hunger remains a persistent problem. Why is that? It seems that the complexity of the cause of hunger has to be taken into account. Several factors that cause hunger are (i) extreme poverty, (ii) climate change, (iii) conflict between countries, (iv) gender inequality, (v) global food systems that are not conducive to the purpose, and (vi) COVID-19 (Acharya and Chakraborty 2018; Ahern 2021). Chansanam and Li stated that future research on poverty should place more emphasis on the poverty line, social policies, and living standards (Chansanam and Li 2022).

The enormous health impacts of COVID-19 have caused misery and increased health-care costs worldwide. A developing country such as Nigeria stands out from the rest. Eighty-four other developing countries also have suffered from the economic downturn, and in the long run, the progress made towards the "zero hunger" goal is at risk of being completely reversed in those countries. The pandemic has triggered living costs to rise significantly while the living standard falls, plunging hundreds of millions of people back into poverty (Ahern 2021; Klingelhofer et al. 2022; The World Bank 2021; Lakner et al. 2020; Saccone 2021). Saengtabtim et al. (2022) also investigated the impact of COVID-19, and came to the conclusion that there is a connection between the health, economic, and tourism aspects caused by the COVID-19 pandemic. Some countries in the South Asia region, for example, are home to some of the largest undernourished communities in the world (Von Grebmer et al. 2020). Meanwhile, Nakao (2019) stated that 822 million people on earth are in food insecure conditions, and as many as 517 million people (62.89% of them) are in the Asia Pacific region.

Indonesia is also facing challenges posed by hunger. Based on the GHI report (2020), especially in Southeast Asian countries, Indonesia ranks 70th out of 107 countries facing difficulties in meeting their psychological needs for food and nutrition with an index score of 19.1. This means that there are still many hungry people in Indonesia. The global hunger index of 18.2 is referred to as being at a moderate level. Therefore, Indonesia cannot yet be considered to have attained a moderate level (Von Grebmer et al. 2020). In the case of Indonesia, the occurrence of the COVID-19 pandemic resulted in an increase in hunger by 0.73%, from 9.22% in 2019 to 9.95% in the third quarter of 2020 (Kompas Newspaper 2020). This increase in the level of hunger has slowed the growth of the Human Development Index to 71.94 in 2020 which is up only 0.02 points from 2019; whereas usually, the increase amounts to around 0.5–0.6 points per year (BPS 2020). Based on Law No. 6 of 2014, the Indonesian Government began to allocate Village Funds in 2015 to eradicate poverty, especially in rural areas.

Many kinds of research have been conducted on hunger and poverty over the last two decades, and poverty studies increase by 10.18% each year. However, different from other studies, this research focuses on how village funds in Indonesia contribute to alleviating hunger and poverty. At the same time, this study seeks to find whether village funds as direct assistance by the Government can be an effective way to reduce poverty in order to achieve zero hunger by 2030.

1.1. Fighting (Combating) Hunger around the World

Governments in various countries have been making significant and various efforts to overcome the hunger problem faced by their populations. Thailand, for example, is pursuing a model for the New Rice Farming System through irrigation water (Watanabe 2017). Meanwhile, Bangladesh has provided cash assistance since 2016 (Regmi and Paudel 2016). India seeks to be hunger-free with its policy of modernization of food procurement (Tanksale and Jha 2015). Meanwhile, in Brazil, national policies, private sector participation, and financial policies have been implemented. (Paes-Suso and Vaitsman 2014).

The following Table 1 describes the strategy of a group of countries around the world designed to overcome hunger and poverty and to achieve "zero hunger".

Table 1. Strategy to Overcome Hunger and Poverty.

#	Cluster	Countries	Strategies Description
1	Africa	Cameroon Eswatini Ghana Guinea-Bissau Lesotho Liberia Mozambique Namibia Nigeria Rwanda Tanzania The Gambia Uganda Zambia Zimbabwe	The NFSP is a food security program (2009) as an adaptation of the Rural Sector Development Strategy (SDSR) in Cameroon, has two objectives: (1) to develop agricultural production and supply in a sustainable manner and (2) to manage the risks of food insecurity. The National Food and Nutrition Policy (NFNP) of 2005 provides a guide for planning nutrition-sensitive interventions in Eswatini. It aims to inform and influence development through enabling legislation, especially regarding food fortification and supplementation, and to promote the mainstreaming of food and nutrition services and concepts into development programs in various sectors. The agriculture, health and nutrition, and social protection sectors are key in the drive towards zero hunger in Ghana. Food and nutrition security is multi-disciplinary, and all sectors have a role to play. These efforts are in line with the Terra Ranka (Fresh Start) Strategic Operational Plan, which indicates food security as one of the priorities to support investment in human capital. Other countries in Africa, namely Guinea Bissau, Lesotho, Liberia, Mozambique, Namibia, Nigeria, Rwanda, Tanzania, Gambia, Uganda, Zambia, and Zimbabwe, also have similar comprehensive strategies and policies in agriculture and food security, social assistance and social protection, food safety and standards, and nutrition security in their own country.
2	Asia–Pacific	Afghanistan Bangladesh Cambodia Indonesia Lao PDR Myanmar Nepal Philippines Sri Lanka Timor Leste	Several policies and frameworks supporting SDG#2 are the Afghanistan National Peace and Development Framework (ANPDF) for 2017–2021, Afghanistan National Health Policy 2015–2020, Afghanistan Essential (EPHS) and Basic Packages of Health Services (BPHS), and Afghanistan Food Security and Nutrition Agenda (AFSeN). Bangladesh policies are: (i) diversified, resilient, and nutrition-sensitive agriculture, (ii) inclusive, efficient, and nutrition-sensitive social protection system and Public Food Distribution System (PFDS), (iii) programs for poor and vulnerable women, a safety net for children, a school feeding (SF) program, and (iv) nutrition-specific interventions. Cambodians have also substantially improved physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences, and to optimize the utilization of this food in order to keep a healthy and productive life. Indonesia has policies, strategies, and programs in Indonesia in the field of food and nutrition security in the National Long-Term Development Plan/Rencana Pembangunan Jangka Panjang Nasional (RPJPN) 2005–2025. Myanmar, the Philippines, Nepal, Sri Lanka, and Timor Leste have a multi-sectoral approach to eliminate hunger and malnutrition, improve food security-sustainability, income generation, health, gender inequality, and all other aspects to achieve zero hunger.
3	Latin America and Caribbean	Colombia	In Colombia, Food Security and Nutrition (FSN) has ceased to be a marginal and sectoral issue and has become a state issue. The government must also ensure that the entities executing government actions review their current schemes and adjust to the broader and more overarching vision to improve their efficiency on FSN and development. The advisory of the World Food Program (WFP) is crucial to the Colombian government.

Table 1. *Cont.*

#	Cluster	Countries	Strategies Description
4	Middle East and Europe	Armenia Iraq Jordan Kyrgyzstan Lebanon State of Palestine Tajikistan Tunisia	National policy framework for food security in Armenia are included in the "Law on Survival Minimum Expenditure Basket and Minimum Survival Budget", the "Law on State Benefits", the "Law on Social Assistance", and the "Family Living Standards Enhancement Benefits" program. The Iraq government development efforts relevant to SDG#2 food nutritional security are National Nutritional Strategy 2012–2021, National Poverty Reduction Strategy 2018–2022, Social Protection Law (Law 11 of 2014), Agriculture and Food Security Policies, and National Poverty Reduction Strategy 2018–2022. Jordan 2025 represents a long-term national vision and strategy rather than a detailed government action plan. It includes more than 400 policies or procedures that should be implemented through a participatory approach between the government, business sector, and civil society. The Kyrgyzstan Republic has a range of targeted policies that reflect the food security as a whole or in its separate components. Lebanon, Syria, and Palestine are also facing a lack of economic access to food that is closely correlated with poverty, as is Tajikistan. Meanwhile, Tunisia has not experienced any situation of food shortage or severe supply difficulties leading to food insecurity in decades. In fact, Tunisia is one of the three African countries to be ranked globally in the "good performance" category in terms of food and nutrition security.

(Source: Zero Hunger Strategic Review 2022).

1.2. Indonesia's Strategy to Overcome Hunger and Poverty

The severe hunger phenomenon occurred specifically in Eastern Indonesia. The population in the eastern part of Indonesia mostly lives from farming; however, agriculture is still very traditional and so the results are not sufficient for living needs. In addition, natural disasters often reduce agriculture yields. The condition of disrupted agricultural productivity is as stated by the Papua Food Security Council et al. (2019).

The Indonesian government is working hard to tackle hunger throughout its territory. Various programs have been carried out to combat this hunger, such as direct cash assistance or village funds. The Village Funds Program has been rolled out since 2015 to increase the empowerment of rural communities in order to overcome the hunger of villagers (Simorangkir 2017; Ishartono and Rahardjo 2016). According to Saragi et al. (2021), over a five-year period there has been a drastic increase in the number of village funds that have been disbursed.

2. Methodology

2.1. Research Method

This research uses a quantitative method with a verification approach (Sekaran and Bougie 2016). This method not only provides an overview of the phenomena that occur in the object of research, namely village funds associated with starvation conditions but also provides an explanation of the configuration of hunger in Indonesia. Based on the results of data processing, the resulting implications will be interpreted and given meaning. The problems studied were also discussed by a group of researcher teams with the Financial Ministry of Indonesia. This is in line with the purpose of this research, which is to examine what the patterns of poverty and hunger data consist of at the national level in Indonesia. In addition, this study aims to establish whether there is a relationship between the implementation of Village Fund assistance and the achievement of SDG#2.

2.2. Research Stages

The steps followed in this study can be described as follows: Stage (1) conducts literature research on hunger and poverty to find the gaps in existing research; Stage (2) collects data from various sources that are linked to the 2018–2020 Village Fund allocation in achieving SDG#2 in Indonesia's rural areas; Stage (3) processes the data using the statistical (regression) method to find the pattern of whether it can achieve "zero hunger"; Stage (4) performs a thorough analysis and data processing with a quantitative descriptive approach and verification, the results of which will be used as the basis for making conclusions and developing some recommendations. These research stages are shown in Figure 1.

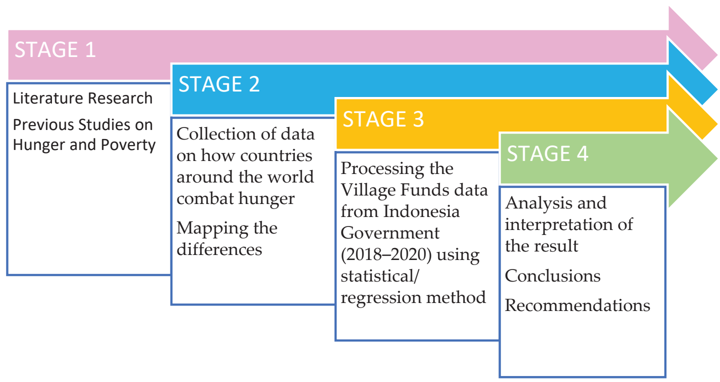


Figure 1. Research Stages.

2.3. Population and Research Sample

The population of this study comprises all data on village funds in Indonesia, which consists of 80,000 villages. Using the poverty and hunger index diagram by province (BPS 2020), it was found that Papua is the province with the highest hunger rate. Kalpika Sunu's research in 2019 also shows that village funds have a positive effect on poverty, hunger, and community welfare (Sunu et al. 2019).

2.4. Data Collection Techniques

The data required for this study are those on the state of poverty and hunger in Indonesia for the period 2000–2020 from the Central Bureau of Statistics (BPS 2021), village funds data from the Information System of the Indonesian Ministry of Finance's Fiscal Policy Agency, data and information on SDG#2, National Socio-Economic Survey data (SUSENAS), data from the National Development Planning Agency (BAPENAS), Asian Development Bank (ADB) data, Food and Agriculture Organization (FAO) data, and data from the Global Hunger Index (GHI).

2.5. Data Processing and Analysis Techniques

All data collected are subsequently classified, summarized, processed, and later analyzed and interpreted. (1) For data on hunger conditions in Indonesia 2000–2020, the processing uses Microsoft Excel software to create charts so that the directions can be analyzed, and their meaning interpreted. (2) Mapping of SDG#2 targets and indicators for village funds in all areas of Indonesia villages. Each activity code is identified in relation to the indicators and targets in SDG#2. Then, the indicators and target code of activities in each province are entered, after which the data are processed to make a summary, calculate the ratio, and make the chart.

3. Results

3.1. Indonesia's Poverty and Hunger Index (PHI)

The Poverty and Hunger Index (PHI) is a composite index that is a multidimensional indicator of poverty and hunger, which has been used to monitor the achievement of the 2015 millennium development goals (MDGs) (Nazamuddin and Jayanti 2019). Meanwhile, the criteria for measuring hunger levels are based on the basic human physiological needs for food and nutrition as carried out by BPS (2020).

By studying the measurement of hunger in Indonesia, this study can find how the Village Funds Program can contribute to fighting hunger. The aim is to find out whether it can be estimated when the Village Funds Program can eliminate and solve the problem. The following Figure 2 is presented the condition of the poor population in Indonesia that is closely related to hunger during 2000–2020 (BPS 2021).

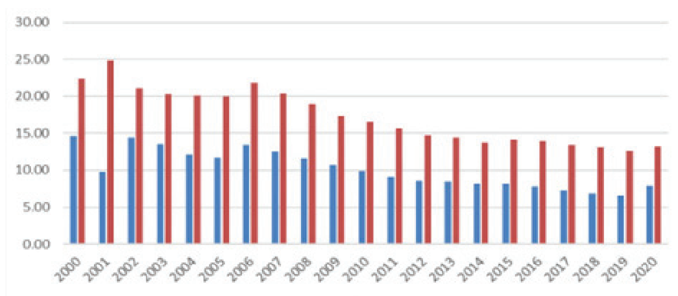


Figure 2. The percentage of Indonesia's poor population in urban (the blue one) and rural areas (the red one) from 2000 to 2020. Source: (BPS 2021).

The percentage of poor people in Indonesia both in urban and rural areas, from 2000 to 2020 decreased continuously. In 2020, it rose again compared to the previous year. This is generally caused by the pandemic that has occurred in Indonesia since December 2019.

3.2. Village Fund

A village is a place of life for traditions, customs, and local wisdom that becomes the culture and personality of the nation. Therefore, the village is one of the bulwarks of the country's resilience (Soekarnoputri 2021). As such, it is also referred to as the spearhead area for the government in serving its people.

The definition of a village fund based on Act 6/2014 states that village funds are funds allocated in the National Revenue and Expenditure Budget, specifically for villages that are transferred through the district/city's Regional Revenue and Expenditure Budget and used to finance government administration, development implementation, community development, and community empowerment (KPPN Bukit Tinggi 2021).

Village Funds were first distributed by the Government in 2015 in the amount of 47 trillion (Simorangkir 2017). The first distribution of village funds is prioritized to finance local-scale programs and activities to develop villages and empower communities. This conforms to the regulation of the Minister of Villages, Development of Underdeveloped Areas, and Transmigration No. 21/2015 on setting priorities for the use of village funds (Ishartono and Rahardjo 2016). Moreover, in 2020, the distribution of village funds had reached 99.95% of IDR 71.1 trillion from the total of IDR 71.139 trillion (Simorangkir 2017). It appears that the amount of village funds disbursed over a six-year period has increased very sharply, as observed in Saragi's study (Saragi et al. 2021), which also found a drastic increase in village funds over a five-year period.

Act 6/2014 has explained that the objectives of Village Funds are as follows: (1) improving public services in the village; (2) alleviating poverty; (3) advancing the village economy; (4) overcoming development gaps between villages; and (5) strengthening rural communities as subjects of development. Indonesia's Minister of Finance Sri Mulyani's foreword to the book entitled *Smart Village Fund* stated that results of the evaluation of the use of Village Funds (2015–2016) show that the Village Fund has succeeded in improving the quality of life of rural communities, as indicated by a decrease in the rural inequality ratio from 0.34 (2014) to 0.32 (2017), and a decrease in the percentage of rural poor people from 14.09% (2015) to 13.93% (2017) (Ministry of Finance 2017).

3.3. Sustainable Development Goals 2—Zero Hunger

Ratification of SDGs was accomplished on 25–27 September 2015 at the UN headquarters, where the SDGs had 17 goals and 169 indicators. There were 193 UN member countries that unanimously adopted a document entitled *Transforming Our World: The 2030 Agenda for Sustainable Development* (United Nations 2015b).

The goal of the global SDGs is to maintain a balance between the three dimensions of sustainable development (i.e., environmental, social, and economic). The SDGs have five main foundations, specifically (1) People, (2) Planet, (3) Welfare, (4) Peace, and (5) Partnership. Together, these five foundations are used as the basis for achieving noble goals: (1) ending poverty, (2) achieving prosperity, and (3) overcoming climate change (United Nations 2015a). Meanwhile, the goals of Indonesia's SDGs as set by the President of the Republic of Indonesia are *to develop Indonesia from the periphery, that is to say from the countryside* (Iskandar et al. 2020; Soekarnoputri 2021). Furthermore, Iskandar et al. (2020) stated that the elaboration of national SDGs into village SDGs was set with one of the objectives to achieve billages without poverty and hunger (SDG#2).

Zero hunger, as goal number 2, illustrates that the world has agreed to end poverty and hunger in any form, including Indonesia. The achievement of goal 2 is closely related to other global goals because there are partnerships in achieving these 17 goals (United Nations 2015a). With regards to goal 2 as an example, the objectives relate to: a world without poverty, good health and well-being, quality education, gender equality, clean and affordable water, and so on. Consequently, partnerships are very important in achieving these goals (Satriatna 2020).

3.4. Legal Base for SDG Implementation in Indonesia

The legal base is very important in implementing the SDGs in Indonesia due to their usefulness in evaluating the achievement of the SDGs. The legal base that oversees the implementation of Indonesia's SDGs, one of which is the Regulation of the Minister of National Development Planning/Head of the National Development Planning Agency No. 7 of 2018, is concerned with the coordination of planning, monitoring, evaluating, and reporting of the implementation of sustainable development goals. In principle, the implementation of Indonesia's SDGs is always monitored through the SDGs implementation of monitoring the report concerning SDGs (Peraturan Menteri Perencanaan Pembangunan Nasional No. 7 Tahun 2018).

4. Discussion

4.1. Configuration of Data of Indonesian Poverty and Hunger for the Period 2000–2019

The results of data collection show that the characteristics of Indonesian farmers are often shaped by their inability to live a decent life, and often the experience of suffering from hunger because they still resort to traditional farming. The wages they receive are generally low, due to their low productivity. In addition, the failure of their agriculture is caused by disasters: floods that resulted in crop failure, drought, and difficulties in accessing remote areas (Nurhadi 2021). Furthermore, as the results of the research by Olawuyi (2019) show, in the Oyo state area of Nigeria, approximately 48.25 percent of smallholder farmers are food insecure. This shows that farmers in rural Indonesia still need a lot of assistance in terms of knowledge and technology to carry out farming work more effectively and with better yields.

This is similar to the reality of the condition of farmers in Papua. The total population of Papua amounted to 3 million people in 2020 (BPS 2020). Demographically, the Papuans have always lived from farming with an undeveloped knowledge of farming, so hunger often occurs. Currently, there is still hunger in the pockets of remote areas, although the numbers are decreasing (Food Security Council of Papua et al. 2019). Bad hunger conditions occurred in Papua in 2018, in which 100 people died due to malnutrition that year alone, occurring in the Asmat Regency and the Bintang Mountains. Famine also hit 156 districts, specifically in the following 9 districts: Jayawijaya, Nabire, Yapen, Waropen, Keerom, Boven Digoel, Biak Numpor, Asmat, and the Bintang Mountains (Food Security Council of Papua et al. 2019).

Based on research in Sorong, West Papua (Kusaly 2020), currently agriculture in Papua is fairly evenly distributed and yields are increasing. According to these sources, the famine that occurred in Tambrau Regency, West Papua, was probably caused by the ineffective management of aid from the Government. The ineffectiveness of aid management was also stated by Mulawarman (2020) and Priyarsono (2021) who argued that there is still a need to increase the effectiveness of government aid management. The delay in aid management is also due to the absence of complete and valid statistics on support for food and agriculture, and that is why they are often mistargeted (Gennari 2020). There are other weaknesses, namely the shift in the function of agricultural land to non-food plantations, such as palm oil (Astuti et al. 2011) which also reduces food yields. Even so, the government is trying to overcome the problem with plans to develop food estates in the regencies of Boven Digoel, Mappi, and Merauke so that agriculture in Papua can be more advanced. (Madani Insight 2021). At the same time, these findings show a lack of knowledge in farming and managing government financial assistance to alleviate poverty and hunger.

As for the development of data on the amount of hunger in Indonesia, observing Indonesia's Susenas data every year, BPS data, Bappenas reports, and ADB reports, the development of the number of Indonesian people who experience hunger can subsequently be arranged hierarchically, as displayed in Table 2.

Table 2 shows that the amount of hunger in Indonesia, both in terms of numbers and in percent of the total population, shows a number that continues to decline during the period 2000–2020. The continuous decline indicates better conditions and is in line with the Government's target to eliminate hunger in Indonesia by 2030 as stated in SDG#2. The data pattern for Indonesia's hunger level for 2000–2020 can be seen in the Figure 3.

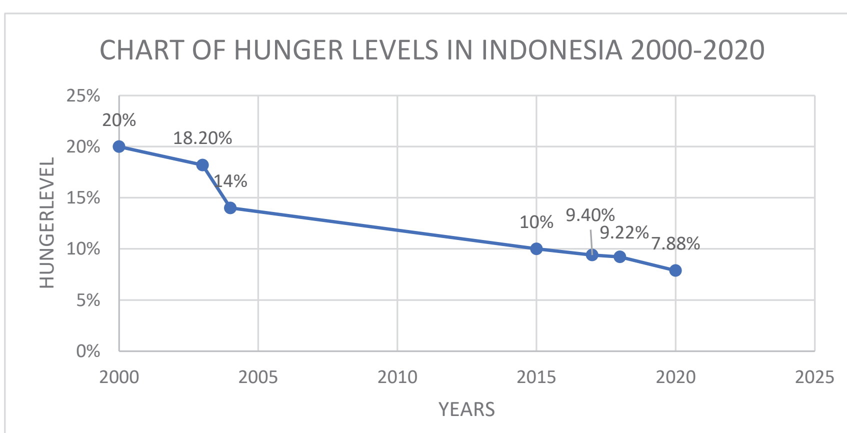


Figure 3. Decreasing patterns of hunger levels in Indonesia 2000–2020. Source: Data processing result.

Table 2. Hierarchy of development of total amount hunger among the Indonesian population 2000–2020.

Period	Description
Period of 2000	ADB says the number of hungers in Indonesia was 42 million people or 20% of the total population in Indonesia in the year 2000
Period between 2000–2005	Ministry of National Development Planning/Bappenas (through Propenas 2000–2004) mentions four policies to overcome hunger: (1) the expansion of opportunities; (2) community empowerment; (3) human resource capacity building; and (4) social protection. This policy resulted in 18.2% of the population being poor and starving in 2002, and 14.0% in 2004.
Period up to 2015	Still according to Bappenas, the Government of Indonesia's long-term 25-year target for the 1999–2015 period is to be able to reduce the amount of hungry people by 50% with the following indicators: (1) prevalence of toddlers aged under five with malnutrition, and (2) the proportion of the population below the minimum consumption level of 2100 kcal/capita/day. *
Period between 2016–2018	ADB said that in 2016–2018 there had been a reduction in the amount of people in the hunger category in Indonesia to 22 million people. Compared to 2000, there has been a decrease of 47.6%. This reduction rate is exactly what was targeted in MDG1, which was a target of a 50% reduction in the number of hungry people by 2015. **
In the year 2019–2020	Indonesian BPS data shows the number of 24.79 million poor and hungry people in Indonesia as of 2019, or 9.22% of the total population. This condition illustrates that the MDG1 target has been exceeded, with a decline of 54%.
Target for 2030	According to the SDGs goal 2, it is stated that by 2030 it is expected that the amount of people suffering from hunger in Indonesia can be eliminated. ***

Source: * Ministry of National Development Planning/Bappenas (2016, 2018), Priority use of Village Funds is for the infrastructure sector 2016. Available at: http://www.bappenas.go.id/beritadansiaranpers/sektor-infrastruktur-prioritas-penggunaan-dana-desa-2016 (Accessed: 17 June 2021). ** Asian Development Bank (ADB 2020) Report: 22 million Indonesians Suffer from Hunger, available at: http://www.news.detik.com/dw/d-4776060/lap-adb-22-juta-orang-Indonesia-menderita-kelaparan (Accessed 27 September 2020). *** United Nations (2015a). Department of Economic and Social Affairs—Sustainable Development. Available at: http://www.sdgs.un.org/goals (Accessed 13 June 2021).

Figure 3 shows a decreasing pattern of hunger levels in the 2000–2019 period, while the 2020–2030 period is the target line for the target (2030) which is point 0. The decreasing hunger level means that the amount of hunger in Indonesia is decreasing, and Indonesia's condition is improving. Assuming that hunger rates in Indonesia keep decreasing, the impact of COVID-19 can be overcome, that the Village Funds Program is still running, and the definition of hunger remains based on the human physiological needs for food and nutrition, it is possible that Indonesia will approach zero hunger in 2032.

4.2. Discussion on the 2018–2020 Village Fund Allocation over the Achievement of SDG#2

Below the results of matching 250 village fund activity codes in each village are presented, which are contained in the village fund allocation data with all targets and indicators of goal 2. This matching is carried out consistently over four provinces, so as to produce interpretations that do not vary. The following is the relationship between village fund activity codes and all SDG#2 targets and indicators, as shown in Table 3.

Table 3. Relationship between village fund activity codes and indicator codes and target SDG#2.

Village Fund Activity Codes	Village Fund Activity Description	SDG#2 Targets	SDG#2 Indicators	SDG#2 Indicator Descriptions
1305	Participatory Mapping and Analysis of Village Poverty		2.1.1	Indicator 2.1.1—prevalence of undernourishment
1408	Development Village Information System		2.1.1	Indicator 2.1.1—prevalence of undernourishment
1409	Coordination/Cooperation of Government Administration and Village Development (Between Villages/Districts/Districts, Third Parties, etc.)	2.A		target 2A—expansion of agriculture, productive capacity and plant and animal gene banks in developing countries
1412	Facilitating the Distribution of Prosperous Rice (Rastra)		2.1.1	Indicator 2.1.1—prevalence of undernourishment
2201	Implementation of Village Health Posts (PKD)/Village-Owned Polindes (Medicines; Additional Incentives for Village Midwives/Village Nurses; Provision of Family Planning Services and Contraceptives for Poor Families, etc.)		2.1.2	Indicator 2.1.2—prevalence of population with moderate or severe food insecurity, based on experience on the scale of food insecurity
2202	Posyandu Implementation (Supplementary Meals, Pregnant Women Class, Elderly Class, Posyandu Cadre Incentives)	2.2		Target 2.2. 2030, eliminating all forms of malnutrition, by 2025 reach the international target for stunted children <5 years of age
2206	Joint Care or Family Development for Toddlers (BKB)		2.2.2	Indicator 2.2.2—prevalence of malnutrition in children aged <5 years
2301	Village Road Maintenance		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2302	Maintenance of Neighborhood/Alley Roads		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2303	Maintenance of Farming Business Roads		2.3.2	Indicator 2.3.2 Average income of small-scale agricultural producers by type and customary status
2304	Maintenance of Village-Owned Bridges		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2305	Maintenance of Village Road Infrastructure (Culvert, Sewer, Box/Culvert Slab, Drainage, Other Road Infrastructure)		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2308	Maintenance of Village-Owned *Embung*		2.4.1	Indicator 2.4.1. establishment of sustainable food agriculture areas
2310	Development/Rehabilitation/Improvement/Paving of Village Roads		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2311	Construction/Rehabilitation/Improvement/Paving of Residential Neighborhood Roads/Alley		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector

Table 3. *Cont.*

Village Fund Activity Codes	Village Fund Activity Description	SDG#2 Targets	SDG#2 Indicators	SDG#2 Indicator Descriptions
2312	Development/Rehabilitation/Improvement/Paving of Agricultural Business Roads		2.3.2	Indicator 2.3.2. Average income of small-scale agricultural producers by type and customary status
2313	Construction/Rehabilitation/Improvement/Hardening of Village-Owned Bridges		2.A.1	Indicator 2.A.1.—government expenditure index for agriculture
2314	Development/Rehabilitation/Improvement of Village Road Infrastructure (Culvert, Sewer, Box/Culvert Slab, Drainage, Other Road Infrastructure)		2.A.1	Indicator 2.A.1.—government expenditure index for agriculture
2319	Development/Rehabilitation/Improvement of Village *Embung*		2.4.1	Indicator 2.4.1. establishment of sustainable food agriculture areas
2323	Providing stimulants for the development of padukuhan infrastructure		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2324	Village Transportation Management		2.3.1	Indicator 2.3.1—Agricultural value added divided by the number of workers in the agricultural sector (IDR)
2402	Maintenance of Village-Owned Infiltration Wells		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2403	Maintenance of clean water sources belonging to the village (springs/reservoirs for collecting rainwater/drilling wells, etc.)		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2404	Maintenance of Clean Water Connections to Households (piping, etc.)		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2405	Maintenance of Residential Sanitation (Culvert, Sewer, Trench, etc., outside road infrastructure)		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2408	Maintenance of Wastewater Disposal Systems (Drainage, Household Wastewater)		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2410	Construction/Rehabilitation/Improvement of Infiltration Wells		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2411	Development/Rehabilitation/Improvement of Village Owned Clean Water Sources (Springs/Tandon for Rainwater Storage/Drilling Well, etc.)		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2412	Construction/Rehabilitation/Improvement of Clean Water Connections to Households (piping, etc.)		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2413	Construction/Rehabilitation/Improvement of Settlement Sanitation (Culvert, Sewer, Trench, etc., outside road infrastructure)		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector

Table 3. *Cont.*

Village Fund Activity Codes	Village Fund Activity Description	SDG#2 Targets	SDG#2 Indicators	SDG#2 Indicator Descriptions
2416	Construction/Rehabilitation/ Improvement of Wastewater Disposal Systems (Drainage, Household Wastewater)		2.A.2	Indicator 2.A.2. Total development assistance and other assistance in the agricultural sector
2419	Land Clearance		2.4.1	Indicator 2.4.1. establishment of sustainable food agriculture areas
2501	Village Owned Forest Management		2.4.1	Indicator 2.4.1. establishment of sustainable food agriculture areas
2502	Village Environmental Management		2.4.1	Indicator 2.4.1. establishment of sustainable food agriculture areas
2503	Training/Outreach/Counseling/ Awareness about Environment and Forestry		2.4.1	Indicator 2.4.1. establishment of sustainable food agriculture areas
3108	Providing Social Benefits for the Poor		2.1.2	Indicator 2.1.2—prevalence of population with moderate or severe food insecurity, based on experience on the scale of food insecurity
4101	Maintenance of Karamba/Inland Fishery Ponds belonging to the Village		2.2.2.(C)	Indicator 2.2.2. (C). The quality of food consumption is in accordance with the expected food pattern score; and the level of fish consumption
4102	Maintenance of Village-Owned River/Small Fishing Ports		2.2.2.(C)	Indicator 2.2.2. (C). The quality of food consumption is in accordance with the expected food pattern score; and the level of fish consumption
4103	Maintenance of Village-Owned River/Small Fishing Ports		2.2.2.(C)	Indicator 2.2.2. (C). The quality of food consumption is in accordance with the expected food pattern score; and the level of fish consumption
4104	Development/Rehabilitation/ Improvement of Village-Owned River/Small Fishing Ports		2.2.2.(C)	Indicator 2.2.2. (C). The quality of food consumption is in accordance with the expected food pattern score; and the level of fish consumption
4105	Fishery Assistance (Seeds/Feed/etc.)		2.2.2.(C)	Indicator 2.2.2. (C). The quality of food consumption is in accordance with the expected food pattern score; and the level of fish consumption
4106	Training/Technical Guidance/Introduction to Appropriate Technology for Inland Fisheries/Fishermen	2.A		target 2A—expansion of agriculture, productive capacity and plant and animal gene banks in developing countries
4201	Increased Production of Food Crops (Production Tools and agricultural processing, rice/corn milling, etc.)		2.5.1	Indicator 2.5.1—the number of varieties of poultry and animals for released food
4202	Increase in Animal Husbandry Production (Production Tools and livestock processing, stables, etc.)		2.5.1	Indicator 2.5.1–the number of varieties of poultry and animals for released food

Table 3. *Cont.*

Village Fund Activity Codes	Village Fund Activity Description	SDG#2 Targets	SDG#2 Indicators	SDG#2 Indicator Descriptions
4203	Strengthening Village Level Food Security (Lumbung Desa, etc.)		2.4.1	Indicator 2.4.1.—establishment of sustainable food agriculture areas
4204	Maintenance of Tertiary/Simple Irrigation Channels		2.A.1	Indicator 2.A.1.–government expenditure index for agriculture
4205	Training/Bimtek/Introduction to Appropriate Technology for Agriculture/Animal Husbandry		2.5.1	Indicator 2.5.1- the number of varieties of poultry and animals for released food
4207	Irrigation Channel Construction/Maintenance Activities		2.A.1	Indicator 2.A.1.—government expenditure index for agriculture
4208	Procurement of plant and livestock seeds		2.5.1	Indicator 2.5.1—the number of improved plant and animal varieties for released food
4209	River Normalization/river restoration activities		2.A.1	Indicator 2.A.1.—government expenditure index for agriculture
4503	Procurement of Appropriate Technology for Non-Agricultural Rural Economic Development	2.3		Target 2.3.—double agricultural productivity and income of small-scale food producers for women, indigenous people, through safe and equal access to land, knowledge, and other non-agriculture by 2030.
4603	Village BUM Equity Participation	2.3		Target 2.3.—double agricultural productivity and income of small-scale food producers for women, indigenous people, through safe and equal access to land, knowledge, and other non-agriculture by 2030.
4701	Maintenance of Village Markets/Kiosks owned by the Village	2.3		Target 2.3.—double agricultural productivity and income of small-scale food producers for women, indigenous people, through safe and equal access to land, knowledge, and other non-agriculture by 2030.
4702	Development/Rehabilitation/ Improvement of Village Markets/Kiosks belonging to the Village	2.3		Target 2.3.—double agricultural productivity and income of small-scale food producers for women, indigenous people, through safe and equal access to land, knowledge and other non-agriculture by 2030.
4703	Village level small industry development	2.3		Target 2.3.—double agricultural productivity and income of small-scale food producers for women, indigenous people, through safe and equal access to land, knowledge and other non-agriculture by 2030.
4704	Formation/Facilitation/Training/ Assistance for productive economy business groups (craftsmen, traders, home industries, etc.)	2.3		Target 2.3.—double agricultural productivity and income of small-scale food producers for women, indigenous people, through safe and equal access to land, knowledge and other non-agriculture by 2030.

Table 3. *Cont.*

Village Fund Activity Codes	Village Fund Activity Description	SDG#2 Targets	SDG#2 Indicators	SDG#2 Indicator Descriptions
4705	Procurement, construction, utilization and maintenance of facilities and infrastructure for services and small industries that are focused on the one village one superior product policy	2.A		Target 2.4.—2030, ensure sustainable food production systems and resilient agriculture that increase productivity, progressively improve soil and land quality
5100	Disaster management	2.4		Target 2.4.—2030, ensure sustainable food production systems and resilient agriculture that increase productivity, progressively improve soil and land quality

Source: Data processing result.

Next, the mapping of village funds was carried out based on the activity code against SDG#2 targets and indicators in all Indonesian villages. The results of mapping village funds against SDG#2 and their configuration are analyzed in the description below.

4.3. Results of Mapping Village Funds against All SDG#2 Targets and Indicators

Data on village funds for all Indonesian villages are presented in the mapping of each target and indicator. The results of the mapping in the form of Village Fund allocation configurations against goal 2 can be seen in Figure 4.

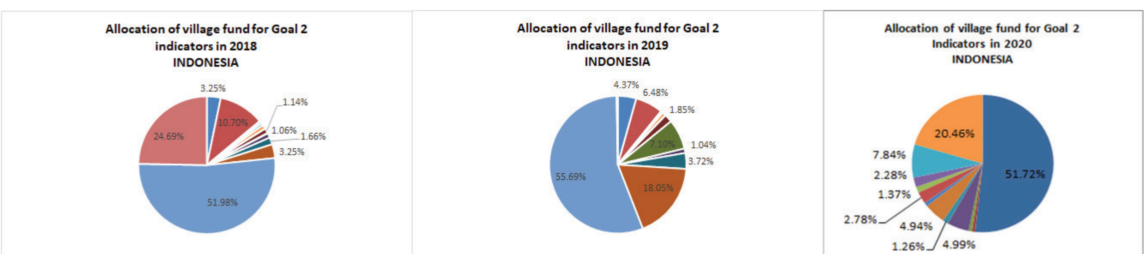


Figure 4. Configuration of Indonesia Village Fund allocation for SDG#2 in 20182020.

Figure 4 shows that in 2018–2020, Indonesia allocated referred Village Funds to fight hunger which were prioritized based on on SDG#2 indicators: indicator 2.1 namely prioritizes eliminating hunger and providing nutritious food; indicator 2.A.2 namely prioritizes the agriculture sector and regional development; indicator 2.A.1 namely prioritizes agriculture expenditure; indicator 2.3 namely prioritizes increasing agriculture productivity; and indicator 2.3.2 namely prioritizes small scale agriculture income.

Observing the results of the mapping of the allocation of Village Funds against SDG#2 targets and indicators at Figure 4, and taking into account Figure 3, which is the pattern of reducing hunger levels in Indonesia, it can be concluded that the allocation of Village Funds can be intensified by aiming at indicators (2.1), (2.A.2), (2.A.1), (2.3), and (2.3.2).

4.4. The Impact of the 2018–2020 Village Fund on SDG#2 in All Indonesia Villages

To test the impact of Village Fund allocations on SDG#2, data processing with the use of regression is subsequently carried out using SPSS V-6. The independent variable is the Indonesia Village Fund Data with 251 activity codes per village. The dependent variable is the allocation of Village Funds to targets and indicators contained in SDG#2.

The regression result of the 2018–2020 Village Fund Allocation toward SDG#2 per province is shown in Table 4.

Table 4. The Result of Village Fund Regression towards SDG#2 in Indonesia.

Regression Statistics:							
Multiple R	0.0						
R Square	0.0						
Adjusted R Square	0.0						
Standard Error	140,654,979.4						
Observations	870,670.0						
	Coefficient	Standard Error	*tStat*	*p-value*	Lower 95%	Upper 95%	Lower 95%
Intercept	103,238,244.2	174,639.4	591.2	-	102,895,956.8	103,580,531.6	102,895,956.8
46,100,000	0.0	0.0	7.0	0.0	0.0	0.0	0.0

Source: Data processing result.

Table 4 shows the effect of the Village Funds 2020 on SDG#2 targets, and indicators are significant with a p-value of 0.00 at an alpha of 5%, where Y is the Village Fund allocation for SDG#2 and X is the total of the Village Fund. This significant effect shows that each increase in the allocation of Village Funds will increase the funds to fight hunger. The meaning of this statistical result is that the Village Fund is proven to be allocated effectively to fight hunger when it is aimed at indicators (2.1.), (2.A.2), and (2.A.1).

4.5. Relationship between Village Fund Allocation to Achieve SDG#2 and Decreasing Hunger Rates

The success of implementing SDGs in rural areas is carried out under supervision and control by the Ministry of Villages, Development of underdeveloped areas and Transmigration, Governors, and Village Heads. An example of this control, for example, can be found in the village of Walari which applies an inclusive village approach with the principle of "no one left behind" (Iskandar et al. 2020). An inclusive village is a village for all residents, meaning that development involves all villagers, for the purpose of increasing their empowerment, and whose implementation is continuously subjected to careful monitoring.

The level of hunger in Indonesia shows a pattern that continued to decline from the period of 2000 to 2020. This decline indicates a better condition, due to the decreasing level of hunger, and this is in line with the Government's target to eliminate hunger in Indonesia by 2030.

The reality of the pattern of decreasing hunger levels is apparently influenced by the allocation of village funds as a government policy to tackle poverty and hunger, and to increase village community empowerment. By matching 250 village fund activity codes in each village, with the targets and indicators in goal 2, and mapping the allocation of village funds with SDG #2, it has been found that the four provinces prioritize the allocation of funds to increase agricultural productivity in their area. There is an awareness that the higher the productivity of agricultural products, the more the level of hunger can be reduced, such as the results of statistical regressions which show that the 2018–2020 Village Fund allocation for SDG#2 in Indonesia has had a significant impact.

Research Implication

This research has several practical implications, especially for the development of local government policies in tackling hunger in villages. The implications of this policy can be seen in Figure 5.

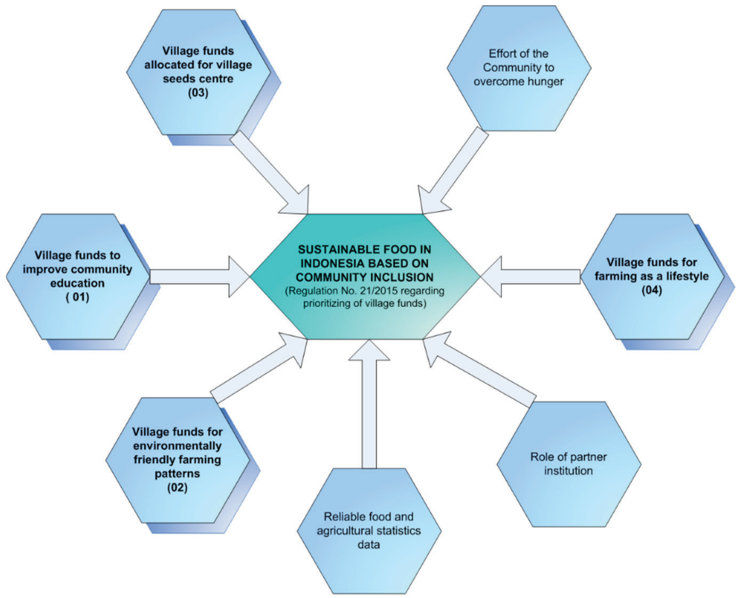
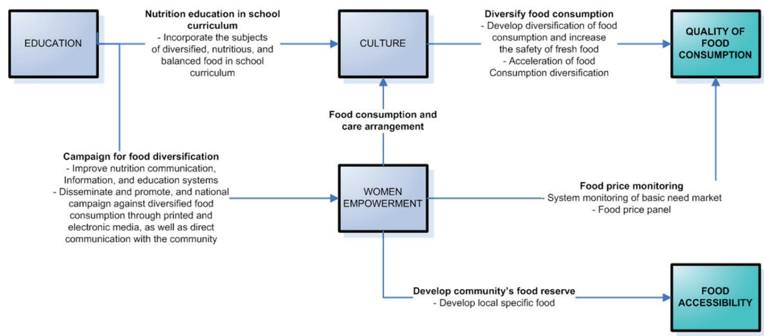


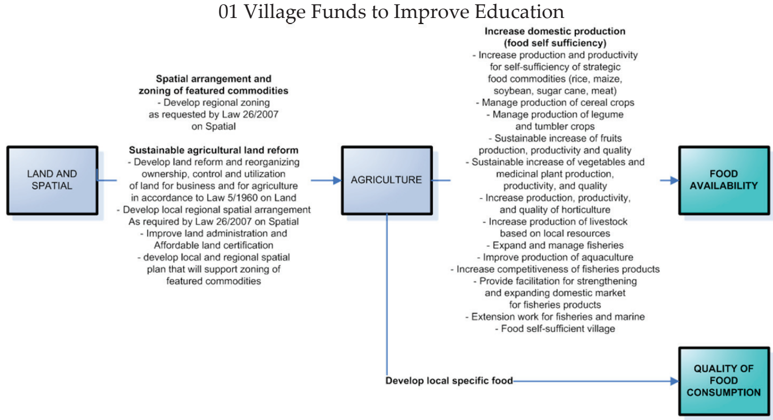
Figure 5. Village fund-based sustainable food inclusion policy. Source: data processing result.

Figure 5 shows that, based on the results of this study, there is a large delay in the reduction of hunger, especially for Papua. This study recommends that Village Funds in Papua must support sustainable food inclusion policies. Village funds must be allocated to strengthen this policy through the allocation of various elements. (1) Village seed centers where every village, for instance in Papua, strives to have a seed center for both wheat/rice and cow seeds so that each harvest in each village can contribute sufficiently to the needs of the entire population (Iskandar et al. 2020). (2) An increase in public education can ensure human resources which are more educated and knowledgeable, so that management in the agricultural sector is more productive so that it can overcome food insecurity (Nakao 2019; Iskandar et al. 2020). (3) Non-governmental organizations have contributed a great deal to overcoming hunger (Papua Food Security Council et al. 2019). The flow of economic assistance from the community through social institutions can be maintained when considering that the Indonesian people have a closely-knit culture of mutual cooperation. (4) The role of formal institutions such as the Ministry of Social Affairs, the Ministry of Health, and the central government has a very large impact in dealing with hunger, especially in abandoned villages, such as Papua. (5) Environmentally friendly farming patterns are also an important reference so that the agricultural sector can be sustainable (D. Mulyadi 2015). (6) The role of partner institutions has been proven to be able to tackle hunger, such as in Mimika Province in Papua, which collaborated with community institutions which aimed to reduce the number of stunted children (M. Mulyadi 2010). (7) Planting as a lifestyle, as carried out by the Minister of Forestry who planted 1 billion Trembesi trees together with students from various universities, with the aim of making the younger generation like agriculture (Indonesia Islamic University (IIU) 2020).

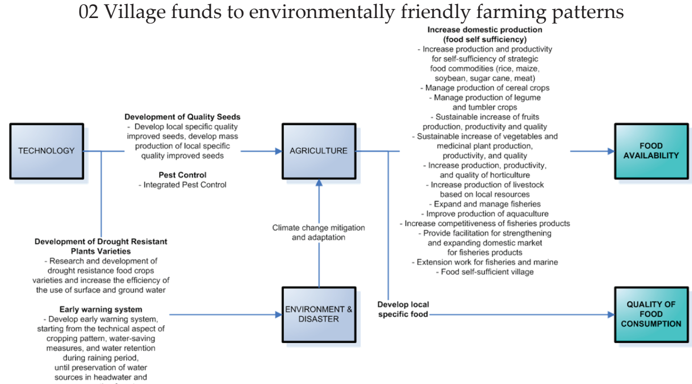
To explain more meaningful food security or sustainability in all areas of Indonesian villages, the following Figure 6 describes the detailed Villages Fund Program in Indonesia.



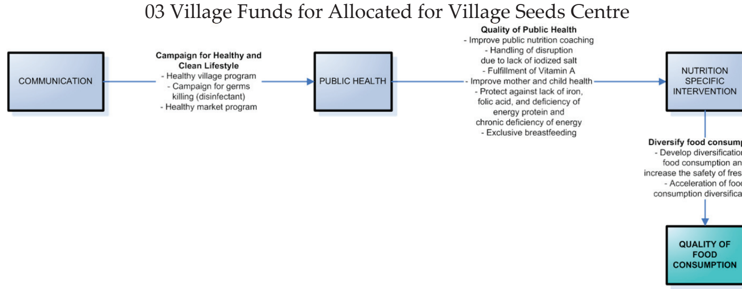
01 Village Funds to Improve Education



02 Village funds to environmentally friendly farming patterns



03 Village Funds for Allocated for Village Seeds Centre



04 Village Funds for Healthy and Clean Lifestyle (e.g., Farming as a Lifestyle)

Figure 6. Detailed village fund program for sustainable food inclusion. Source: data processing result.

5. Conclusions

The data configuration of poverty and hunger in Indonesia during the 2000–2020 period shows a decreasing pattern. This decrease means that the conditions were better because the amount of hunger was decreasing. The results of the mapping of village funds on the implementation of the SDG#2 target and indicators show the generally allocated village funds, especially for indicators (2.1), (2.A.2), (2.A.1), (2.3), and (2.3.2). of the total for SDG#2. The meaning of the decreasing level of hunger in Indonesia and the intensive allocation of village funds in indicators (2.1.), (2.A.2), (2.A.1), (2.3), and (2.3.2) show that village funds contribute to overcoming hunger. In addition to having a statistically significant impact (p-value 0.00) between the allocation of village funds and SDG##2, the village funds are proven to be effective in fighting hunger if they are allocated to indicators (2.1.), (2.A.2), (2.A.1), (2.3), and (2.3.2).

Therefore, this study has tested and proven that the allocation of Village Funds from the government for all of rural Indonesia has proven effective in reducing poverty and hunger. However, the central and local governments need to focus more on addressing poverty and hunger. In particular, what is really needed is help in the form of assistance, knowledge transfer, and good farming practices that produce quality agricultural products since conditions there require more knowledge. In addition, more attention is needed to assist village officials who will distribute these village funds to farmers, so that the allocation of village funds can be better managed according to their needs and allocations in each of the rural areas studied specifically, and throughout rural areas in Indonesia in general. This is important to accelerate the achievement of "zero hunger" as is the second SDG point by 2032.

The recommendation to other countries to use the Village Fund's policy government and its continuation, and define the hunger based on human physiological needs for food and nutrition can solve the impact of COVID-19. Consequently, other countries can benchmark the Indonesian Village Fund Program by intensifying its allocation to indicators (2.1), (2.A.2), (2.A.1), (2.3), and (2.3.2).

Village Funds need to be managed comprehensively by considering various other aspects or dimensions, namely education, friendly farming (agriculture), a village seeds center, and a healthy and clean lifestyle. This study has data processing, that should be carried out directly concerning the effect of Village Fund allocation on achieving SDG#2 in reducing hunger, using panel data statistical software which uses a longer period, as its main limitation. Therefore, further researchers are suggested to elaborate on this matter further, and confirm the results of the FGD by more complex analysis with statistical tools.

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Impacts of Overall Financial Development, Access and Depth on Income Inequality

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Abstract: There is dense literature on the relationship between financial sector development (FSD) and income inequality. However, most of these studies employ a depth measure of FSD. This study argues that different components of FSD have a heterogenous impact on income inequality. This study first empirically tests the overall impact of FSD on income inequality. Thereafter, I investigate both the linear and nonlinear impact of financial sector development dimensions (depth and access) on income inequality. The study's novelty lies in using financial access data such as ATM per adult and financial access index and comparing their impact on income inequality versus the impact of financial sector depth (growth in domestic credit) on inequality. Adding to this, fewer studies have investigated the overall impact of FSD. To solve the endogenous problem, the study uses the system General Method of Moments (GMM) on the panel data of 120 countries, from 2004 to 2019. The findings of the study are threefold. Firstly, the study finds that the overall FSD index, individual financial institutions, and market development index all narrow income inequality. Secondly, this study finds that different dimensions of FSD have heterogenous impacts on income inequality, where increased access to financial services reduces income inequality in both linear and nonlinear models. While financial sector depth narrows income inequality in the linear model, the nonlinear model reveals that the Too Much Finance hypothesis holds, as the results confirm a U-shaped relation with income inequality. These results are important for policy decisions concerning financial reforms and income distribution. These results imply that financial sector reforms can be shaped to reduce income inequality by increasing access to credit and through credit policy provisions.

Keywords: income inequality; financial sector development; GMM

JEL Classification: G20; G21

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1. Introduction

Increasing income inequality has been at the forefront of public debate. For instance, alleviating income inequality is goal number ten of the Sustainable Development Goals (SDGs) for the 2030 Agenda of the United Nations. Subsequently, policymakers worldwide are concerned about rising income inequality's economic and social consequences. This paper aims to show that financial sector development (FSD) can be one of the tools for reducing income inequality. FSD has been rising, with advanced countries leading and developing countries catching up. Financial institutions have grown, in volumes of trade and geographical presence. As the financial sector grows, so does the complexity and the number of financial instruments. Borderless banks seen in the present era continue to prosper. It is natural to study their effects on income distribution as FSD affects the economic opportunities of individuals. According to theoretical and empirical literature, financial institutions and markets shape the gap between rich and poor (1) by determining who receives a loan to start a business or finance education (access to human capital financing), (2) through capital rent/profit accumulation, (3) by promoting the participation of poor households in economic activity and helping them to reduce economic vulnerabilities, and (4) through the composition of labor demand.

In addition, access to the financial sector represents inequality of opportunity. For example, rural area residents, women and poor households are the most unbanked households. Consequently, strengthening access to financial services, especially for the poor, is one of the main tools for achieving goal 8 (Economic growth and descent work) of the UN SDGs. Increased access to financial services was the focus of the World Bank Groups Universal Financial Access 2020 initiative, as financial inclusion can boost economic growth and reduce income inequality by mobilizing savings and fostering the formalization of labor and firms.

As such, the main goal of this paper is to investigate the overall impact and different components of FSD on income inequality. Thus, this paper attempts to contribute to the following questions: (i) What is the overall impact of FSD on income inequality? (ii) How does financial sector depth (growth in domestic credit) affect income inequality? (iii) How does increased access to financial services affect income inequality? Empirical results from these questions can be informative for financial sector reform and fair shared prosperity. It is pivotal to ask what the gains from FSD are and who is benefiting the most from these developments. This concern is reasonable as there are far greater negative consequences for macro-stabilities in cases where financial system assets are concentrated. Subsequently, this study hypothesizes that, on average, FSD reduces income inequality, while different dimensions of FSD can produce different impacts on income inequality.

Thus, the study contributes to the available literature by distinguishing the contribution of overall FSD, financial depth and access to income inequality. This is because there are very few studies investigating the impact of FSD. Adding to this, according to my knowledge, no study has empirically tested the development impact of financial institutions and market indexes on income inequality. The study is carried out on yearly data from 2004 to 2019, and the system GMM methodology is employed. The applied robust methodology also serves as a contribution to the mixed literature. Robust system GMM is advantageous over difference GMM as it offers lower variance and bias. Robust system GMM also offers efficient and robust heteroscedasticity and autocorrelation results. Subsequently, the study finds that overall FSD reduces income inequality, chiefly through access to financial institutions rather than through financial markets. Again, the study finds that financial institution depth tends to have a significant impact on income inequality, while financial market depth has no significant impact.

The rest of the paper is organized as follows: Section 2 covers the theoretical framework and review of the literature, including the stylized facts of FSD and income inequality. Section 3 discusses the data collection and methodology. Section 4 presents the results. Sections 5 and 6 provide a discussion on the implications of the findings, and the conclusions, respectively.

2. Theoretical Framework and Review of Literature

2.1. Theoretical Framework

For the theoretical framework, I begin the analysis by building on the outstanding work of Demirguc-Kunt and Levine (2009), specifically focusing on their contribution to finance in theories of persistent inequality. By decomposing total income into income from labor and physical capital (see Equation (1) below), we can analyze how FSD can affect inequality (Demirguc-Kunt and Levine 2009).

$$\text{Total inequality} = \text{Labor income inequalities} + \text{physical capita inequality} \tag{1}$$

Equation (1) was proposed by Demirguc-Kunt and Levine (2009) and Piketty (2014). The argument is as follows: wage income accounts for around 70 per cent of income inequality and is highly correlated with human capital development (Demirguc-Kunt and Levine 2009; Francese and Mulas-Granados 2015). Meanwhile, income from physical capital magnifies inequality through rent seeking (Demirguc-Kunt and Levine 2009; Piketty 2014; Mihalyi and Szelenyi 2019). The argument is that inequalities from physical capital are larger than from labor income. For example, Piketty (2014) focused on the rent earned by the top 1% income group and postulated that inheritance wealth, capitalist environment and profit growth exacerbate inequality. In contrast, Mihalyi and Szelenyi (2019) emphasize the rent accruing in the top 20% income group and distinguish different types of rent in the capital system. Different from the work of Piketty (2014), Mihalyi and Szelenyi (2019) place a distinction between profits and rent. From this distinction, Mihalyi and Szelenyi (2019) find that higher profits and wage income positively affect economic growth, while rent growth lowers it. Subsequently, the theories of persistent inequality in financial sector development are discussed concerning wage and physical capital income inequalities. Demirguc-Kunt and Levine (2009) argue that financial institutions' imperfection (e.g., information and contract costs that hinder investment screening and monitoring of financial contracts) outlines the dynamics of inequality, such as wealth and education accumulation.

The difference between skilled versus unskilled labor income is the main direct source for rising income inequality, as wage income typically reflects an individual's education level. In a perfect credit market, parents' education and wealth are unimportant as a household can borrow to finance education (Demirguc-Kunt and Levine 2009). Meanwhile, in the presence of imperfect credit markets on education investment, inequality of opportunity explains the distribution of skills. Parents' education and wealth constrain next generations' access to credit for human capital. Thus, borrowing constraints negatively impact human capital accumulation in the absence of public education. This creates a gap in human capital accumulation, increasing wage inequality (Demirguc-Kunt and Levine 2009). At the same time, increased access to financial services for education investment to poor households who were previously excluded reduces income inequality through human capital accumulation (Galor and Zeira 1993; Demirguc-Kunt and Levine 2009).

On the other hand, the developed financial sector can curb shocks to poor households' income by allowing them to continue investing in human capital instead of opting for low-skill employment when hit by income shocks. Thus, the developed financial sector helps households to smooth income shocks (Demirguc-Kunt and Levine 2009). FSD lacking increased access to financial services can increase inequality as the sector only caters to selected individuals with financial investment (Greenwood and Jovanovic 1990). Increasing financial institution size and innovation can boost economic growth, pushing up the labor market demand, signifying that the effects of FSD on labor market demand and income inequality are a double-edged sword, in the sense that FSD increases the demand for only skilled labor and magnifies income inequality (Demirguc-Kunt and Levine 2009; Piketty 2014). FSD also increases wage inequality between sectors. For example, the compensation of portfolio managers increases with the complexity of the financial instrument, and in addition, their bonus compensation is usually based on profits. For instance, in Europe, employees of the financial sector are concentrated in the upper end of the income distribution. Denk (2015) emphasizes how financial sector employees receive rent through wage premia and over-skilling. According to Denk (2015), financial sector employees receive exponential earnings/bonuses (wage premia), more so than employees in other sectors, who make roughly the same profit for their respective firms. In other words, using yearly data of OECD countries, Denk (2015) finds that finance wages are around 50% higher than in other sectors. Thus, in essence, these are not remunerations necessary based on productivity levels but rather rents accruing among financial sector employees—hence, Denk (2015) refers to them as wage premia. As such, wage premia from financial sector employees explain the undesirable relationship between FSD and income inequality. Adding to this, there is still a large gender income gap in the financial sector. For example, in Europe, on average, male employees in the sector earn 22% more than females (Denk 2015). Moreover, in terms of financial inclusion and access, the most unbanked groups are women and uneducated households.

Capital income contains real estate and financial capital; as such, owners of capital benefit greatly from FSD. Generally, physical capital such as bond certificates/share ownership and property embodies more wealth inequality; however, inequality of wealth has a direct transmission to income inequality. For example, wealthy households tend to live in more advanced and developed districts, impacting the quality of schools and other forms of economic opportunities. Education may be centralized or free, but education institutions always allow private funding, which will be coming from the wealthy residents—through such funding, these schools obtain better and more advanced technology than public schools. In the long run, income inequality will also grow due to the gap in skills and human capital development. In addition, middle-income households tend to invest more in property than in financial assets. In contrast, rich households have paid up properties and gained more rent from financial assets such as stock and bonds in the financial markets. This distribution of physical capital suggests that different income groups benefit differently from financial rent.

2.2. Review of Literature

2.2.1. Financial Sector Development and Economic Growth

The link between FSD, economic growth and income inequality is complex as these variables exhibit a bidirectional relationship. For instance, the lending decisions of financial institutions have impacts on education investment, business start-ups and the growth of the small business, which in turn influence real output and inequality. There is large and growing evidence that suggests that FSD plays a substantial role in economic development (Goldsmith 1969; Levine 2004; Gründler and Weitzel 2013; Seven and Coskun 2016; Paun et al. 2019; Ongena and Mendez-Heras 2020). There are positive gains on economic growth when there is growth in the (a) numbers of financial sector branches, (b) stock traded and net foreign assets, (c) financial systems and inclusion (represented by financial access and market sophistication), (d) quality of financial systems such as markets, institutions and financial instruments (Paun et al. 2019; Gural and Lomachynska 2017; Bittencourt 2011; Setiawan 2015; Kapingura 2017; Worku 2014). Other studies also suggest a bidirectional relationship between FSD and growth (Sunde 2012; Oluitan 2012), while some additional studies suggest that the impact of FSD on economic growth depends on the growing private credit ratio on real GDP growth (Ductor and Grechyna 2015). Thus, in developed and developing countries, FSD harms economic growth when there is a speedy growth in private credit without growth in real output. Their findings suggest an optimal level of finance development determined by the economy's characteristics. Lastly, FSD (improved contracts and market) enlarges economic opportunities, thus accelerating growth and reducing inequality.

2.2.2. Financial Sector Development and Income Inequality

The previous subsections focused on the impact of FSD on economic growth as theories of growth overlap those of inequality. Next, I show that there is no consensus in the empirical literature of FSD and income inequality. The bulk of the literature on FSD and income inequality is large. However, as Demirguc-Kunt and Levine (2009) highlighted, the literature lacks a consensus, and to close the gap, they state that further empirical evidence is needed. The grounds for further research lie in finding precise measures or rules of thumb of the impact of FSD on inequality and growth. This is because the theory mirrors a skeleton of inequality trends due to imperfect credit markets. Additionally, before 2004, there were no global cross-country data on financial access measures. This implies that before the year 2004, there were limited global studies on how financial access affects inequality. Simultaneously, the literature on the impacts of financial depth on economic growth and inequality grew.

The literature on FSD and income inequality is divided into four strands: (1) financial narrowing hypothesis, (2) financial widening hypothesis, (3) inverted U-shaped hypothesis of Greenwood and Jovanovic (1990) and (4) the U-shaped hypothesis. The financial narrowing hypothesis suggests that income inequality declines in the presence of an efficient financial market (Banerjee and Newman 1993; Galor and Zeira 1993). These theories emphasize the exacerbating effects of imperfect credit markets on initial wealth distribution and subsequently long-run impacts on income inequality. The widening financial hypothesis was enriched by the book of (Rajan and Zingales 2003) as the title of Chapter 1 of the book was 'Does finance benefit only the rich?' Rajan and Zingales (2003) posit that FSD increases income inequality as its benefits spread to rich households, who had initial access to the credit market. Those who lack collateral view requirements for borrowing as follows: 'you can borrow provided you do not need', and connections to credit imply 'you can borrow provided I know and trust you/your business' (Rajan and Zingales 2003). They argue for good institutions characterized by better legal enforcement, higher levels of general trust, esteem property rights and the developed market to ensure that finance is for all. Table 1 below presents a summary of the literature on narrowing hypotheses and widening hypotheses. Table 1 highlights the mixed measures of FSD and methods applied in the literature. Thereafter, the nonlinear literature is summarized.

Empirical studies confirming the narrowing and widening hypotheses either failed to confirm the nonlinear relationship between finance and inequality or were estimated without including the nonlinear term. Other strands of literature emerge from testing the nonlinear relationship between inequality and FSD. The nonlinear models produce development cycles that resemble the Kuznets (1955) hypothesis or a simple U-shaped relationship on the FSD–inequality nexus. Concretively, the nonlinear hypothesis shows how different stages of FSD affect inequality.

Greenwood and Jovanovic's (1990) model suggests an inverted U-shaped relationship between FSD and inequality. Inequality increases in the primary stages of FSD with the savings rate, supporting the widening hypothesis (Rajan and Zingales 2003). Greenwood and Jovanovic (1990) claim an equalizing effect/a threshold where FSD starts to reduce inequality, as in the narrowing hypothesis of (Banerjee and Newman 1993; Galor and Zeira 1993). This is because, in the maturity stages, the financial sector is developed and efficient; thus, the income distribution of agents is soothed, the savings rate falls, and economic growth converges to higher levels of growth. The inverted U-shaped hypothesis has been confirmed by a growing number of empirical studies (Batuo et al. 2010; Kim and Lin 2011; Shahbaz and Islam 2011; Shahbaz et al. 2015; Emrah and Nısfet 2019; Nguyen et al. 2019; Bittencourt et al. 2019; Younsi and Bechtini 2020).

For instance, Shahbaz et al. (2015) employed the Gini index, real domestic credit to private sector per capita and KOF globalization index as the main variables. Shahbaz et al. (2015) confirmed the inverted U-shaped relationship between FSD and inequality in Iran, using the ARDL bound test for the long-run investigation and the VECM for the causal relationship. The Greenwood–Jovanovich (GJ) hypothesis was also confirmed in 21 emerging market countries by Nguyen et al. (2019), who employed data from 1961 to 2017 and the fixed effect and GMM methodology. Nguyen et al. (2019) and Younsi and Bechtini (2020) both used various measures of FSD, including stock market capitalization as a percentage of GDP, domestic credit to the private sector by banks-to-GDP ratio, domestic credit provided by financial sector-to-GDP ratio and the IMF-proposed financial development index (FDI). Younsi and Bechtini (2020) confirmed the GJ hypothesis in BRICS countries, using data from 1995 to 2015 and employing the POL and GMM estimator. Emrah and Nısfet (2019) confirmed the GJ hypothesis in Turkey, using the Theli index to measure inequality and deposit money bank assets to GDP, financial system deposit to GDP, broad money supply, domestic credit to the private sector and FDI to measure FSD. Bittencourt et al. (2019) decomposed income inequality data from 1976 to 2011 of 50 states from the USA into two groups, the above-average and below-average inequality. They confirmed the GJ hypothesis for the below-average inequality group.

Table 1. The narrowing and widening hypotheses of FSD on income inequality.

	Study	Main Variables in the Model of FSD on Inequality	Geographical Area	Findings
Financial narrowing hypothesis	Beck et al. (2004)	Credit to the private sector by financial intermediaries and poorest quintile income, Gini index. Legal origins, natural resource endowment, religious composition and ethnic fractionalization as instruments for endogeneity.	52 developing and developed countries (1960 to 1999) [1].	Using instrumental variable regression, they found that FSD reduces inequality as it grows faster than average GDP per capita.
	Clarke et al. (2006)	The Gini coefficient and credit to the private sector by financial intermediaries over GDP (private credit). To control Kuznets effects, they include initial real GDP per capita and squared term. Other control variables include: inflation rate, government consumption, ethnolinguistic fractionalization and a measure of the protection of property rights. To control for endogeneity, the legal origins indicator is included.	Using data for 83 developed and developing countries between 1960 and 1995.	The study found that when there is greater/deepened FSD, inequality is less in the long run. The results confirming an inverted U-shaped curve of Greenwood and Jovanovic (1990) were not robust.
	Kapingura (2017)	Gini index. FSD: domestic credit to bank sector as % of GDP, and ATM per 100,000 adults.	South Africa (1990–2012 yearly).	An increase in financial access (ATM) reduces inequality more than increasing financial depth.
	Burgess and Pande (2005) [2]	FSD: the number of bank branches per 100 000 persons and number of banks opened in rural versus urban areas.	India (1977–1990).	Using OLS and IV, they found that financial access reduces poverty, especially in rural areas.
	Liang (2008)	Provincial rural Gini index. FSD: constructed rural FSD based on the ratio of total loans to rural GDP.	China, based on provincial data from 1991 to 2000.	The GMM technique showed that increased access to financial services and credit in rural areas reduces inequality.
	Shahbaz and Islam (2011)	Gini index, domestic credit to the private sector by financial intermediaries over GDP and financial stability measures developed by authors.	Pakistan (1971–2005).	Using ADRL methodology, they found that FSD reduces income inequality while financial instability increases inequality.

Table 1. *Cont.*

	Study	Main Variables in the Model of FSD on Inequality	Geographical Area	Findings
	Prete (2013)	Growth of Gini. FSD: private credit as the ratio of GDP.	30 countries from 1980 to 2005.	Using panel OLS, they find inequality narrowing.
	Dollar and Kraay (2002)	GDP per capita and mean income in the poorest quintile. Commercial bank assets/total bank assets, human capital. Inflation, trade openness, the rule of law/property rights.	137 countries (1950–1999)	FSD increases inequality by a small magnitude compared to the increasing impact on economic growth.
	Hendel et al. (2005)	Developed a model similar to (Rajan and Zingales 2003) for general equilibrium. The model is based on the interest rate, skills premium, subsidies for higher education and wealth fundamentals.	In the United States of America (USA)	Inequality from wage income increases when financial constraints for post-secondary education are reduced as the uneducated pool is left behind.
Financial widening hypothesis	Wahid et al. (2012)	Gini index, domestic credit to the private sector by financial intermediaries over GDP.	Bangladesh (1985–2006).	Using ADRL methodology, they find that FSD increases inequality.
	Jaumotte et al. (2013)	Gin index. Financial openness is measured using the Chinn–Ito index of capital account openness, the ratios of various types of financial liabilities (FDI, portfolio equity and debt) to GDP and the stock of FDI assets expressed as a percentage of GDP.	A total of 51 countries—20 developed and 31 developing countries (1981–2003).	The results show that inequality increases with financial globalization and foreign direct investment, while education and shift from agricultural employment reduce inequality.
	Seven and Coskun (2016)	Gini index. FSD: ratio of private credit to GDP, deposit money bank assets to GDP, M3 to GDP, stock market capitalization to GDP, stock market turnover ratio.	45 emerging market countries (1987–2001).	Using the GMM technique, they find that bank and stock market development increases inequality.

Table 1. *Cont.*

Study	Main Variables in the Model of FSD on Inequality	Geographical Area	Findings
Chiu and Lee (2019)	Gini index. FSD: domestic credit to the private sector and market capitalization.	59 countries, 1985–2015. Panel smooth transition regression model.	From the panel smooth transaction regression model, they find evidence of finance widening inequality in unstable economies, while high-inequality countries can reduce income inequality through FSD.
de Haan and Sturm (2017) Le and Nguyen (2020)	Gini index. FSD: private sector credit. Financial liberalization was measured with 6 sub-indices. Domestic credit is measured as commercial credit as a share of GDP and policy credit as a share of GDP.	121 countries from 1975 to 2005. Using the FE model. Vietnam. Panel study based on 60 provinces. From 2002 to 2016.	They find that all financial variables increase income inequality. Their main findings are robust for using random effects, cross-country regressions and legal origin as financial development instruments. Commercial credit increases income inequality, while policy credit reduces income inequality.

[1] Data for investigating FSD impacts on poverty is from year 1980 to 2000. [2] Contradicting results were reported in India by (Kochar, 2005). Where Kochar (2005) used bank branch data and IV fixed effect method and found increase in district bank branch increases consumption inequality.

The last hypothesis from the literature of finance inequality is the simple U-shaped hypothesis. As with the GJ hypothesis, the U-shaped hypothesis shows that the nonlinear relationship of the finance–inequality nexus depends on the level of FSD. Contrary to the GJ hypothesis, the U-shaped hypothesis posits that FSD benefits that reduce inequality are realized until a certain threshold. Above this threshold, FSD exacerbates inequality. Empirical studies in support of the new U-shaped finance–inequality nexus include (Law and Tan 2012; Park and Shin 2015; Brei et al. 2018; Cihak and Sahay 2020). For example, Law and Tan (2012) confirm the U-shaped relationship using a financial depth measure (credit), in a panel of 35 developing countries, with data samples from 1980 to 2000. They argue that if increases in financial depth increase inequality, financial markets are inefficient. Park and Shin (2015) employed the same measures of FSD used by Nguyen et al. (2019) on a sample of 162 countries from 1960 to 2011. They found a U-shaped relationship between FSD and income inequality using the fixed effect model. Brei et al. (2018) utilized data from 1989 to 2012 from 97 advanced and emerging market economies. Unlike other studies, Brei et al. (2018) utilized the financial development index of Svirydzenka (2016), an aggregated index comprising financial depth, access and efficiency. Brei et al. (2018) also rely upon the financial index's components (financial depth, access and efficiency). Using the GMM methodology on 5-year non-overlapping averages to address endogeneity issues and reverse causality, Brei et al. (2018) found that financial depth and overall FSD index first decrease inequality; after certain points, FSD increases inequality. Thus, the U-shaped hypothesis shows beneficial-to detrimental patterns of FSD on income inequality (Brei et al. 2018). The recent IMF staff discussion note by Cihak and Sahay (2020) used new data such as the financial depth index. The findings of Cihak and Sahay (2020) on 180 advanced and emerging market countries were as follows: financial depth, which refers to the size of the financial sector relative to the economy, narrows within-country inequality up until a threshold, above which it starts to increase inequality, while financial inclusion (access to finance and use of payment service) tends to reduce inequality. Lastly, they find a higher association between financial instability (financial risk) and higher inequality.

2.2.3. Empirical Evidence on Financial Access and Income Inequality

This study focuses on the impacts of FSD and its dimension on financial depth and access to income inequality. A vast number of studies in the FSD–inequality nexus use broader measures of FSD and thus have produced mixed results. However, studies using financial access and inclusion on the FSD–inequality nexus agree that an increase in access to financial services reduces inequality. There is some evidence in support of increasing access to finance to reduce poverty and income inequality (Liang 2008; Demirguc-Kunt and Levine 2009; Dabla-Norris et al. 2015; Kapingura 2017; Hasan et al. 2020; Cihak and Sahay 2020). For instance, the Central Bank mandate of India between 1977 and 1990 on broadening financial access in rural areas significantly reduced rural poverty while increasing output (Burgess and Pande 2005). Burgess and Pande (2005) measured FSD using the number of bank branches per 100,000 persons and decomposed the number of banks opened in rural versus urban areas. Using an instrumental variable methodology to account for indigeneity and three subperiods ending in the year 2000, the study found that rural poverty declined by 4.7% from a single additional bank in the rural area of India (Burgess and Pande 2005). This is because the low-income households benefit from financial access services as they are able to partake in a modern and market-based society. Kapingura (2017) used ATMs per 100,000 adults to measure FSD in South Africa and found that an increase in the number of ATMs reduces income inequality. Hasan et al. (2020) used global sample data, applied the instrumental variable in the Bayesian model and found that increased financial efficiency and access lower wealth inequality. At the same time, Hasan et al. (2020) found that an increase in financial depth/credit volumes increases wealth inequality.

As such, I argue that the measure of FSD should depend chiefly on the question of investigation. Studies on inequality should always include financial access and inclusion when measuring FSD. Increasing access to financial services for economic growth and to reduce inequality is supported by the World Bank Group for Universal Financial Access 2020 initiative and by the UN 2030 SDGs.

2.2.4. The Stylized Facts on Financial Sector Development and Inequality

This section presents a graphical analysis of financial sector development (FSD), income inequality and economic growth. Appendix A, Table A1 presents the list of countries in the full sample, their regions and the income level classification; the methodology applied in classifying inequality categories is shown Figure 1 below.

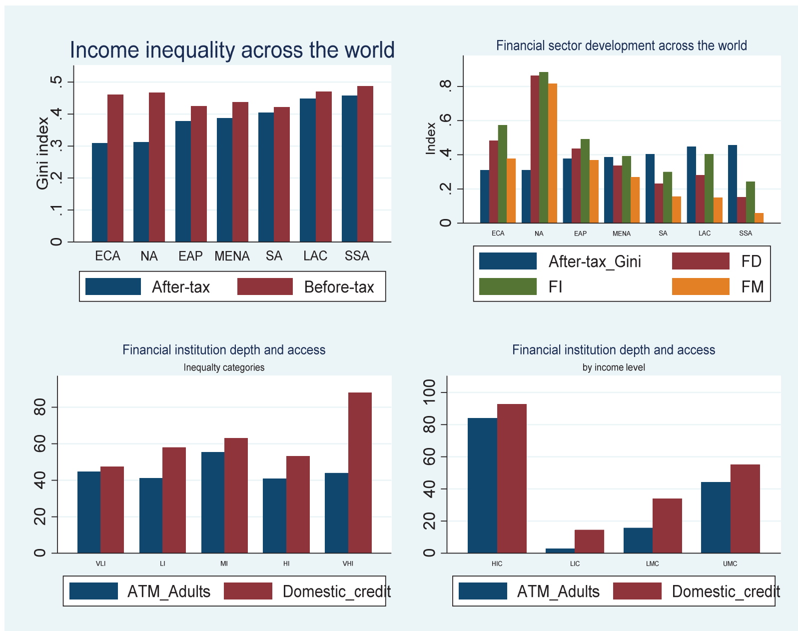

Figure 1. Stylized facts.

The top left graph shows global inequality levels in terms of both after-tax and before-tax Gini index by regions classified by the World Bank. Global income inequality data show that income inequality continues to rise within countries, while a comparison between countries shows that income inequality has declined on average. This is because inequality differs based on region. Regions such as Europe and Central Asia (ECA) have the lowest levels of income inequality. In contrast, sub-Saharan Africa (SSA) and Latin America and Caribbean (LAC) regions have rising and the highest levels of income inequality. For example, in the year 2016, the top 10% income group owned the national wealth of approximately 37% in Europe, 47% in the United States of America–Canada and 55% in sub-Saharan Africa, Brazil and India.

The top right graph shows the level of development in terms of financial sector (FD), financial institution (FI) and financial market (FM) indexes across the world. The North America (NA) region has the most developed financial sector, with all the FSD indexes above 0.80. The SSA, LAC and South Asia (SA) regions have the lowest overall FSD. On average, financial market development (FM) is significantly lower in SSA, LAC and SA regions. For example, South Africa has the most developed financial sector in the SSA region, with other countries depending on it.

The bottom left graph presents the level of financial institution depth (domestic credit) versus access (ATM per 100,000) based on income inequality categories. Countries with very low inequality (VLI) have higher levels of financial access than depth. Interestingly, domestic credit is much higher than access to financial services in very high-inequality countries. This suggests that higher domestic credit coupled with lower access to the financial sector are present in high-inequality countries. Lastly, the right bottom graph shows the level of financial institution depth versus access by income levels. From this figure, we can observe that higher levels of domestic credit by banks do not represent higher access to banking. High-income countries (HIC) have the highest level of both depth and access, while low-income countries (LIC) have the lowest of both. This suggests that FSD also depends on a country's level of development (income level/region).

3. Methodology and Data

3.1. Methodology

The literature on FSD and income inequality lacks consensus, as shown above. The argument is that different measurements of FSD (mainly broader proxies), methodology and sample periods applied in the study can produce mixed results. This study contributes to the literature by investigating the impact of the overall FSD on income inequality and the impact of FSD dimensions (access and depth) on income inequality. This study is interested in testing both the linear and nonlinear relationship, as different stages of financial development can have different effects on income inequality. Empirical studies on the nonlinear relationship hypothesis suggest that measures of FSD be expressed in both linear and nonlinear forms (Greenwood and Jovanovic 1990). The system generalized method of moments (GMM) of Blundell and Bond (1998) and Roodman (2009) is applied. GMM estimation requires the time of data (t) to be smaller than the number of countries (i) in the panel data. GMM is a dynamic estimator used for panel data that uses instrumental variables and corrects for endogeneity. GMM is advantageous as it also controls omitted variable bias and controls for country fixed effect. The robust system GMM estimation technique provides the following diagnostic tests: the serial correlation AR(2), the Sargan test and the Hansen test, where the null hypothesis for the Sargan and Hansen test is that instruments are valid for the model. This study employs a robust system GMM which is an augmented estimator, where one equation is expressed in levels with instruments expressed in the first difference. In the GMM, I regressed the log of after-tax Gini index on its first lagged, whilst building orthogonal conditions in GMM addresses sources of endogeneities; see Gnangoin et al. (2019). In estimating all the GMM, corruption variables are entered as an exogenous instrumental variable. This variable serves as a proxy for institutional quality. Initial GDP per capita and first lagged after-tax Gini are used as endogenous instruments. The choice of instruments is guided by the literature—for example, (Park and Shin 2015; Cihak and Sahay 2020). The collapse instrument option applied in the GMM helps to reduce the number of instruments. Subsequently, all the estimated GMM results have a lesser number of instruments than the number of N. By using robust system GMM, the results report standard errors that are robust to heteroskedasticity and autocorrelation. Finally, the linear model and nonlinear model are estimated using Equations (2) and (3), respectively.

$$\text{Giniit} = \alpha + \beta_0 \text{Gini}_{\text{it-1}} + \beta_1 \text{FSD}_{\text{it}} + \beta_3 \text{X}_{\text{it}} + \varepsilon_{\text{it}} \tag{2}$$

$$\text{Giniit} = \alpha + \beta_0 \text{Gini}_{\text{it-1}} + \beta_1 \text{FSD}_{\text{it}} + \beta_2 \text{FSD}^2{}_{\text{it}} + \beta_3 \text{X}_{\text{it}} + \varepsilon_{\text{it}} \tag{3}$$

where i and t represent countries and time, respectively, while FSD represents the FSD dimensions investigated, X is a set of control variables, and ε is the error term.

3.2. Data

The concept of financial sector development (FSD) is compounded mainly in terms of structure and regulatory framework. However, we can decompose FSD first into two broad components: financial institutions (FI) and financial markets (FM). Financial institutions and markets are developed if they are characterized by increased depth, access, efficiency and stability. A large body of literature on FSD, income inequality and economic growth uses the depth of financial institutions or markets to measure FSD. Subsequently, there is a limited number of studies considering the multidimensions of FSD. After the year 2004, new data on the multidimensions of FSD emerged. Figure 2 below summarizes the multidimensions of FSD and only a selected few from the proxy variables for each category.

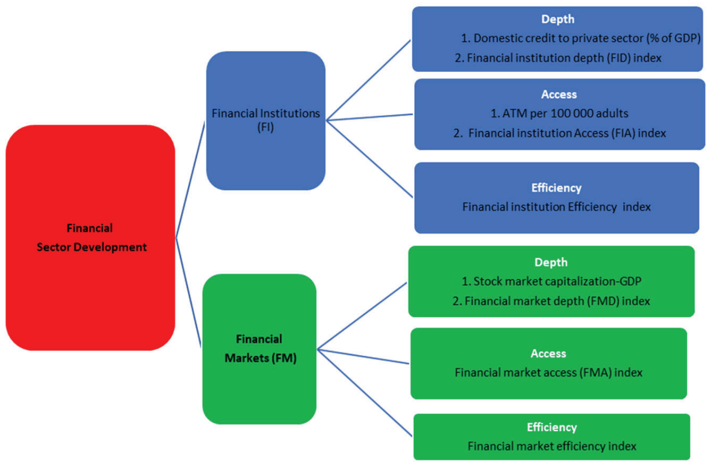

Figure 2. Measuring FSD. Source: Own processing based on Figure 1, on page 12 of Sahay et al. (2015), and Table 1 of Svirydzenka (2016).

The panel data used in the study are sourced from different databases using Stata codes. This study employs yearly panel data of 120 countries (ccode) from the years 2004 to 2019, and the before- and after-tax Gini index from the Standardized World Income Inequality Database (SWIID). SWIID is one of the leading databases for global coverage inequality. Access to the financial sector is measured with the financial institution and market access indexes and the number of ATMs per 100,000 adults. The latter measure is one of the two financial access indicators for the UN 2030 SDGs target 8.10. For the control variables, average school years in the population aged 25 and older is the proxy for the education variable; GDP per capita and trade openness (Trade_op) were sourced from Pen World Tables (PWT). The World Development Indicator (WDI) of the World Bank provides the FSD measures, inflation rate and general government final consumption expenditure as a percentage of GDP(Gov). The consumer price index (CPI) is calculated using inflation data, where the year 2004 is the base year. The financial development indexes and ATM per 100,000 adults were sourced from the International Monetary Fund (IMF) database. The control for corruption variable reflects the 'perception of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests' (Kaufmann et al. 2010). The corruption variable is sourced from the Worldwide Governance Indicator (WGI) of the World Bank. A detailed summary statistic is given in Table A2 of Appendix A. FSD indicators are chosen based on the available limited sample coverage in the panel setup, whilst trying to incorporate other proxy variables which are under test in the empirical literature.

4. Results

This section presents the linear and nonlinear empirical model results on the impacts of financial sector development (FSD) on inequality. Thus, this section presents results on the impact of overall FSD on income inequality, where overall FSD represents the development of both institutions and the market in terms of efficiency, depth and access. This study is interested in also investigating the impacts of FSD components on income inequality. Thus, the overall impact of financial institution (i.e., banks) and market (i.e., stock market) development is considered on income inequality. Thereafter, results on the impact of FSD in two dimensions (access and depth) on income inequality are presented. Financial sector depth (trade volumes and credit) is fundamentally different from access to financial services.

Table 2 reports the results of the linear model (Equation (2)) on the impact of overall FSD on income inequality. The dependent variable is the log of the after-tax Gini index. This is because the after-tax Gini index is an important measure of income inequality, as progressive tax policies are praised for reducing income inequality. In line with the growing and large literature, all three models confirm an overall narrowing impact of FSD on income inequality. These results are consistent with the results of Nguyen et al. (2019). The coefficients of the FSD index and financial market index (model 1 and 3, respectively) are negative and significant at 5%, while the narrowing hypothesis is confirmed only at 10% in the overall development of financial institutions (model 2). Table 2 results suggest that overall FSD reduces inequality with a range of 4 to 6%. The nonlinear results of the overall impact of FSD on income inequality were not significant, and are thus not reported in the study.

Table 2. Impact of overall financial sector development on income inequality.

VARIABLES	(1) Financial Development Index	(2) Financial Institution Index	(3) Financial Market Index
L.log_gini_	0.710 ***	0.735 ***	0.726 ***
	(0.125)	(0.105)	(0.121)
Findev	−0.0644 **	−0.0615 *	−0.0434 **
	(0.0261)	(0.0353)	(0.0187)
GDP	0.00417	0.00295	0.00488
	(0.00377)	(0.00347)	(0.00380)
Log_cpi	0.0106	0.0133	0.00930
	(0.00872)	(0.00820)	(0.00827)
Trade_op	−0.00238	−0.00106	−0.00444
	(0.00706)	(0.00733)	(0.00700)
Log_Gov	0.00769	0.0113	0.00262
	(0.0188)	(0.0204)	(0.0180)
Log_Education	−0.0913	−0.0803	−0.0977 *
	(0.0582)	(0.0524)	(0.0580)
Constant	−0.0728	−0.0590	−0.0647
	(0.0810)	(0.0774)	(0.0794)
Observations	1508	1508	1508
Number of ccode	120	120	120
AR 2 test (*p*-value)	0.558	0.396	0.529
Sargan test (*p*-value)	0.995	0.943	0.305
Hansen test(*p*-value)	0.270	0.308	0.202

Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 3 presents the results of the linear model (model 1, 2, 3) and nonlinear model (model 4–6) on the impact of access to financial services on income inequality. The dependent variable is the log of the after-tax Gini index. The result from both the linear and nonlinear model confirms that access to financial institution services has a significant reducing impact on income inequality (models 1, 2, 5). Increased access to financial institutions also reduces income inequality by promoting informal sector participation in the real economy. However, the model of access to the financial market (model 3, 6) shows that there is not a significant relationship with income inequality.

Table 4 presents the results of the linear model (model 1, 2, 3) and nonlinear model (model 4–6) on the impact of the financial institution and market depth on income inequality. The dependent variable is the log of the after-tax Gini index. As with the findings on financial market access in Table 3, Table 4 also suggests that financial market depth has no significant impact on income inequality. From Table 4, we can infer that in the linear models, only domestic credit by banks (model 1) is negative and significant at a 5% level. The study finds that the Too Much Finance hypothesis holds. In other words, in the nonlinear models, the financial institution depth index (model 5) confirms a U-shaped relationship with income inequality. The U-shaped finance depth and income inequality relationship suggests that increasing depth first narrows income inequality and, after reaching a threshold, growth in depth produces widening effects on income inequality. Thus, excessive credit could widen income inequality.

Table 3. Impact of access to financial institutions and markets on income inequality.

VARIABLES	(1) Financial Institution Access Index	(2) ATM per 100,000 Adults	(3) Financial Market Access Index	(4) Financial Institution Access Index	(5) ATM per 100,000 Adults	(6) Financial Market Access Index
L.log_gini	0.754 ***	0.801 ***	0.812 ***	0.744 ***	0.794 ***	0.853 ***
	(0.118)	(0.0852)	(0.0832)	(0.126)	(0.0834)	(0.0785)
Financial Access	−0.0542 **	−0.0278 *	0.00810	−0.0270	−0.0647 **	0.158
	(0.0234)	(0.0145)	(0.00985)	(0.107)	(0.0316)	(0.100)
Financial Access^2				−0.0280	0.0216	−0.123
				(0.100)	(0.0161)	(0.0850)
GDP	0.00144	0.00473	0.00363	0.00208	0.00159	0.00209
	(0.00355)	(0.00341)	(0.00290)	(0.00372)	(0.00277)	(0.00276)
Log_CPI	0.0183 *	0.0205 **	0.0131 *	0.0182	0.0221 **	0.0172 **
	(0.0103)	(0.00875)	(0.00688)	(0.0110)	(0.00846)	(0.00808)
Trade_op	0.00801	0.000966	−0.00462	0.00783	0.00383	−0.00766
	(0.00719)	(0.00660)	(0.00600)	(0.00753)	(0.00690)	(0.00674)
Log_Gov	0.0253	0.0217	0.00193	0.0265	0.0185	−0.00747
	(0.0227)	(0.0201)	(0.0165)	(0.0221)	(0.0200)	(0.0160)
Log_Education	−0.0883	−0.0891 *	−0.0892 **	−0.0988	−0.0652 *	−0.0891 **
	(0.0542)	(0.0484)	(0.0433)	(0.0608)	(0.0367)	(0.0429)
Constant	−0.00868	0.0233	−0.0131	−0.000560	−0.0270	−0.00933
	(0.0882)	(0.0854)	(0.0722)	(0.0877)	(0.0851)	(0.0721)
Observations	1508	1416	1508	1508	1416	1508
Number of ccode	120	119	120	120	119	120
AR 2 test (p-value)	0.498	0.211	0.339	0.643	0.226	0.361
Sargan test (p-value)	0.994	0.908	0.729	0.995	0.952	0.898
Hansen test (p-value)	0.656	0.644	0.250	0.613	0.587	0.366

Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

All the GMM results in Tables 2–4 above present the GMM diagnostic test results in the last three rows, where all the models showed no evidence of serial correlation, as indicated by the Arellano–Bond test for serial correlation (AR2). The Sargan and Hansen test investigates the validity of the chosen instruments of the model. The Sargan test of overidentifying restrictions is a special case of the Hansen test, as it assumes homoskedasticity and no serial correlation in the error terms, while the Hansen test does not rely on these strong assumptions (Roodman 2007). The Hansen test of overidentifying restrictions depends on the estimate of an optimal or robust weighting matrix, while the Sargan test does not (Roodman 2007). Thus, the Hansen and Sargan test results have different p-values. The p-values for both Sargan and Hansen tests in all the above results are above 10%, suggesting that, under both assumptions on error terms, the model instruments are valid. For robust standard errors, this study places emphasis on the Hansen test on instrument validity, while noting that Hansen test p-values below 0.25 should be viewed with caution (for example, model 3 of Table 2; model 3, 5 and 6 of Table 4) (Roodman 2007). However, the debate in the literature regarding the p-values of the Hansen test and the number of instruments in GMM continues; hence, this study also uses the collapse option to ensure that the number of instruments does not produce bias in the test of instrument validity (Roodman 2007).

Table 4. Impact of financial institution and market depth on income inequality.

VARIABLES	(1) Domestic Credit % of GDP	(2) Financial Institution Depth Index	(3) Financial Market Depth Index	(4) Domestic Credit % of GDP	(5) Financial Institution Depth Index	(6) Financial Market Depth Index
L.log_gini	0.763 ***	0.821 ***	0.782 ***	0.764 ***	0.761 ***	0.774 ***
	(0.120)	(0.0661)	(0.0890)	(0.118)	(0.0813)	(0.0884)
Financial depth	−0.0221 **	0.0198	−0.0100	−0.0294	−0.232 **	−0.0329
	(0.0110)	(0.0350)	(0.0114)	(0.0356)	(0.103)	(0.0298)
Financial depth^2				0.00364	0.185 **	0.0215
				(0.0175)	(0.0843)	(0.0259)
GDP	0.00540	0.00340	0.00395	0.00535	0.000844	0.00383
	(0.00422)	(0.00273)	(0.00306)	(0.00427)	(0.00285)	(0.00313)
Log_CPI	0.0157	0.0137	0.0116	0.0158	0.00804	0.0113
	(0.00977)	(0.00837)	(0.00733)	(0.00962)	(0.00772)	(0.00746)
Trade_op	0.00109	−0.00465	−0.00630	0.00134	0.000720	−0.00609
	(0.00769)	(0.00561)	(0.00655)	(0.00819)	(0.00620)	(0.00664)
Log_Gov	0.0259	−0.00246	0.00160	0.0267	0.00837	0.00132
	(0.0225)	(0.0182)	(0.0169)	(0.0214)	(0.0196)	(0.0169)
Log_Education	−0.111 *	−0.0929 *	−0.0882 *	−0.110 *	−0.0411	−0.0873 *
	(0.0612)	(0.0485)	(0.0461)	(0.0643)	(0.0479)	(0.0467)
Constant	0.0377	−0.00852	−0.0388	0.0385	−0.101	−0.0454
	(0.101)	(0.0758)	(0.0739)	(0.0971)	(0.0751)	(0.0728)
Observations	1465	1508	1508	1465	1508	1508
Number of ccode	119	120	120	119	120	120
AR 2 test (*p*-value)	0.769	0.281	0.355	0.712	0.185	0.385
Sargan test (*p*-value)	0.997	0.726	0.822	0.994	0.923	0.805
Hansen test(*p*-value)	0.450	0.275	0.177	0.413	0.224	0.218

Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5. Discussion

This study investigated the impact of overall FSD, and two dimensions of FSD, on income inequality. As such, the discussion is threefold, as follows.

Overall Impact of FSD on Income Inequality

The results presented in Table 2 contribute to the literature by providing an overall effect of FSD on income inequality. Few studies have empirically tested the impact of overall FSD on income inequality (Nguyen et al. 2019). The study of Nguyen et al. (2019), confirms an inverted U-shaped relationship between the FSD index of IMF and income inequality in emerging market countries. According to my knowledge, there are no studies empirically testing the impacts of the overall financial institution and market indexes on income inequality. Rather, what is common in the literature is studies using mostly financial depth to proxy overall FSD.

Impact of Financial Access on Income Inequality

The models of access to financial institution services (Table 3) confirm a narrowing impact on income inequality. These results are in line with the literature arguing for increased access to reduce income inequality (Kapingura 2017; Hasan et al. 2020; Cihak and Sahay 2020). For instance, Cihak and Sahay (2020) utilized three methods including Arellano and Bond (1991) GMM and confirmed the narrowing impact of financial access to income inequality on the five-year non-overlapping data of 128 economies and in a sub-group of emerging markets and developing countries. Cihak and Sahay (2020) and Hasan et al. (2020) both proxied financial access by the number of ATMs and commercial banks per 100,000 adults, while this study adds to the literature on financial access and income inequality by including results from the financial institution access index. Thus, this paper adds consensus on the effect of the access dimension of FSD on income inequality. Lastly, in Table 3, the linear model suggests that access to the financial market increases income inequality, while the nonlinear model suggests an inverted U-shaped relation. However, the models of financial market access to income inequality were both insignificant. Intuitively, having access to the financial market seems to have no significant impact on income inequality. For instance, average-income households with little or no savings will not participate in the financial market even if they have access to them. This suggests that participation especially in the financial market is highly connected to an individual's wealth and education. Access to financial institutions allows households of any income level to be able to build banking relations and credit scores.

Impact of Financial Depth on Income Inequality

In terms of financial institution depth (Table 4), the study first confirms a narrowing hypothesis on income inequality in the linear model—only when depth is measured as domestic credit as a share of the GDP. The impact of financial market depth on income inequality was insignificant in both the linear and nonlinear model. The insignificant results suggest that financial market depth maybe has a direct relation with inequalities of wealth, rather than income. This is because financial market development tends to widen wealth inequalities as compared to income. For example, the findings of Eurofound (2021) suggest that homeownership increases the bottom quintile wealth levels, and there are a relatively lower number of renters holding financial assets beyond deposits within the EU member state. At the same time, the wealthiest groups in the EU member state tend to earn income from a self-employed business, holding financial assets and real estate. This distribution of capital suggests that different income groups benefit differently from financial rent. While the linear results of the financial institution depth index were not significant, they become significant after adding the nonlinear term. Furthermore, the nonlinear model results from the financial institution depth index reveal that the Too Much Finance hypothesis is evident, thus suggesting a U-shaped relationship between financial depth and income inequality. The U-shaped relationship on finance depth and income inequality was also confirmed in the literature (Brei et al. 2018; Cihak and Sahay 2020; and de la Cuesta-González et al. 2020). For instance, Cihak and Sahay (2020) confirm the U-shaped finance depth and inequality nexus using financial institution and market depth. de la Cuesta-González et al. (2020) confirm the U-shaped hypothesis using both domestic credits as a share of GDP and stock market capitalization on the income inequality of nine OECD countries, using a two-step GMM. The widening effect of higher credit on inequality is explained by how credit is highly dependent on collateral, firm structure and sector of activity. Bank credit decisions can have a negative or positive influence on an individual's future income. According to Delis et al. (2021), in 5 years, individuals who are accepted for loan applications can grow their future income by 11% versus those who were rejected. For example, an individual accepted for a mortgage loan will have a higher net worth than those rejected. A firm receiving a loan for investment tends to be more profitable than those rejected for loans. These firms are expected to develop and implement certain rules as per the loan agreement. The growth of these firms with accepted loans produces increases in their wages, thus widening income inequality as the wages and productivity of the firms who were declined credit do not increase. Thus, income distribution is much tighter among accepted loan applications versus the wider distribution seen on a rejected loan application.

In addition, when the credit market triggers speculative investment, domestic credit increases income inequality in Vietnam (Le and Nguyen 2020). Financial policies focusing on alleviating income inequality should also incorporate credit policy provisions, whilst reviewing the banking business model to safeguard credit distribution in the direction of inclusive growth and sustainable development (de la Cuesta-González et al. 2020). The widening impact of domestic credit on inequality can also be reduced through policy interventions to increase access to credit efficiently. For example, the European Bank for

Reconstruction and Development (EBRD) provides credit to individuals, firms and SMEs that are credit-constrained but have good investment plans or good business financials.

6. Conclusions

The literature on income inequality and financial sector development (FSD) is dense, with extensive studies using broader measures of FSD. This study adds to the literature by looking first at the overall impact of FSD on income inequality using the FSD index, as done by Nguyen et al. (2019), whilst also investigating individually the impact of financial market and institution development on income inequality. This study also investigates the multidimensional perspective of FSD on income inequality. More specifically, this paper investigates the impact of financial sector depth (domestic credit) and access on income inequality. I used panel data of 120 countries from 2004 to 2019 and estimated the system GMM. The empirical results show a negative overall impact of FSD on income inequality. Furthermore, this study finds that access to financial institutions tends to narrow income inequality in both linear and nonlinear models. The narrowing hypothesis of financial access on inequality is evident in the literature, especially in the case of India, where the national bank used a policy mandate to broaden access to finance in rural areas. This includes poor households in the formal economy, allowing them to save and invest; it gives informal workers such as street vendors in Africa an opportunity to bank their income and thus start building credit for future loans. As such, access to financial institution services is the most important component of FSD when it comes to income inequality. However, both financial market access and depth seemed not to impact income inequality.

Contrary to financial access results, the empirical results on financial depth and income inequality were twofold. Firstly, in the linear model, financial depth as measured by domestic credit narrows income inequality. Secondly, only in the nonlinear financial depth index model, the study confirms a U-shaped relationship, suggesting that the Too Much Finance hypothesis holds. The U-shaped finance depth and inequality hypothesis implies that financial depth narrows income inequality up until a certain threshold, beyond which growth in financial depth widens income inequality. The findings of this study point towards incorporating inclusive FSD, by targeting inclusive credit policies and increasing access to financial services to reduce income inequality. This study does not disregard the other factors driving income inequality, such as wages (skills/education); however, the study points out other measures that can be taken to tackle inequalities. Exclusion from the financial sector reflects exclusion from the formal economy. While Fintech and other digital means of financial transaction are growing in Africa and India, this study leaves the analysis for future research.

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Appendix A

Table A1. List of Countries.

Full Sample	County Codes	Region Names [1]	Income Levels [2]	Gini Category [3]	High Inequality Countries	Low Inequality Countries
Angola	AGO	SSA	LMC	HI	✓	
Albania	ALB	ECA	UMC	MI		
Armenia	ARM	ECA	UMC	MI		
Australia	AUS	EAP	HIC	MI		
Austria	AUT	ECA	HIC	MI		

Table A1. *Cont.*

Full Sample	County Codes	Region Names [1]	Income Levels [2]	Gini Category [3]	High Inequality Countries	Low Inequality Countries
Burundi	BDI	SSA	LIC	LI		
Belgium	BEL	ECA	HIC	MI		
Benin	BEN	SSA	LMC	MI		
Burkina Faso	BFA	SSA	LIC	MI		
Bangladesh	BGD	SA	LMC	VLI		
Bulgaria	BGR	ECA	UMC	LI		
Bolivia	BOL	LAC	LMC	MI		
Brazil	BRA	LAC	UMC	VHI	✓	
Barbados	BRB	LAC	HIC	MI		
Botswana	BWA	SSA	UMC	VHI	✓	
Canada	CAN	NA	HIC	MI		
Switzerland	CHE	ECA	HIC	VLI		
Chile	CHL	LAC	HIC	HI	✓	
China	CHN	EAP	UMC	LI		
Cameroon	CMR	SSA	LMC	MI		
Congo	COG	SSA	LMC			
Colombia	COL	LAC	UMC	HI		
Cyprus	CYP	ECA	HIC	MI		
Czech Republic	CZE	ECA	HIC	MI		
Germany	DEU	ECA	HIC	MI		
Denmark	DNK	ECA	HIC	LI		✓
Dominican Republic	DOM	LAC	UMC	MI		
Algeria	DZA	MENA	LMC	VLI		
Ecuador	ECU	LAC	UMC	MI		
Egypt	EGY	MENA	LMC	MI		
Spain	ESP	ECA	HIC	LI		
Estonia	EST	ECA	HIC	MI		
Ethiopia	ETH	SSA	LIC	VLI		
Finland	FIN	ECA	HIC	LI	✓	
Fiji	FJI	EAP	UMC	LI		
France	FRA	ECA	HIC	LI		✓
Gabon	GAB	SSA	UMC			
United Kingdom	GBR	ECA	HIC	HI		
Ghana	GHA	SSA	LMC	MI		
Gambia	GMB	SSA	LIC	MI		
Greece	GRC	ECA	HIC	MI		
Guatemala	GTM	LAC	UMC	MI		
Hong Kong	HKG	EAP	HIC	MI		
Honduras	HND	LAC	LMC	MI		
Croatia	HRV	ECA	HIC	LI		✓
Hungary	HUN	ECA	HIC	LI		✓
Indonesia	IDN	EAP	UMC	LI		

Table A1. *Cont.*

Full Sample	County Codes	Region Names [1]	Income Levels [2]	Gini Category [3]	High Inequality Countries	Low Inequality Countries
India	IND	SA	LMC	MI		
Ireland	IRL	ECA	HIC	MI		
Iran	IRN	MENA	UMC	LI		
Iceland	ISL	ECA	HIC	LI		✓
Israel	ISR	MENA	HIC	MI		
Italy	ITA	ECA	HIC	MI		
Jamaica	JAM	LAC	UMC	LI		
Jordan	JOR	MENA	UMC	VLI		
Japan	JPN	EAP	HIC	LI		✓
Kazakhstan	KAZ	ECA	UMC	VLI		
Kenya	KEN	SSA	LMC	MI		
Kyrgyzstan	KGZ	ECA	LMC	LI		
Cambodia	KHM	EAP	LMC	VLI		
Korea	KOR	EAP	HIC	VLI		
Laos	LAO	EAP	LMC	VLI		
Sri Lanka	LKA	SA	LMC	LI		
Lesotho	LSO	SSA	LMC	HI	✓	
Lithuania	LTU	ECA	HIC	MI		
Luxembourg	LUX	ECA	HIC	LI		✓
Latvia	LVA	ECA	HIC	MI		
Morocco	MAR	MENA	LMC	LI		
Moldova	MDA	ECA	LMC	HI		
Madagascar	MDG	SSA	LIC	MI		
Maldives	MDV	SA	UMC	LI		
Mexico	MEX	LAC	UMC	MI		
Malta	MLT	MENA	HIC	LI		
Myanmar	MMR	EAP	LMC			
Mongolia	MNG	EAP	LMC	VLI		
Mozambique	MOZ	SSA	LIC	MI		
Mauritania	MRT	SSA	LMC	LI		
Mauritius	MUS	SSA	HIC	VLI		
Malaysia	MYS	EAP	UMC	MI		
Namibia	NAM	SSA	UMC	VHI	✓	
Niger	NER	SSA	LIC	LI		
Nigeria	NGA	SSA	LMC	MI		
Nicaragua	NIC	LAC	LMC	MI		
Netherlands	NLD	ECA	HIC	MI		
Norway	NOR	ECA	HIC	MI		✓
Nepal	NPL	SA	LMC	LI		
New Zealand	NZL	EAP	HIC	MI		
Pakistan	PAK	SA	LMC	VLI		
Panama	PAN	LAC	HIC	HI		
Peru	PER	LAC	UMC	HI	✓	

Table A1. *Cont.*

Full Sample	County Codes	Region Names [1]	Income Levels [2]	Gini Category [3]	High Inequality Countries	Low Inequality Countries
Philippines	PHL	EAP	LMC	MI		
Poland	POL	ECA	HIC	MI		
Portugal	PRT	ECA	HIC	MI		
Paraguay	PRY	LAC	UMC	MI		
Qatar	QAT	MENA	HIC	LI		
Romania	ROU	ECA	HIC	LI		
Russia	RUS	ECA	UMC	MI		
Rwanda	RWA	SSA	LIC	HI	✓	
Saudi Arabia	SAU	MENA	HIC			
Sudan	SDN	SSA	LIC	LI		
Senegal	SEN	SSA	LMC	LI		
Singapore	SGP	EAP	HIC	LI		✓
El Salvador	SLV	LAC	LMC	LI		
Serbia	SRB	ECA	UMC	MI		
Slovakia	SVK	ECA	HIC	LI		✓
Slovenia	SVN	ECA	HIC	VLI		✓
Sweden	SWE	ECA	HIC	MI		✓
Togo	TGO	SSA	LIC			
Thailand	THA	EAP	UMC	MI		
Tajikistan	TJK	ECA	LIC	VLI		
Tunisia	TUN	MENA	LMC	LI		
Turkey	TUR	ECA	UMC	LI		
Tanzania	TZA	SSA	LMC	LI		
Uganda	UGA	SSA	LIC	MI		
Ukraine	UKR	ECA	LMC	VLI		
Uruguay	URY	LAC	HIC	HI	✓	
Vietnam	VNM	EAP	LMC	LI		
South Africa	ZAF	SSA	UMC	VHI	✓	
Zambia	ZMB	SSA	LMC	HI	✓	
Cote d'Iviore	CIV	SSA	LMC	HI	✓	
Comoros 4	COM	SSA	LMC	HI	✓	

[1] Region names/classification are based on the World Bank classification. [2] Income level classification is based on the World Bank classification. [3] Inequality categories that are used for Figure 1 in the manuscript were constructed as follows: 1. I use before tax Gini index, where: (a) Gini index ranging between 0–0.3999 = Very low inequality (VLI), (b). Gini index ranging between 0.399901–0.44999 = 2= Low inequality (LI), (c). Gini index ranging between 0.45–0.5299 =3= Middle inequality (MI), (d). Gini index ranging between 0.53–0.599 =4= High inequality (HI), and (e). Gini index ranging between 0.6-max = Very High inequality (HLI). 4 Country Cote d'Iviore and Comoros are not included in the full sample estimated in the GMM models but are included in the subsample for high inequality regions.

Table A2. Descriptive Statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max	Data Source
gini disp	1962	0.386	0.082	0.23	0.674	SWIID
gini mkt	1962	0.459	0.065	0.219	0.725	SWIID
GDP	2272	1.885	2.036	0.025	16.652	PWT
ATMadult	2110	0.46	0.459	0	2.886	IMF
Dom credit	2309	0.568	0.465	0	3.046	WDI
Fin markets	1034	0.727	1.311	0	13.496	WDI
FD	2320	0.336	0.236	0.029	1	IMF
FIA	2320	0.36	0.277	0.003	1	IMF
FMA	2320	0.241	0.288	0	1	IMF
FID	2320	0.279	0.271	0	1	IMF
FMD	2320	0.245	0.287	0	1	IMF
Urban pop	2320	0.578	0.23	0.091	1	WDI
Trade op	2272	0.645	0.565	0.001	5.49	PWT
yr sch	2016	8.242	3.342	0.759	15.802	PWT
CPI	2240	1.662	1.16	0.99	25.777	WDI
Gov	2127	0.157	0.053	0.035	0.435	WDI
corruption	2320	0.018	1.012	−1.681	2.47	WGI

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agriculture

Review

Rice for Food Security: Revisiting Its Production, Diversity, Rice Milling Process and Nutrient Content

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Abstract: Rice is food consumed regularly and is vital for the food security of over half the world's population. Rice production on a global scale is predicted to rise by 58 to 567 million tonnes (Mt) by 2030. Rice contains a significant number of calories and a wide variety of essential vitamins, minerals, and other nutritional values. Its nutrients are superior to those found in maize, wheat, and potatoes. It is also recognised as a great source of vitamin E and B5 as well as carbohydrates, thiamine, calcium, folate, and iron. Phytic acid and phenols are among the phenolic compounds found in rice, alongside sterols, flavonoids, terpenoids, anthocyanins, tocopherols, tocotrienols, and oryzanol. These compounds have been positively linked to antioxidant properties and have been shown to help prevent cardiovascular disease and diabetes. This review examines recent global rice production, selected varieties, consumption, ending stocks, and the composition of rice grains and their nutritional values. This review also includes a new method of paddy storage, drying, and grading of rice. Finally, the environmental impacts concerning rice cultivation are discussed, along with the obstacles that must be overcome and the current policy directions of rice-producing countries.

Keywords: food security; rice cultivation; rice diversity; rice production; rice nutrient; rice milling

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1. Introduction

Rice is a crop that provides food for approximately half of the world's population. Rice is a vital crop globally, accounting for over 21% of human caloric requirements and up to 76% of the calorific intake of Southeast Asian inhabitants [1]. Figure 1 shows that global paddy rice production increased from 1994 to 2019 [2]. According to the United States Department of Agriculture (USDA) [3], the primary rice production for 2020/2021 is 148.30 million tonnes (Mt) in China, followed by 120.00 Mt in India, 35.30 Mt in Bangladesh, 34.90 Mt in Indonesia, and 27.10 Mt in Vietnam. Furthermore, Thailand produced 18.6 Mt, the Philippines produced 12 Mt, Japan produced 7.62 Mt, Pakistan produced 7.60 Mt, Brazil produced 7.48 Mt, the United States produced 7.23 Mt, Nigeria produced 5.04 Mt, the European Union produced 1.96 Mt, Malaysia produced 1.83 Mt, and Turkey produced 0.59 Mt. Figure 2 illustrates rice and paddy production (average 1994–2019). Asia produces 90.6% of the global rice production, making it the world's largest producer [2,4].

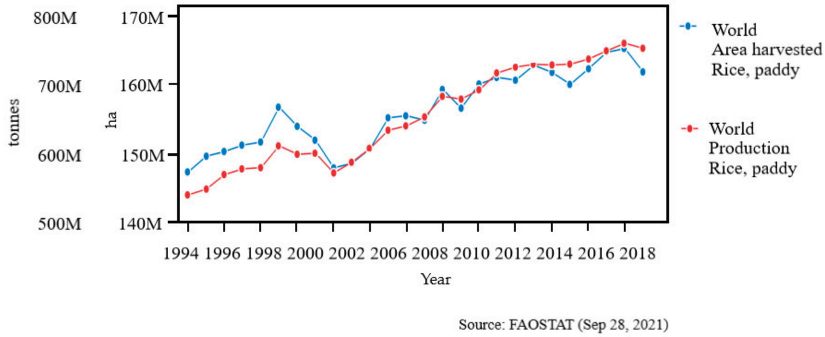

Figure 1. Production/yield quantities of rice paddy in the world (1994–2019) [2].

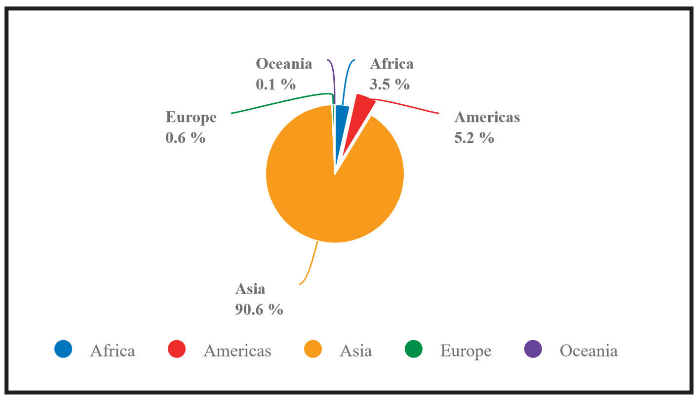

Figure 2. Production share of rice paddy by region (Average 1994–2019) [2].

According to OECD/FAO [5], rice is primarily a staple food in Asia, the Caribbean and Latin America, and is becoming progressively popular in Africa. In the decade ahead, global rice consumption is expected to expand by 0.9% per year, down from 1.1% per year in the previous decade. Asia is expected to account for up to 65% of the projected rise in world rice consumption; however, the growth rate will decrease by −0.15% per annum (Table 1). Rice consumption is predicted to increase significantly in Africa, while remaining stable or declining in all other regions. Future rice demand will be driven primarily by Africa, owing to a combination of population growth, dietary changes, and yield improvement on existing land (intensification) [6].

Table 1. Rice per capita consumption (kg/person/year) [5].

Country	2018–2020	2030	Growth Rate (% p.a.)
Africa	27.4	31.5	1.2
Oceania	13.5	14.2	0.44
North America	6.3	6.6	0.42
Europe	20.7	25.6	−0.08
Latin America and Caribbean	28.0	28.1	−0.14
Asia	77.2	77.5	−0.15

Source: OECD/FAO (2021), "OECD-FAO Agricultural Outlook", OECD Agriculture statistics (database), http://dx.doi.org/10.1787/agr-outl-data-en (accessed on 1 October 2021).

The current review discusses recent global rice production, consumption, and ending stock, the composition of the rice grain, the nutritional values of rice, rice varieties, the milling process of rice, the environmental impacts of rice cultivation, and the challenges to overcoming obstacles and current policy directions.

2. Global Rice Production, Consumption, and Ending Stock

Table 2 shows the FAOSTAT data regarding rice production worldwide in 2019 [2]. In 2020/2021, the world's rice consumption was 697.09 Mt. However, only 513.7 Mt (milled rice) was the world's rice production for that year [7]. Although food consumption is expected to increase, food consumption growth is expected to account for the largest share of this annual increase, maintaining world per capita rice consumption at approximately 54 kg/person [8].

Table 2. Production quantities of rice by country worldwide in 2019 [2].

Country	Total Rice Production (Tonnes)	Country	Total Rice Production (Tonnes)
Afghanistan	444,452.15	Democratic Republic of the Congo	557,205.58
Albania	0	Denmark	0
Algeria	438.12	Dominican Republic	721,733.42
Angola	15,556.69	Ecuador	1,426,523.23
Argentina	1,193,141.73	Chile	133,629.04
Australia	772,382	China	195,488,413.9
Azerbaijan	8675.65	China, Hong Kong SAR	0
Bangladesh	42,178,999.19	Egypt	5,555,313.96
Belgium	0	El Salvador	38,195.92
Belize	14,115.96	Estonia	0
Benin	142,182.08	Eswatini	605.81
Bhutan	62,148.04	Ethiopia	60,023.92
Bolivia (Plurinational State of)	390,846.77	Fiji	11,576.42
Brazil	11,225,080.35	Finland	0
Brunei Darussalam	947.15	France	106,261.54
Bulgaria	34,938.38	French Guyana	24,066.54
Burkina Faso	189,713.31	Gabon	1281.96
Burundi	66,475.62	Gambia	36,824.31
Cambodia	6,585,414.31	Germany	0
Cameroon	126,887.38	Ghana	393,680.42
Central African Republic	24,122.92	Greece	204,750.77
Chad	169,578.62	Guatemala	29,947.27
Chile	133,629.04	Guinea	1,507,327.77
China	195,488,413.9	Guinea-Bissau	137,708.42
China, Hong Kong SAR	0	Guyana	580,718.54
China, mainland	193,772,091.5	Haiti	130,727.5
China, Taiwan Province of	1,716,322.38	Honduras	40,117.42
Colombia	2,263,214.04	Hungary	9842.65
Comoros	22,560.42	India	142,410,885.6
Congo	1232.73	Indonesia	54,883,555.81
Costa Rica	213,232.54	Iran (Islamic Republic of)	2,384,846.77
Côte d'Ivoire	1,090,520.46	Iraq	258,179.85
Croatia	0	Ireland	0
Cuba	513,772.5	Italy	1,447,809.31
Cyprus	0	Jamaica	70.31
Czechia	0	Japan	11,337,059.62
Democratic People's Republic of Korea	2,327,908.92	Kazakhstan	314,242.15
		Kenya	72,811.35
Kyrgyzstan	21,005.46	Saudi Arabia	0
Lao People's Democratic Republic	2,773,653.88	Senegal	439,096.38
Latvia	0	Sierra Leone	702,817.46

Table 2. *Cont.*

Country	Total Rice Production (Tonnes)	Country	Total Rice Production (Tonnes)
Liberia	203,410	Slovakia	0
Lithuania	0	Slovenia	0
Luxembourg	0	Solomon Islands	2665.62
Madagascar	3,383,336.15	Somalia	5770.42
Malawi	93,924.08	South Africa	3070.85
Malaysia	2,345,032.54	Spain	791,654.73
Mali	1,438,024.58	Sri Lanka	3,341,954.46
Malta	0	Sudan	27,487.5
Mauritania	137,731.69	Sudan (former)	14,913.78
Mauritius	161.08	Suriname	218,101.96
Mexico	288,067.85	Sweden	0
Micronesia (Federated States of)	129.92	Syrian Arab Republic	149.33
Morocco	41,000.62	Tajikistan	62,629.96
Mozambique	163,375.15	Thailand	29,621,346.69
Myanmar	24,700,326.04	Timor-Leste	66,275.96
Nepal	4,294,742.65	Togo	103,441.65
Netherlands	0	Trinidad and Tobago	4232.5
Nicaragua	322,352.46	Turkey	618,820.19
Niger	76,839.92	Turkmenistan	80,366.54
Nigeria	4,464,072.04	Uganda	162,392.73
North Macedonia	18,914.5	Ukraine	90,938.69
Pakistan	8,394,983.38	United Republic of Tanzania	1,519,746.96
Panama	281,628.96	United States of America	9,157,048.46
Papua New Guinea	772.88	Uruguay	1,182,819.15
Paraguay	343,408.69	Uganda	162,392.73
Peru	2,392,461.08	Ukraine	90,938.69
Philippines	15,025,640.73	United Republic of Tanzania	1,519,746.96
Poland	0	United States of America	9,157,048.46
Portugal	158,642.77	Uzbekistan	289,830.31
Puerto Rico	36.38	Venezuela (Bolivarian Republic of)	852,740.23
Republic of Korea	6,244,369.88	Vietnam	36,613,011.5
Réunion	123.85	Zambia	25,104.19
Romania	29,653.5	Zimbabwe	869.04
Russian Federation	735,256.92		
Rwanda	56,898.92		

Rice consumption per capita is steadily declining in several Asian countries, due to changing dietary habits brought about by the influence of the Western diet, such as increased consumption of meat, dairy, and fast foods [9]. The rice consumption in China is 149,000 thousand metric tonnes (TMT), followed by India, Bangladesh, Indonesia, Vietnam, the Philippines, Thailand, Burma, Japan, and Brazil, which consume 106,500, 35,900, 35,800, 21,250, 14,400, 12,500, 10,400, 8250, and 7350 TMT of rice, respectively [10]. Even though rice production is declining, the current population projections show that Asia will need an extra 8 Mt of rice per year [11]. Due to the increasing number of Asian communities living in Western countries, the demand for rice in Western world has increased, as has the awareness and appreciation of the people for rice-based dishes [12]. Therefore, future rice production will need to significantly improve resource efficiency to meet notably increasing demand and discerning consumer demands. Figure 3 depicts the world's total rice utilisation from 2011 to 2021.

For the foreseeable future, rice is expected to remain a key component of Asian diets. Rice will also continue to play a significant role in African diets in the future. Africa will demand more rice due to growing consumer preferences and population increase. African women find rice to cook easier than coarse cereals, roots and tubers, which are major source of calorie supply in Africa [13,14].

As a result, it has always been of concern to ensure that an adequate rice supply is available to meet this growing demand. By 2030, the total cereal share is expected to reach 18%, primarily due to increased rice trade. However, rice will continue to be a scarce commodity. Asia has a more significant rice surplus. India, Vietnam, and Thailand will lead the global rice trade. Myanmar and Cambodia are forecast to expand in rice exports, while China's exports will last beyond 2010–2016 [4].

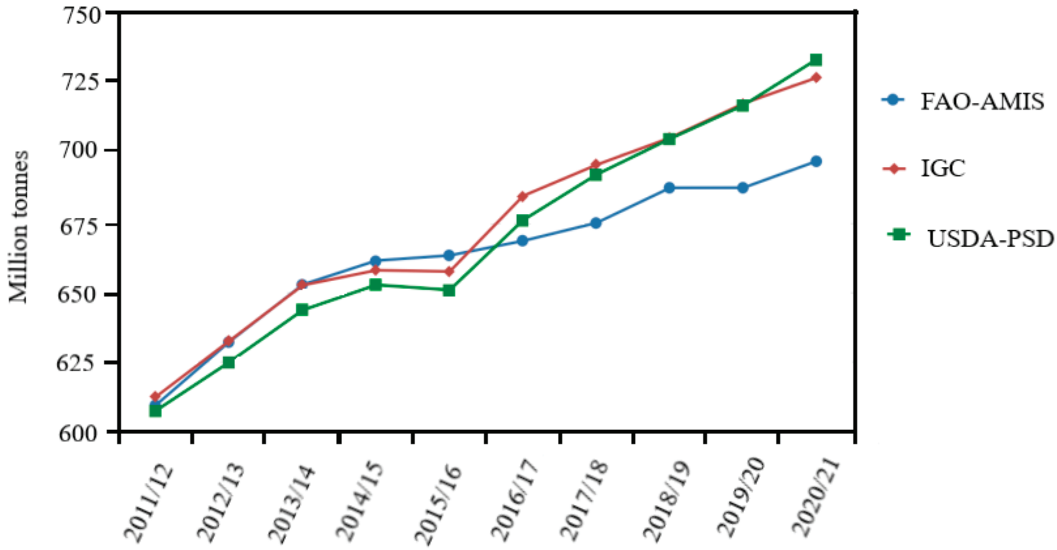

Figure 3. World rice total utilisation from 2011–2021 [7].

3. Variety of Rice

In total, 110,000 different cultivated rice varieties are grown globally, but only the species of *Oryza sativa* and *Oryza glaberrima* are widely cultivated. *Oryza sativa* is also Asian rice, and *Oryza glaberrima* is African rice [15]. *Oryza sativa* is cultivated worldwide. However, *Oryza glaberrima* is cultivated exclusively in Africa. *Oryza sativa* is classified into subspecies, indica, which produces rice with long-grain, and japonica, rice with a round grain. Japonica rice is grown and consumed primarily in China, Korea, the European Union, Australia, Taiwan, Russia, Japan, Turkey, and the United States of America. Rice varieties of the genus indica are widely grown all across Asia [16]. Additionally, these varieties include fragrant types sold at a premium price. The leading fragrant varieties are Thai Hom Mali, Indian (Haryana and Punjab) and Pakistani Basmati (Punjab). Basmati, Jyothi, Joha, Pusa, Navara, Ponni, Jaya, Sona Masuri, Boli, Palakkad Matta, Kalajiri (aromatic) and others are widely cultivated in India. The coloured varieties include the following: Himalayan red rice; Jyothy, Matta rice, Kairali, Asha, Rakthashali, Bhadra from Kerala; Kaivara Samba, Red Kavuni, Mappillai Samba, Poongar, and Kuruvi Kar from Tamil Nadu [17]. In terms of length and shape (length and width), rice differs from one region to another. The variation in the length and shape of rice across regions is depicted. Certain regions prefer a variety of grain lengths and shapes [18].

In rice markets, granulometric measurements of grain length and whiteness are highly regarded for grading and quality criteria. The palatability characteristics (e.g., appearance, cohesiveness, tenderness, and flavour) are considered when determining a food's quality [19,20]. Figure 4 shows the regular white rice, brown rice, fragrant rice, basmati, glutinous or waxy rice, japonica rice, weedy rice and the genetically modified rice such as golden rice.

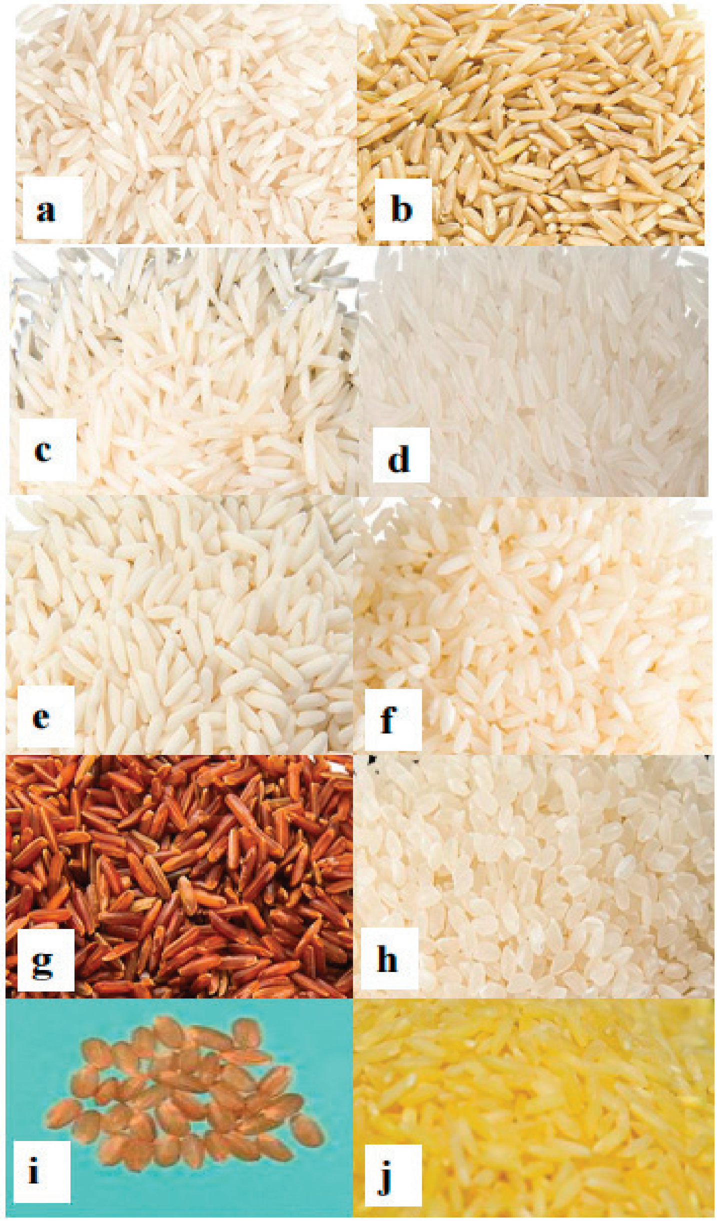

Figure 4. The various varieties of rice: (**a**) white rice, (**b**) brown rice, (**c**) basmati, (**d**) fragrant rice (**e**) glutinous rice, (**f**) ponni rice (**g**), red rice, (**h**), japonica rice, (**i**) weedy or red rice, and (**j**) golden rice [11,21].

3.1. White Rice

White rice is grown with a moderate white kernel and a translucent endosperm. White rice has a long-grain length of greater than 7.0 mm, an average whole grain length of greater than 7.0 mm, and a length to width ratio greater than 3.0. After cooking, the grains are tender but firm, and there is no discernible aroma. It is adaptable to a wide variety of recipes [21].

3.2. Brown Rice

Brown rice is also referred to as hulled rice or unmilled rice. Brown rice is composed of bran layers and embryos, which contain biofunctional components and a variety of nutritional aspects such as dietary fibre, oryzanol, vitamins, and minerals. Brown rice is consumed at a lower rate than white rice, due to its inferior texture when cooked. The rice retains its mild nutty flavour and chewiness. The cooked rice is fluffy and light with a distinct texture. Brown rice is excellent in making fried rice and pairs well with various healthy side dishes, such as vegetables or beans. The rice takes longer to prepare because the bran layer prevents water absorption [22].

3.3. Fragrant Rice

Fragrant rice is famously known for its aromatic characteristics. The crucial ingredient in fragrant rice that makes it smell good is 2-acetyl-1-pyrroline (2AP). The nithine or proline, glutamate, 1-pyrroline-5-carboxylic acid (P5C), 1-pyrroline,-aminobutyraldehyde, and acetyl groups are all essential precursors in the synthesis of 2AP. On the other hand, enzymes such as 1-pyrroline-5-carboxylate synthase (P5CS, EC 2.7.2.11/1.2.1.41), diamine oxidase (DAO, EC 1.4.3.22), ornithine aminotransferase (OAT, EC 2.6.1.13), and proline dehydrogenase (PDH, EC 1.5.99.8) have been reported to be critical enzymes in 2AP bio [23].

3.4. Basmati Rice

Basmati rice is a popular dish with an intoxicating aroma that makes it a popular choice for cooking [24]. Rice of the Basmati and Jasmine varieties is traded at a premium in domestic and international markets. It is a long, thin grain of rice with a long, slim shape originated in India and Pakistan and is now grown worldwide [25]. Although it is white, the blade shape has a slight curve. When baked, it nearly doubles in size and emits a faint aroma, but it retains its separation and light texture while keeping separate, and it has a shiny texture [26].

3.5. Ponni Rice

Compared to other rice varieties, Ponni rice has a plump, shorter and nearly circular kernel [27]. While still firm, cooked grains have a slight springiness to the bite. This rice, which has its origins in India, is an excellent choice for everyday cooking [28]. When it comes to the Indian population, it is well known for being served alongside delicious meals and spicy curries [27].

3.6. Glutinous or Waxy Rice

Many countries, including the Lao People's Democratic Republic, Japan, China, Thailand, Vietnam, Myanmar, Bangladesh, Cambodia, Malaysia and India, grow glutinous rice varieties. The Laotians eat glutinous rice as their main meal. It has always been usually served as a breakfast cereal, dessert, or steamed glutinous rice folded in banana leaves that is served for breakfast. Owing to the unique starch composition of glutinous rice, the rice exhibits unique processing properties. The productivity of rice milling and grain quality can be enhanced through various pretreatments such as tempering during the post-harvest tempering process and parboiling, which reduces internal slits and increases head rice output [29,30].

3.7. Red Rice

Red rice is versatile and frequently found in Asian cuisine. In the case of red rice, it can either be hulled wholly or partially hulled. Its nutritional profile is similar to that of brown rice. In comparison with white rice, red rice has a high antioxidant content. This rice is nuttier, chewier, and sweeter than white rice, making it an excellent substitute. Since red rice takes longer to cook than other types of rice, soaking it for 30 min prior helps soften the rice texture and speeds up the cooking time [31].

3.8. Japonica Rice

Japonica is a staple food in Japan. Its shorter, plumper presence recognises it compared to other plant family members. When grains are uncooked, their appearance is slightly glassy and translucent. It is tender and moist, and it has quite a sticky texture. Japonica has lower amylose content than indica [32]. While the rice is excellent at absorbing flavours, it possesses the characteristics of Japanese Koshihikari and thus is less expensive. This ingredient significantly enhances the flavour of sushi and other Japanese dishes.

3.9. Weedy or Red Rice

Weedy rice is an undesirable plant in the genus Oryza that exhibits some undesirable cultivation characteristics and poses a significant menace to the global rice industry's sustainability. Unluckily, it is now one of the most prevalent weeds worldwide, infesting rice fields. Weedy rice, also known as red rice, is nearly identical to cultivated rice (*Oryza sativa*) appearance [33]. The characteristics are nearly similar to those of cultivated rice. However, it can be differentiated from cultivated rice by its long and powerless culm, diverse grain shapes, red pericarp, higher level of seed torpidity, and shattering seed [34].

3.10. Golden Rice

Golden rice is slated to become the first genetically modified biofortified crop commercially available with enhanced quality and micronutrients, particularly vitamin A in rice [35]. The colour of golden rice is yellow, as is the beta-carotene contained in the rice. It is believed to be the most cost-effective way to tackle vitamin A deficiency in millions of people, particularly in developing countries where poorer people eat rice as their primary food [36,37]. Generic engineers have developed a solution by expressing the provitamin A precursor in its grain [38,39]. It exhibits comparable resistance to pests and yields performance to cultivated rice. A study by Mallikarjuna Swamy et al. [40] described the characterisation of GR2E Golden rice introgression lines in grain golden rice. It was reported that the best-performing lines found in each genetic background had unique carotenoids in the milled grains. These lines meet approximately 30–50% of the average vitamin A need.

4. Composition of Rice Grain

4.1. Rice Anatomy

Rough rice in its mature state (complete grains with intact husks) is composed of a brown kernel surrounded by a husk. The husk, also known as the hull, is the most visible element of a rough rice grain. The hull is the outer layer that surrounds the caryopsis and, while it is inedible, it accounts for approximately 20% to 25% of the total grain weight [29]. The hull acts as a barrier against invasion and environmental changes. Sterile lemmas, palea, rachilla and lemma comprise the hull. The lemma covers two-thirds of the seed, with the edges of the palea fitting snugly inside to form a tight seal around the seed. The embryo and starchy endosperm are contained within the caryopsis, enclosed by the pericarp and seed coat [41].

4.2. Starch

Approximately 90% of the dry weight of milled rice is starch [42]. Starch is a polymer composed of D-glucose linked α-(1–4) and typically consists of two fractions: an essentially linear fraction called amylose and a branched fraction called amylopectin. The ratio of amylose to amylopectin is vital for the structure, appearance, and eating quality of rice grains. The normal amylose content percentage in rice endosperm is classified as waxy (0% to 2%), very low (2% to 10%), low (10% to 20%), intermediate (20% to 25%), or high (25% to 33%) [43]. Table 3 summarises the various physicochemical properties of starch fractions. Branches are connected via α-(1–6) linkages. Rice amylose has two to four chains, a number-average degree of polymerisation (DPn) of 900 to glucose units, and a β-amylolysis limit of 73% to 87%. It is a mixture of branched and linear molecules with DPn values ranging from 1100 to 1700 and 700 to 900 [44].

Table 3. Properties of starch fractions in rice endosperm [29].

Property	Amylose	Amylopectin
Molecular Structure	Linear (α-1–4)	Branched (α-1–4; α-1–6)
Dilute Solutions	Unstable	Stable
Gels	Stiff, irreversible	Soft, reversible
Films	Coherent	_
Complex Formation	Favourable	Unfavourable
Iodine Colour	Blue	Red-Purple
Digestibility, β-Amylase	100%	60%
Degree of Polymerization	1500–6000	3×10^5–3×10^6

Amylose comprises branched fractions that account for 25% to 50% of the total number and 30% to 60% of the total weight. Rice amyloses have a 20% to 21% iodine affinity by weight. Rice amylopectin has a 56% to 59% β-amylolysis limit, chain lengths of 19 to 22 glucose units, a DPn of 5000 to 15,000 glucose units, and a chain count of 220 to 700 chains per molecule. Rice amylopectin has an iodine affinity of 0.4% to 0.90% in low- and intermediate-amylose rice, but only 2% to 3% in high-amylose rice. Isoamylase-debranched amylopectin has longer chain fractions (DPn > 100) (9–14%) in high-amylose samples and a higher iodine affinity than low- and intermediate-amylose samples (2–5%) and waxy rice amylopectin (0%) [29,45]. Milled rice is classified as waxy (1–2%), very low amylose (2–12%), low amylose (12–20%), intermediate (20–25%), or high (25–33%) based on colourimetric starch–iodine colour absorption standards at 590–620 nm [46,47].

The waxy endosperm is transparent and contains air spaces between the starch granules, resulting in a lower density than the non-waxy endosperm [48]. Although the starch granule structure remains unknown, crystallinity and staling are ascribed to the amylopectin fraction [49]. It is widely accepted that amylopectin molecules are composed of short amylose chains containing 6100 glucosyl residues, and elucidating the fine structure assembled by these chains is extremely difficult due to their high molecular weight [50].

4.3. Protein

The physicochemical properties of rice are influenced by its protein content [51]. As depicted in Table 4, rice typically has low protein content compared to most cereals. Additionally, it contains little fibre and lipids. However, rice has the highest net protein usage and digestible energy compared to all cereals such as wheat, corn, barley, millet, sorghum, rye, and oat [41].

Table 4. Protein and fibre content of cereal [29].

Property	Brown Rice	Wheat	Corn	Barley	Millet	Sorghum	Rye	Oat
Protein (N × 6.25) (%)	7.3	10.6	9.8	11.0	11.5	8.3	8.7	9.3
Fibre (%)	0.8	1.0	2.0	3.7	1.5	4.1	2.2	5.6
Net protein utilization (%)	73.8	53.0	58.0	62.0	56.0	50.0	59.0	59.1
Digestible energy (kJ (100 g)$^{-1}$)	1550	1360	1450	1320	1440	1290	1330	1160

Brown rice has a protein content ranging from 6.6% to 7.3%, milled rice has a protein content ranging from 6.2% to 6.9%, and milled basmati rice has a protein content ranging from 8.2 to 8.4%. Certain wild rice varieties found in China and North America contain a significant protein. These varieties may contain between 12.0 and 15.0% protein. The proportion of protein and fat in food reduces proportionally as the degree of polish increases. This component is primarily found in the outer layers of the kernel [29].

Endosperm (milled rice) contains several protein fractions, including 5.0–8.0% prolamin, 15% albumin plus globulin, and the remaining portion of glutelin [52]. Rice bran proteins contain more albumin than endosperm proteins and are found in the aleurone layer and germ as distinct protein bodies called globoids [53]. The shapes differ from endosperm protein bodies [54]. A recent study discovered that purple rice bran included anthocyanins and proanthocyanins. Anthocyanins are antioxidants that are used to modulate immune responses. They may help prevent Type 2 diabetes, cardiovascular disease, and even some cancers [15,55].

The endosperm protein is found primarily in sizeable spherical protein bodies in the endosperm (PB). Proteins are typically estimated to be between 0.5 and 4 microns in size. The glutelin-rich crystalline protein bodies (PB-II) and the prolamin-rich large spherical protein bodies (PB-I) are found in abundance in the crystalline protein bodies [56]. Using immunofluorescence microscopy, the PB-I in rice endosperm comprises a core region containing 10 kDa prolamin, an inner layer containing 13 kDa prolamin, two middle layers containing 13 and 16 kDa prolamin, and an outermost layer containing 13 kDa prolamin. It was discovered that the 13 kDa prolamins were a large group of prolamins found in rice [57].

4.4. Lipids

Indica and japonica rice varieties contain a diverse range of lipid groups in nearly identical proportions [58]. However, they are not distributed uniformly across the rice. Additionally, endosperm lipids contained a significantly higher amount of polar lipids. Rice contains the majority of its lipid or fat content in the bran fraction (20% on a dry basis), specifically as lipid bodies or spherosomes (0.1–1 m) in the aleurone layer and bran; however, about 1.5–1.7% is present in milled rice, primarily as non-starch lipids extracted with ether, chloroform-methanol, and cold water-saturated butanol [59,60].

Additionally, the protein bodies, particularly the core, contain a high concentration of lipids. These lipids are primarily composed of linoleic, oleic, and palmitic acids [61]. Rice oil contains between 29 and 42% linoleic acid and between 0.8 and 1% linolenic acid as essential fatty acids [62]. While grains' essential fatty acid content is likely to increase with temperature, the total oil content will likely decrease. Palmitic and linoleic acids are the primary fatty acids in starch lipids, with a trace of oleic acid [63]. The majority of starch lipids are monoacyl lipids [64]. The starch–lipid content of waxy starch granules is the lowest (0.2%) [65]. It is highest for rice with a moderate amount of amylose (1.0%) and might be slightly less for rice with a high amount of amylose. Waxy milled rice contains a higher concentration of non-starch lipids than non-waxy milled rice. However, starch lipids contribute only small energy to the rice grain.

4.5. Non-Starch Polysaccharides

Non-starch polysaccharides contain both insoluble and soluble and dietary fibre [66]. They may form a complex with starch and exert hypocholesterolemic properties. The endosperm contains less dietary fibre than the rest of the brown rice [67]. The values obtained for neutral detergent fibre range from 0.7 to 2.3%. Additionally, the endosperm or milled rice cell wall contains a small amount of lignin but a high amount of pectic substances or pectin. Endosperm pectin contains more uronic acid than other grain tissues but has a lower arabinose-to-xylose ratio. Additionally, endosperm's hemicellulose has a lower arabinose-to-xylose ratio than the other three grain tissues [68].

Non-starch polysaccharides are typically long polymeric carbohydrate chains containing thousands of monomeric units [69,70]. They are primarily composed of celluloses, hemicelluloses, and pectins, while fructans, glucomannans, and galactomannans are less abundant in the plant [71]. Mucilages, alginates, exudates, gums, and b-glucans are all classified as non-starch polysaccharide constituents [72]. Non-starch polysaccharides are used as a marker in dietary guidelines to provide useful information about food labelling to consumers [73]. In terms of health benefits, non-starch polysaccharides are effective at softening stool and are believed to help prevent diabetes, atherosclerosis, and high cholesterol levels. Non-starch polysaccharides are used as functional ingredients in the food industry, particularly in bakery products, to alter the rheological properties and dough characteristics [74].

4.6. Phenolic Compound

Rice grains contain various chemical compounds, including anthocyanins, oryzanol, flavonoids, terpenoids, sterols, phenols, phytic acid, tocopherols, and tocotrienols. Rice grain total phenolic content is positively correlated to antioxidant properties [75]. Additionally, the total phenolic content is used to regulate blood lipid levels, which aids in preventing the spread of cardiovascular disease and diabetes [76].

Numerous studies have demonstrated the antioxidant properties of phenolic compounds [77]. Antioxidants help prevent and mitigate damage caused by reactive oxygen species (ROS) in foods by delaying the oxidation process, thus further extending the quality and shelf-life of functional foods [78]. Additionally, phenolic compounds, ascorbic acid, and beta-carotene all play critical roles in inflammation reduction, human ageing, and the prevention of certain cancers [79]. Unfortunately, these compounds, including anthocyanins, phenolic acids, and proanthocyanidins, are the most abundant secondary metabolites in rice grains. They are found in pigmented grains and are widely regarded as the most potent antioxidants found in nature [80]. The most common phenolic components are described further below.

4.6.1. Phenolic Acids

Phenolic acids are found in both insoluble and soluble forms in rice grains [81]. The insoluble form, referred to as bound phenolics, adheres to the cell walls [82]. However, the soluble form, which includes the conjugated and free forms, can be extracted using solvents such as ethanol, acetone or aqueous methanol, while the conjugated form can be hydrolysed from soluble phenolics using alkali. The most abundant phenolic fraction is insoluble bound phenolic acids, followed by soluble conjugated phenolic acids, and finally, soluble free phenolic acids, which are the least abundant [83]. Furthermore, phenolic acids are found primarily in ice bran and trace amounts in the endosperm of various rice genotypes. Phenolic acids are classified into two subclasses: hydrobenzoic acids and their derivatives, and hydroxycinnamic acids and their derivatives [84]. Protocatechuic, p-hydroxybenzoic, syringic, and gallic acids are all derivatives of hydroxybenzoic acid [85].

4.6.2. Flavonoids

Flavonoids are secondary plant metabolites with a polyphenolic structure similar to that of phenolic acids that have been shown to have a variety of health-promoting properties and to contribute to a decreased risk of chronic disease [79]. Rice phenolic compounds, particularly those belonging to the flavonoid subgroup, are secondary metabolites believed to be the protective response of plants to these biotic and abiotic stressors. Flavonoids are the most diverse compounds in the plant kingdom, with a 15-carbon skeleton organised by a 3-carbon chain (C6–C3–C6 structure). Flavonoids are classified into various subclasses, including flavones, flavanols, anthocyanins, and isoflavones. The most abundant flavonoids in rice are flavanols, flavones, flavonols, anthocyanins, and flavanons [86].

4.6.3. Proanthocyanidins and Anthocyanins

Proanthocyanidins and anthocyanins are bioactive compounds found in several rice varieties [87]. These vibrant bioactive pigments are found in the aleurone layer of the rice grain. Pigmented rice has a wide range of colours, owing primarily to the high anthocyanin content of the grain [88]. Numerous pigmented rice varieties have been reported, such as brown, dark brown, red-grain rice, black, and dark purple, the colour determined by the type of pigment used [89].

Proanthocyanidins

Proanthocyanidins are a class of polymeric flavan-3-ol compounds that include afzelechin, catechin, epiafzelechin, gallocatechin, epicatechin and epigallocatechin. The tannins are a group of more complex proanthocyanidins that share this very same polymeric building block. Proanthocyanidins can be classified as A-type or B-type, with flavan-3-ol units doubly linked via C2-O7 and C4-C6 or C2-O7 and C4-C8 for the former primarily via C4-C6 or C4-C8 for the latter. B-type proanthocyanidins are incredibly abundant in nature. Catechin and epicatechin form the proanthocyanidin block unit in red rice. In plants, proanthocyanidins are synthesised via anthocyanidins as critical intermediates. Additionally, these pigmented substances are responsible for rice's red and purple hues [90].

Anthocyanins

Anthocyanins are a class of water-soluble flavonoids found in pigmented rice and other cereal grains [91]. Anthocyanidins, or aglycons, are the basic structural units of anthocyanins. They are composed of an aromatic C6 (A ring) bonded to a heterocyclic C3 (C ring) containing oxygen, which is bonded to a third aromatic C6 (A ring) via a carbon–carbon bond (B ring). When anthocyanidins are glycosidically linked to a sugar moiety, they are referred to as anthocyanins. They are found in plants as mono, di, or tri-glycosides of O-glycosides and acylglycosides of anthocyanidins [92]. Individual anthocyanidins differ in terms of their hydroxyl group count, the type, number, and position of sugars attached to the molecule, and the presence of aliphatic or aromatic acids attached to the sugar molecule. Anthocyanins are composed of the six most abundant anthocyanidins (aglycones), delphinidin, cyanidin, peonidin, petunidin, pelargonidin, and malvidin. Numerous anthocyanins have been isolated and identified from pigmented rice, such as cyaniding 3-galactoside, cyaniding 3-glucoside, malvidin 3-galactoside, cyaniding 3, 5-diglucoside, cyaniding 3-rutinoside, pelargonidin 3, 5-diglucoside, and peonidin 3-glucoside [93]. The primary chemical structures of the significant anthocyanidin Cyanidin-3-O-glucoside have been defined as having a significantly higher concentration in black rice than in other rice varieties [94].

4.7. Volatile Components

The volatile components of rice are of interest for the study of flavour constituents because they travel to the nose during eating and stimulate the olfactory receptors in the nasal cavity [95,96]. As a result, the primary sensory qualities of rice are its flavour volatiles, aroma, and texture [97,98]. Rice volatile materials are considered to fall into various classes, including aldehydes, alcohols, terpenes, benzenoids, and derivatives of amino acids and fatty acids [76]. The major volatile compounds responsible for the aroma of traditional varieties have been identified, including hexanal, octanal, non-anal, (E)-2-octenal, 1-octen-3-ol, guaiacol, and vanillin [99]. Aromatic rice contains a volatile aroma component with a popcorn-like flavour. 2-acetyl-1-pyrroline [100]. Volatiles found in cooked rice include ammonia, hydrogen sulphide, and acetaldehyde. After cooking, all aromatic rice contains the primary aromatic principle of 2-acetyl-1-pyrroline [101].

Hexanal, pentanal, non-anal, 2-heptene aldehyde, heptanal, octanal, benzene formaldehyde, and decyl aldehyde have been found in both indica and japonica [102]. Hexanal was the most abundant aldehyde, accounting for an average of 13.31% of total aldehydes (14.69% for indica and 1.93% for japonica), followed by non-anal at 7.93%. Benzene formaldehyde, decyl aldehyde, hexanal, pentanal, non-anal, and heptanal were detected at relatively high concentrations. Some twenty-three different volatile ketones were identified, with 19 being found in indica rice and 13 in japonica rice [29]. The ketones were significantly less abundant than the aldehydes [103].

Additionally, Lin et al. [104] examined the volatile compounds present in various indica and japonica rice varieties. The most abundant volatile alcohols in indica rice were n-octanol, 2-hexyl-1-octanol, and 3,7,11-trimethyl-1-12 alcohol; n-octanol, 2-hexyl-1-octanol, and 3,7,11-trimethyl-1-12 alcohol were the most abundant volatile alcohols in japonica rice. In other literatures Ashokkumar et al. [76] determined the total phenolic content (TPC) and profiled all the volatile organic compounds (VOCs) in eight popular traditional rice varieties cultivated in South India, namely Seeraga samba, Kaiviral samba, Kichili samba, Mappilai samba, Karuppu kavuni, Kuzhiyadichan, and Kattuyanam, as well as two modern rice varieties such as CO 45 and CR 1009 cultivated in South India. The majority of the predominant components identified were not identical, indicating variation among rice varieties. There were significant differences between rice varieties in terms of total terpenes (12.6 to 30.7%), total aliphatic alcohols (0.8 to 5.9%), total phenols (0.9 to 10.0%), total alkanes (0.5 to 5.1%), total alkenes (1.0 to 4.9%), and total fatty acids (46.9 to 76.2%). Palmitic acid, elaidic acid, linoleic acid, and oleic acid were all found in concentrations ranging from 11.1 to 33.7%, 6.1 to 31.1%, 6.0 to 28.0%, and 0.7 to 15.1%, respectively. Palmitic acid content was higher in modern varieties (26.7 to 33.7%) than in traditional varieties (11.1 to 20.6%). However, all traditional varieties contained a higher percentage of linoleic acid (10.0 to 28.0%) than modern varieties (6.0 to 8.5%). Traditional varieties contained significant amounts of phenolic compounds such as butyric acid, stearic acid, and glycidyl oleate, which were lacking in modern varieties.

5. Nutritional Value of Rice

Rice is regarded as an energising and reviving food, similar to other cereals [105]. While white rice is a significant source of calories, it also contains various essential minerals [1,39,40]. Table 5 shows the chemical composition of white and brown rice. Carbohydrates, mainly starch, account for approximately 80% of the dry matter of the grain, while proteins account for approximately 7%. The amino acid profile of rice reveals a high aspartic acid and glutamic content, with lysine being the limiting amino acid [106]. Brown rice contains polyunsaturated fatty acids such as oleic acid (18:1), linoleic acid (18:2), linolenic acid (18:3), and Eicosenoic (20:1). Polyunsaturated fatty acids can help prevent osteoarthritis, cancer and autoimmune disorders [107]. Additionally, brown rice is higher in dietary fibre, vitamins and minerals, particularly the B group such as Thiamine (B1), Ribofavin (B2), Niacin (B3), Pantothenic acid (B5), Pyridoxine (B6) and Biotin (B7). Another recent finding illustrates that B vitamins' anti-inflammatory properties prevents from tau hyperphosphorylation and cognitive impairment caused by 1,2 diacetyl benzene [108]. The higher fibre content of brown rice compared to the white rice may help with appetite control and weight loss, as well as contribute to the reduction in LDL cholesterol [109].

Table 5. Nutritional composition of rice. Modified from [1,29].

Nutrient	Brown Rice	Milled Rice
Digestible carbohydrates	84.8–88.2	89.1–91.2
Crude protein	6.5–10.0	7.3–8.3
Crude ash	1.2–1.7	0.3–0.9
Crude fat	1.9–3.9	0.3–0.65
Crude fibre	1.6-2.8	0.3-0.5
Carbohydrates	85.2–88.9	91.07
Water (% of fresh weight)	11.37–16.4	12.31–15.5
Starch	77.2	90.2
Free sugars	0.8–1.5	0.3–0.5
Neutral detergent fibre	4.5	0.8–2.7
Dietary fibre/insoluble		0.5
Total dietary fibre	3.9	0.5–2.8
Crude fibre	0.7–1.2	0.2–0.6
Hemicelluloses		0.1
Pentosans	1.4–2.4	0.6–1.6
Lignin		0.1
Energy (kJ/g)	17.2–18.7	17.0–18.1

Table 5. *Cont.*

Nutrient	Brown Rice	Milled Rice
Protein fraction (% of total protein)		
Albumin (soluble in water)		2–5
Glutelin (soluble in aqueous alkaline solution)		60–65
Prolamin (soluble in alcohol)		20–25
Globulin (soluble in salt water)		2–10
Amino acid composition (% of dry matter)		
Aspartic acid		0.59–0.96
Arginine		0.52–0.88
Alanine		0.37–0.59
Cystine		0.15–0.28
Histidine		0.16–0.27
Glycine		0.32–0.48
Glutamic acid		1.06–1.88
Isoleucine		0.22–0.40
Leucine		0.51–0.85
Lysine		0.26–0.40
Methionine		0.14–0.34
Phenylalanine		0.32–0.55
Threonine		0.23–0.38
Proline		0.25–0.46
Serine		0.30–0.53
Tyrosine		0.21–0.51
Tryptophan		0.05–0.13
Valine		0.37–0.59
Fatty acid component (% of total fatty acids)		
Myristic (14:0)		0.5–1.1
Pentadecanoic (15:0)		0.1–0.3
Palmitic (16:0)		18.2–31.2
Palmitoleic (16:1)		0.1–0.2
Heptadecanoic (17:0)		0.1–0.6
Stearic (18:0)	1.5–2.8	
Oleic (18:1)	30.9–40.2	
Linoleic (18:2)	26.1–39.0	
Linolenic (18:3)	0.9–1.6	
Arachidic (20:0)	0.4–0.7	
Eicosenoic (20:1)	0.4–0.6	
Behenic (22:0)	0.2–0.6	
Docosenoic/erucic (22:1)	0.1–0.2	
Tetracosenoic (24:1)	0.1–0.3	
Lignoceric (24:0)	0.4–0.9	
Others	4	
Macro-minerals (mg/g dry matter)		
Calcium	0.1–0.6	0.1–0.3
Magnesium	0.2–1.7	0.2–0.6
Potassium	0.7–3.2	0.8–1.5
Phosphorus	2.0–5.0	0.9–1.7
Sulphur	0.3–2.2	0.9
Silicon	0.7–1.6	0.1–0.5
Micro-minerals (μg/g dry matter)		
Copper	1–7	2–3
Iron	2–60	2–33

Table 5. *Cont.*

Nutrient	Brown Rice	Milled Rice
Manganese	2–42.24	7–20
Sodium	20–395	6–100
Zinc	7–33	7–27
Vitamin (μg/g dry matter)		
Retinol (A)	0–0.13	0-trace
Thiamine (B1)	3.4–8.1	0.2–1.3
Ribofavin (B2)	0.2–1.6	0.2–0.7
Niacin (B3)	41–134.7	15–28
Pantothenic acid (B5)	11–17	4.8
Pyridoxine (B6)	1.8–11	0.5–1.4
Biotin (B7)	0.05–0.12	0.01–0.07
Choline, total	1100	450–1020
Folic acid (B9)	0.1–0.6	0.03–0.16
Cyanocobalamin (B12)	0–0.005	0–0.0016
Alpha-tocopherol (E)	8.9–29	Trace-3
Beta-tocopherol	0.5–1.4	
Delta-tocopherol	0.1–0.6	
Gamma-tocopherol	2.2–4.8	

The reduction in the nutritional components including antioxidant activity, dietary fibre, and other chemical components were found after various milling processes [110]. According to Paul et al. [111], the degree of rice milling has an effect on the loss of zinc content as well as lower the yield of head rice. Kim et al. [112] suggested that as the degree of rice milling increased, the phenolic contents in organic, the fatty acid, pesticide-free grains Vitamin E homolog, and conventional rice grains decreased significantly. 2,2-diphenyl-1-picrylhydrazyl demonstrated a significant reduction in radical scavenging activity as a function of degree of milling. Another recent study found that the microstructures of cooked rice were altered by the degree of milling, which in turn affected the starch digestibility of cooked rice in vitro [113].

A diet high in wholegrain cereals, such as rice, is healthier than one high in refined cereals [114]. Consumption of whole grains has been shown in recent epidemiological studies to reduce obesity and the risk of metabolic disorders, particularly Type 2 diabetes mellitus [115], cardiovascular disease [116], and certain types of cancer [117].

6. Rice Processing

After harvesting and processing, rice can be classified as either white or brown, depending on the milling characteristics obtained [118]. As aforementioned, the paddy is composed of three layers: the husk on the outside, rice bran in the annular portion, and white rice in the centre [119]. Although there are a wide variety of rice processing methods available, each of which produces a different rice quality, it has been observed that the fundamentals of rice production remain the same [120,121]. Rice processing entails a series of steps that must be completed correctly, using various methods and equipment [122]. Figure 5 depicts the general steps of paddy drying, paddy cleaning, paddy destoning, husk separation, paddy separation, whitening, grading, packing, and storage in the rice milling process.

6.1. Storage of Paddy

There are several aspects that affect rice grain storage strategies: (a) oxygen, temperature, moisture content as well as relative humidity of the storage condition; (b) must be protected from insect such as *Sitophilus oryzae* (Rice weevil) and rats/mice activity, as well as mould growth; (c) socioeconomic factors such as farmers' family size, grain storage duration, route efficiency, grain market price, off-farm income, and grain safety during storage all need to be considered [123]. Traditional methods of preserving and storing rice grains include the use of Silo, Nahu, Camphor, Dole, Motka, jute bags, Obeh and polypropylene bag [124]. The new method of storing rice grain, which includes hermetic bags such as the GrainPro, AgroZ, and Purdue Improved Crop Storage (PICS), have been reported [125–127]. The interest of farmers in hermetic bags has been sparked by the aim to cut rice grain storage losses due to insect pests and the difficulties (inefficacy) associated with current storage methods [128,129]. The hermetic bag is made of plastic, which has a low permeability to O_2, CO_2 and other atmospheric gases. Inside the hermetic bag, respiration by grain, insects, and fungi leads to a reduction in oxygen and an increment in carbon dioxide [130]. Fungal and insect growth become hampered in a short period of time. Kanta (2016) studied the use of GrainPro bag for paddy storage. Due to the hermetic nature of the GrainPro bag, the moisture content of stored paddy remained nearly unchanged. Owing to the absence of insect attack and the high moisture content of the GrainPro bag containing seeds, the germination rate was enhanced.

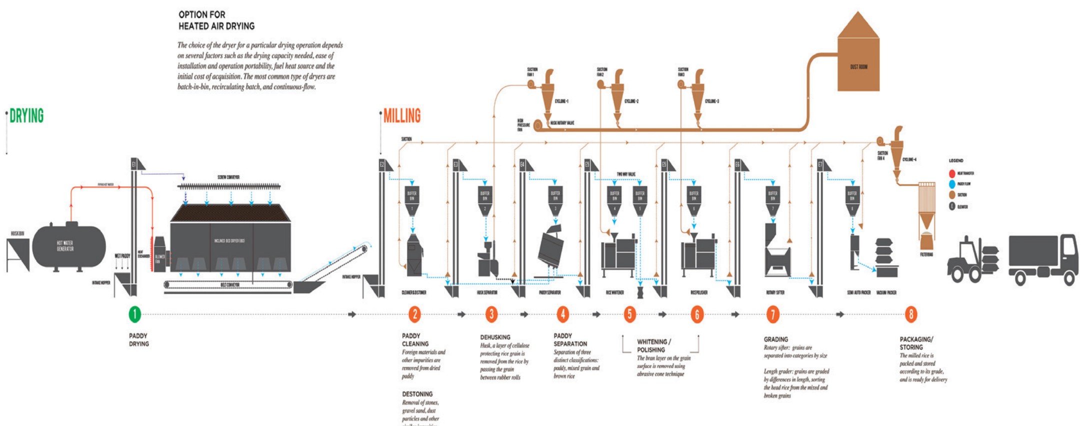

Figure 5. Rice milling process of rice [21].

6.2. Paddy Drying

Drying and storage techniques are critical components of post-harvest technology for improving paddy quality and reducing paddy loss, thereby facilitating nations in achieving socioeconomic empowerment and food security [131–133]. Oikeh et al. [134] reported the conventional paddy drying process in rice milling. Paddy is automatically conveyed into the dryer via a belt conveyor. The paddy is recirculated, and cross-flow hot air passes through the drier. A heat exchanger is used to heat the ambient air. The most suitable dryer for a particular drying operation is determined by several factors, including the required drying capacity, ease of installation and operation, fuel heat cost, and initial acquisition cost. The most common types are batch-in-bin, recirculating batch, and continuous-flow dyers.

To date, numerous cost-effective drying techniques have been developed, including solar, infrared, convective, desiccant, fluidised, and spouted bed dryers [135]. Solar dryers appear to be a promising alternative for small farmers, due to low energy consumption, as well as reasonable investment and operating costs when compared to commercial dryers that heat the air with petrol fuels [136]. The infrared drying is believed to extend the shelf life of brown and white rice by inactivating the lipase enzyme and thus minimising lipid oxidation by using infrared heating. High drying rates, good milling quality, effective disinfestation and disinfection of rough rice, an increase in shelf life rice and improved storage stability of rice bran were achieved through infrared drying [137]. A modified convective dryer incorporating ultrasound intervention resulted in a significant reduction in niacin and TPC losses over a shorter drying time [138]. A comparison of fluidised bed and spouted bed drying for seeds revealed that a fluidised bed dryer had a faster drying rate, whereas a spouted bed dryer was superior in terms of lower specific energy consumption [139]. A hybrid drying system combining a heat pump dryer and a fluidised bed dryer resulted in a significant increase in head rice yield and a decrease in the number of fissured grains [140].

6.3. Cleaning and Destoning

When paddy enters the mill, it may be contaminated with foreign materials such as weed seeds, straw and soil. If these items are not removed prior to hulling, the huller's efficiency and milling recovery will be reduced [141]. The pre-cleaning procedure is divided into two stages: cleaning and de-stoning. The paddy cleaner is the most critical piece of equipment in a rice mill because it removes all impurities such as clay, straw, dust, sand, and large particles of any size from the paddy [142]. Cleaning removes foreign materials from the paddy, such as sand, stones, straw, and seeds. The input paddy is highly impure. These impurities are removed before entering the soaking chamber using a two-stage sieve and air blasting. The first stage involves the removal of light impurities such as chaff and dust. Heavier impurities such as stone and brick are removed [143]. Adetola and Akindahunsi [144] reported the performance of rice de-stoning machines. The de-stoning efficiency ranged from 40.8 to 99.75%, the capacity ranged from 1.8 to 7500 kg/h, and the operating speed ranged from 200 to 2980 rpm.

6.4. Dehusking and Separation of Husk

The husks, brown rice, and unhusked rice were separated using a tray-type paddy separator. The paddy separator separates it from the brown rice by dehusking the paddy [145]. Rice dehusking is the process of removing the husk and bran from paddy rice to produce head-sized white rice grains that are sufficiently milled, impurity free, and contain as few broken grains as possible [146]. It is the process of removing the husk from the paddy and then separating the husk from the paddy with the least amount of damage to the grain. Husking is carried out with the aid of a rubber-roll huller. The rice is then reintroduced unhusked to the huller [147].

6.5. Whitening and Polishing

White rice results from rice milling process by machines that involve removing of husk and bran layers. Abrasion and friction are the two processes used to remove the bran from the grain. This abrasion removes the bran layers, exposing the rice to be white or polished [41,148]. On the other hand, polishing refers to removing small bran particles that adhere to the rice surface following whitening and imparting a shiny appearance to the rice grains. Brown rice is polished using an abrasive polisher [118,134]. A novel rice whitening method uses enzymes such as xylanase and cellulase to degrade the rice grain's surface structure [149]. According to Xu et al. [150], the rate and duration of rice polishing affected the rice's physicochemical and rheological properties. Compared to unpolished rice starches, the swelling power and solubility index of low- and high-amylose rice starches elevated with milling speed and duration.

6.6. Rice Grading

The process of classifying and grading rice is vital in determining the quality of the rice and the subsequent market price [151]. When determining rice grades, two critical factors must be considered: (a) the grading technique and (b) the grading determinants used [152]. Numerous advanced approaches have been used to ascertain the characteristics of rice for grading [153–155]. These include image processing in conjunction with support vector machines [156], neural networks [153], wavelet packets [157], contact angle analysis (for separating contacting rice grains), image processing in conjunction with an adaptive network-based fuzzy inference system (ANFIS) [158], a multi-threshold method based on maximum entropy (chalkiness) [159], image processing in conjunction with computer vision and a minimum rectangle (MER) (length and width) [160], and image processing in conjunction with neural networks [161]. Another recent study discovered that MATLAB's Image Processing Toolbox can be used to grade rice grains, as it aids in extracting the grains' morphological characteristics [155].

7. Environmental Impacts of Rice Cultivation

According to FAOSTAT [162], the total emissions (CO_{2eq}) including CO_2, methane, nitrous oxide and other anthropogenic greenhouse emissions from rice cultivation were 674,367.27 kilotonnes (kt) (AR5) in 2019, compared to 620,852.75 kt in 1990 (Figure 6). For almost two decades, it has been an increase of approximately 8%. Figure 7 shows the total emissions caused by rice cultivation on earth from 1990 to 2019. Figure 8 depicts the top 10 emitters (emissions CO_{2eq} (AR5)) from rice cultivation (average 1990 to 2019). China is the world's largest emitter at 148,343.14 kt, followed by India at 128,314.06 kt, Indonesia at 67,670.17 kt, Thailand at 45,545.03 kt, the Philippines at 38,694.92 kt, Vietnam at 36,084.7 kt, Bangladesh at 30,034.81 kt, and Myanmar at 28,837.39 kt, the United States of America at 11,803.87 kt, and Cambodia at 10,310.73 kt of total emissions (CO_{eq}), respectively. Asia accounts for the largest share of global emissions (CO_{2eq} (AR5)) caused by rice cultivation, accounting for 88.9% of total emissions.

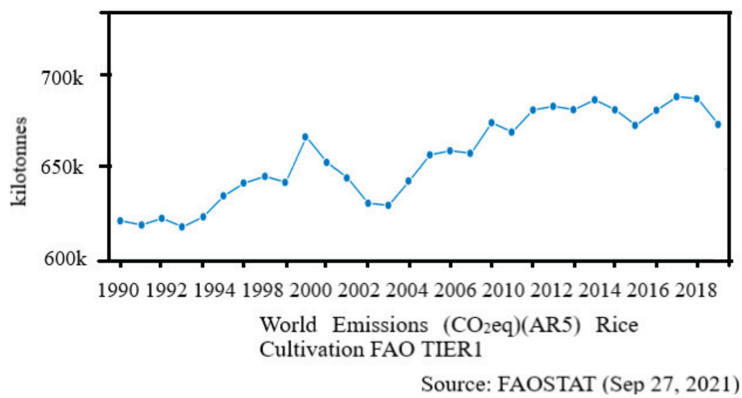

Figure 6. Total emissions from rice cultivation on a global scale (1990–2019) [162].

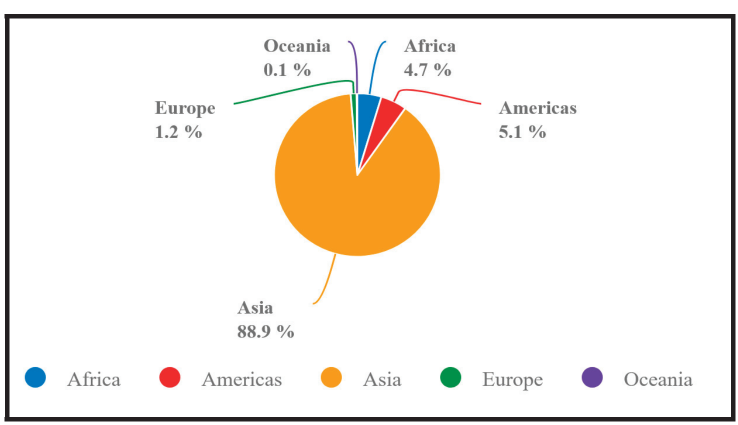

Figure 7. Share of emissions (CO_2eq (AR5)) by continent, rice cultivation in 2019 [162].

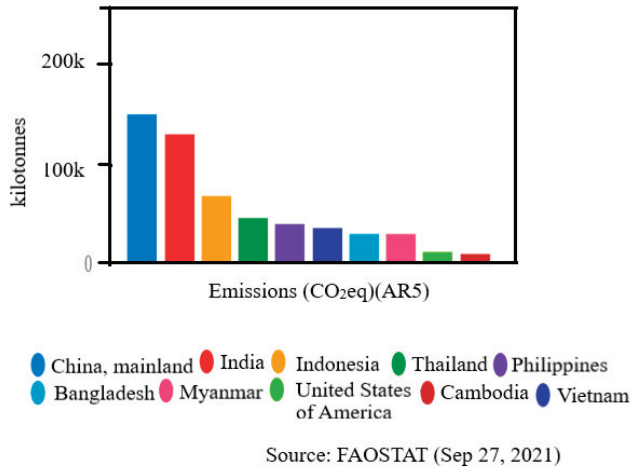

Figure 8. Top 10 emitters (emissions CO_2eq (AR5)) from rice cultivation (average 1990–2019) [162].

Methane is among the most significant greenhouse gases after CO_2, accounting for approximately 15 to 20% of global warming. Globally, rice cultivation is one of the largest sources of agricultural methane emissions [163]. Flooded rice fields contribute significantly to methane emissions, which account for 48% of agricultural greenhouse gas emissions [164,165]. Methane emission from paddy is primarily influenced by water management practices and soil conditions [166]. The water from flooded rice restricts oxygen from permeating the soil, creating ideal conditions for bacteria that emit methane. The longer flooding persists, the greater the accumulation of methanogenic bacteria. The methane emission is the net result of two contrasting bacterial processes, production in anaerobic microenvironments and consumption and oxidation in aerobic microenvironments, which occur simultaneously in flooded rice soils [167]. Alternate wetting and drying (AWD) have been identified as one of the most promising techniques for reducing methane emissions from rice cultivation. Using the methodologies outlined by the Intergovernmental Panel on Climate Change, the AWD scenario could reduce annual methane emissions by 32% compared to the continuously flooded scenario [168]. Other strategies for reducing methane emissions from paddy rice fields include the addition of sulphates and the preference of rice varieties [169].

Climate change is expected to affect rice production and trade. Koizumi et al. [170] established Rice Economy Climate Change (RECC) model to account for the effects of climate change on rice production in 24 countries. Climate change is expected to affect japonica and indica rice, based on RECC baseline projections and scenario simulations. In particular, the international price of japonica rice is expected to be more volatile compared to the price of indica rice. Additionally, Firdaus et al. [171] investigated the effects of climate change, focusing on Malaysia. The analysis demonstrated that the minimum (Tmin) and maximum (Tmax) temperatures in the granary areas increased by 0.3 °C to 0.5 °C and 0.2 °C to 0.3 °C, respectively, in each decade, using Mann–Kendall and Sen's slope. Simultaneously, precipitation has increased, ranging from 133 mm to 200 mm. The findings indicated that climate change poses a significant threat to paddy production, which will eventually affect food security, same as reported by other literatures [172–175].

In rice milling, rice husk is an abundant agricultural waste in rice production [176–179]. When rice husk ash is dumped directly into the environment, it contributes significantly to water and land pollution [180], resulting in various health problems [120]. Environmental pollution has been linked to rice milling factors producing large amounts of effluent high in nutrients, solid wastes, and organic matter [181,182]. According to Kumar et al. [183], rice mill effluent contains a sufficient amount of pesticides and nutrients to result in groundwater pollution and eutrophication.

8. Challenges to Overcoming Barriers and Current Policy Directions

According to FAO [184], 45 countries, 34 of which are in Africa, continue to require food aid from outside sources. The COVID-19 pandemic's impact, mainly in terms of income losses, is a significant driver of global food insecurity, worsening and exacerbating already uncertain conditions. Conflicts, weather events, and pests continue to be major contributors to the high levels of intense food insecurity [185,186]. Table 6 shows the challenges to the sustainability of the food production system, with a focus on rice production, as well as strategies for overcoming those challenges.

Table 6. Challenges to the sustainability of the rice production system and suggested proposed solutions [187,188].

Challenges to the sustainability of the rice production system
• Increasing food prices • Depletion of the soil's nutrient pool • Degradation of soil health • Decline in soil structure • Depletion of ground water supplies • Rising production costs • Labour deficit • Burning of crop waste • Greenhouse gas emissions • Climate change vulnerability • Resistance to herbicides in weeds • Crop reaction to applied fertilisers has decreased. • A diverse weed flora • Increasing labour cost • Issues with residue management • Abiotic stresses such as drought, salinity, flood, storm, and very low and high temperatures • Rice grain quality
How can we overcome the challenges?
• Agricultural diversification • Conservation agriculture • Direct seeded rice • Dry-wet method of irrigation in rice • Furrow irrigated raised bed (FIRB) system of planting • Automated irrigation systems • Early sowing of zero-till wheat • Sustainable residue/waste management practices • Precision nutrient management • Short or medium season rice varieties • Success in capacity building of the stakeholders • Integrated weed management with herbicide rotation

Table 7 summaries current government policies designed to increase rice production and quality by global rice producers. In terms of Malaysia, Che Omar et al. [189] stated that in the future, agricultural policies relating to food in Malaysia should no longer be driven solely by production targets. The recommendations include giving farmers and farm-related organisations equal credit for adopting Malaysia's Good Agricultural Practices (MyGAP), efficient water use, and soil management in order to increase paddy production. At the midstream level, it is advised to recognise stakeholders who follow Good Manufacturing Practices (GMPs), conduct Hazard Analysis Critical Control Point (HACCP) analyses, and promote manufacturing and marketing transparency, such as the use of Blockchain technology.

Table 7. Current policies development [190].

Countries	Date	Policy Instrument	Summary
China (Mainland)	5.2021	Stock release	After auctioning 1.81 million tonnes of paddy on 14 May 2021, 155,007 tonnes of paddy harvested from state reserves were sold.
India	5.2021	Export promotion, trade facilitation	Rice shipments were inaugurated through the Odisha state's Paradip International Cargo Terminal (PICT).
Mali	4.2021	Price controls	Set a ceiling of XOF 340 (USD 0.63) per kg on market prices of non-fragrant broken rice. A limit of XOF 290,000 (USD 537) for each tonne would implement
Turkey	4.2021	Government procurement, purchasing prices	Government purchase prices have been revised for the 2020 season, increasing them from TRY 3500 to 4750 for each tonne.
Bangladesh	3.2021	Import tariff	Imported non-parboiled (white, non-fragrant) rice duties and charges reduced from 62.5% to 25%
European Union	3.2021	Import tariff	Reduced tariffs on imported non-basmati husked rice from EUR 65 to EUR 30 per tonne outside of current trade agreements.
Malaysia	12.2020	Import rights	Renewed Padiberas Nasional Berhad's (BERNAS) exclusive import rights for another ten years, beginning in January 2021.

Note: A complete set of rice policy, beginning in January 2011 is available at: https://www.fao.org/economic/est/est%20commodities/commodity%20policy%20archive/en/?groupANDcommodity=rice (accessed on 20 December 2021).

9. Conclusions

Although the COVID-19 pandemic and some natural disasters, such as floods, have posed numerous challenges to global rice production, 513.7 Mt of milled rice have been produced worldwide in 2020. Rice is such a vital crop that it is a source of high-energy or high-calorie foods with a high nutritional value. Starch accounts for approximately 90% of the dry weight in milled rice, along with lipid, protein, non-starch polysaccharide and numerous volatile components. Furthermore, rice contains phenolic compounds that have anti-inflammatory, anticancer, and anti-diabetic properties. It contributes significantly to health benefits and disease prevention for humankind.

The rice milling process includes the process of paddy drying, paddy cleaning, paddy destoning, husk separation, paddy separation, whitening, grading, packing, and storage. In order to ensure food security, a substantial persistent quality improvement has been made in the rice's quality, post-harvest handling, and the milling process. In 2019, global emissions due to rice cultivation were 674,367.27 kt (CO_{2eq} (AR5). For almost two decades, there has been an increase of approximately 8%. Asia accounts for the most significant global emissions (CO_{2eq} (AR5)), accounting for 88.9%.

The rise in the global population and the effects of climate change in the region influence the need to boost rice production and improve its quality. The recent food crisis has also spurred a revisiting of self-sufficiency goals of rice. For sustainability of agriculture, rice-producing countries have created rice policies that emphasise productivity and quality growth to ensure adequate food supplies for the people.

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Article

The Analysis of Trade Liberalization and Nutrition Intake for Improving Food Security across Districts in Indonesia

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Abstract: The debate on the effect of trade liberalization on food security poses solid arguments, both in favor as well as against the issue. This study aims to analyze the linkages between trade liberalization (measured using food import tariff exposure) and food security (measured using nutrition intake) in the case of Indonesia. The national food import tariff is decomposed into district-level import tariff exposure and is analyzed based on sectoral tariffs such as agriculture tariffs and food manufacture import tariffs. The analysis employs panel data of 496 Indonesian districts and postulates an association between trade and food security by using fixed-effect regression. By analyzing the effects of tariff exposure towards food consumption in all districts and grouping the districts into 5 (five) islands, we can contribute to the literature on trade liberalization and food security. First, it is found that import tariff exposure is negatively impacting nutrition intake and each sector has a different effect on each nutrition intake. Furthermore, the impact of manufacturing tariffs on calorie and protein intake is slightly higher than that of agriculture tariffs. Second, it is shown that both sectoral import tariffs' effects vary across islands in Indonesia. Furthermore, the research is expected to contribute to and become a reference for the government in regulating tariffs and other trade liberalization schemes to support households to be food secure.

Keywords: import tariff; tariff exposure; food security; nutrition intake

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1. Introduction

Although global population growth and food growth are almost equal, the disproportion between regions with high food production and population distribution has caused an imbalance in access to nutrition. For instance, the share of people residing in industrial countries is less than that of those who live in lower-income countries, and populations living in the latter may be unable to share in the abundance of food because of their lack of purchasing power. Accordingly, it is projected that the world population will increase three times in 2050, which means more food demand will arise. It is stated that human numbers are increasing and food supply is also increasing; however, it is unclear whether food production can keep up with the pace of population growth [1].

In the era of globalization, providing and supplying adequate food and nutritious food to the household level is challenging for a country. The definition of food security according to the Food and Agriculture Organization (FAO) is "All people at all times have both physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preference for their active and healthy life". It is a measure of the availability of food and individuals' accessibility to food, where accessibility includes affordability. Based on the FAO definition of food security, there are four dimensions of food security such as food availability (on farms and markets), accessibility (by all households), utilization (function of food safety, nutritional status, and health), and food stability.

In developing countries, food insecurity and malnutrition have become a challenge in which a lot of people still suffer from this condition [2]. Thus, food security is not only a matter of individuals and households, but it is also important at the national level, where the government holds the responsibility of fulfilling the food needed at a reasonable price. It is also believed that trade can become an important element in achieving food security in which food trade and trade policy may encourage people, either producers or consumers, to utilize the available resource economically [3]. Therefore, trade can potentially bridge this mismatch and impact a country's development process, either directly or indirectly, at the macro and micro levels.

There are two basic reasons why countries engage in trade: first, countries benefit from their mutual differences, either geographically or with regard to their economic resources; and second, they want to achieve economic scale in production. Ricardian's model, which is the theory of comparative advantage, explains the gains arising from international trade, driven by the differences in each country's productivity and opportunity cost [4].

Trade liberalization enables countries to produce more goods and services because they have a comparative advantage. Moreover, trade improves countries' access to larger markets and, subsequently, improves their capacity to specialize in their production. There are two categories of countries that benefit from trade openness: first, countries where the poor constitute the majority net buyer of food and food imports are restricted; and second, countries where the poor constitute the net seller, while food exports are restricted [5].

The effect of trade on food security is still debatable. Many studies on trade have focused more on its relationship with growth, inequality, and poverty [6–8]; only several studies relate trade impacts to food security [9–11]. Yet, the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) have emphasized the association between both poverty and food security with nutrition security [12], and trade has been highlighted as a critical macroeconomic driver that must be considered in improving diets, nutrition, and chronic disease prevention. In particular, trade liberalization has been found to increase economic activity and reduce poverty [13].

Nonetheless, the effect of trade on food security, to some extent, has drawn many researchers' attention [14–16]. For instance, research on the effect of import bans on households as consumers was done [17] in which import restrictions measured through tariffs resulted in price increases. The results showed that the poorest households will bear the burden of import reduction policies because they are net food buyers who typically spend a large proportion of their budget on basic food consumption [17]. On one hand, a prior study found that trade liberalization positively contributes to food security and the stability of food supply in Bangladesh [18].

With ever-increasing globalization, ensuring adequate availability and supply of food and nutrition at the household level is a major challenge for countries to overcome. In identifying the core reasons why food consumption is characterized by malnutrition [19], it is reported that households simply lack income sources to afford sufficient food. Thus, increases in food prices harm poor consumers due to the high proportion of their budget spent on food, and rising prices thereby result in rising poverty. Food security is closely related to consumption and consequently, to household poverty. Hence, any resources that have the potential to raise household income and benefit the poor would enhance food security and thereby, nutrition.

Therefore, trade not only improves household access to food by way of increasing their income but also enhances food availability by ensuring affordable prices. Reduced tariffs can boost the global food trade, subsequently increasing the quantity of food available. On the other hand, it is argued that it might also adversely affect domestic production because importing countries may be vulnerable to the volatility of global prices and supply [11]. The study is about the effect of trade on food security in China, which finds that international trade increases China's dependence on food imports and negatively affects the country's food security. Another study [20]—an empirical examination of the effect of trade liberalization on food availability in 37 developing countries using dietary energy supply (DES) per capita as a measure of food security—also finds that trade liberalization exerts a negative influence on food security in the short run.

These mixed findings indicate that there still remains the empirical question of whether trade liberalization has a positive or negative effect on the dimension of food security and through what channels do those trade impacts travel to affect food security. In this study, the relationship between those two factors—tariffs and food security—will be explored by analyzing the effects of tariffs on food nutrition (calorie and protein) intake. We examine the effects at a regional level in Indonesia to obtain a richer picture of the dynamics in each district, as the variation in geographical and cultural characteristics at the sub-national level may contribute to different concentrations of effects in particular areas.

The rest of the paper is organized as follows. The next section covers the theoretical background, followed by Section 3, which presents the methodology used in this study. Section 4 presents the results and discussion, and the last section concludes the paper.

2. Theoretical Background

2.1. Overview of Indonesia's Trade Liberalization and Food Security

Nowadays, trade policy among countries has been governed by the General Agreement on Tariffs and Trade (GATT)—an international treaty—for almost 70 years. Since 1994, the World Trade Organization (WTO) has enforced international trade rules, through which it can tell the country if its policies have violated the agreements [4]. Nonetheless, each country has its own unique shape of policy intervention regarding trade and food security.

Globally, the number of people that suffer from being undernourished is increasing, which is revealed in the world prevalence of undernourishment (PoU) index. Specifically the PoU index of Indonesia is slightly increase from 6.4% in 2018 to 6.5% in 2019 (see Figure 1). This means that more people around the world are unlikely to have enough food that meets the dietary requirement. In Indonesia, the prevalence of people who suffer from insufficient food consumption has slightly increased from 8.32% to 8.34% from 2017 to 2020 (it is based on BPS data).

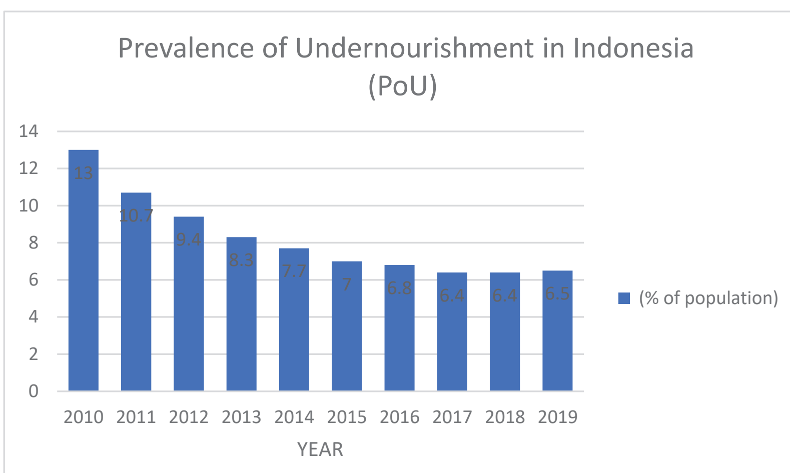

Figure 1. The PoU index of Indonesia from 2010-2019. Source: authors modified the chart from World Bank Data 2022. (https://data.worldbank.org/indicator/SN.ITK.DEFC.ZS?locations=ID, accessed on 6 March 2022).

Food and nutrition security policies in Indonesia are influenced by regional and international commitments and initiatives such as the Millennium Development Goals

(MDGs), the Association of South-East Asian Nations (ASEAN) Integrated Food Security Framework, the ASEAN Plus Three Emergency Rice Reserve, the Zero Hunger Challenge, and Scaling-Up Nutrition (SUN).

In addition, based on the global food security index (GFSI)-the index measures food security across most of the countries in the world- data shown in Figure 2, the index of GFSI Indonesia is fluctuating in an increasing trend. It represents the overall national food security index in which the rate is actually varied across regions based on the geographical circumstances, wealth and natural resources of the region.

Figure 2. GFSI of Indonesia 2012–2020. Source: The Economist Intelligence Units, Databox. (https://databoks.katadata.co.id/datapublish/2021/02/26/ketahanan-pangan-indonesia-menurun-pada-2020, accessed on 12 February 2022).

Thus, in general, the food security index reveals an increasing trend; however, there are some regions where the overall food intake is still below the national threshold of food dietary needs. It is estimated that 38% of Indonesians cannot afford food that meets the dietary needs as suggested in the nutrient guideline. Based on the data of Statistics Indonesia, the poor are more likely to live in the eastern part of Indonesia; for instance, the highest poverty rate is found in Papua and West Papua which accounted for 26.64% and 21.37%, respectively [21]. Accordingly, Indonesia not only needs to increase consumption but also the variety of nutritious food intake.

Indonesia has participated in multilateral and regional trade agreements. The transformation of Indonesia's trade policy has fallen into five phases [22]. First, the era when trade was controlled through import bans, quotas, and tariffs, which ended when trade began to be normalized; second, the era when the oil boom induced the government to implement import substitution policies and move away from its dependence on oil exports; third, the era when the government adopted an aggressive export diversification strategy, which coincided with the establishment of the ASEAN Free Trade Area and the formation of the World Trade Organization (WTO); fourth, the era characterized by the domination of IMF program along with a removal of all import restrictions, the reductions of tariffs and importing of agricultural products, in addition to changes in major institutional mechanisms, the establishment of Bulog (The National Logistic Agency) and the initiation of the ASEAN Economic Community (AEC) and Free Trade Agreement (FTA); and fifth, the current era, in which trade policy has been simplified by reducing trade restrictions and improving transparency.

In addition to trade openness in Indonesia as a percentage of GDP, the trend can be seen in Figure 3, which shows a fluctuation from 2010 to 2020.

Figure 3. Trade openness of Indonesia (2010–2020). Source: authors modified the chart from the world bank data on World Bank Group, 2022. (https://data.worldbank.org/indicator/NE.TRD.GNFS.ZS?end=2020&locations=ID&start=2010, Indonesia's trade percentage of GDP, accessed on 12 February 2022).

2.2. The Link between Trade and Food Security

There are certain pathways through which households experience the effect of trade, with varying impacts on different dimensions of food security such as food availability, accessibility, and utilization. In order to simplify the complexity of the food security concept, we follow the concept developed in previous research [23] and focus only on the three dimensions of aggregate food availability, household food accessibility and individual-level food intake.

International trade can impact the accessibility of food through lower food prices and greater household incomes because international trade may enhance economic growth and stimulate household incomes. Thus, trade can create employment, resulting in an increase in individual earnings, thereby enabling them to buy more food, in terms of quantity and diversity. Further, food access emphasizes the adequacy of household incomes to obtain a variety of food for household consumption. Food intake determines the nutritional status of an individual, which is influenced by household income to afford an adequate supply of food [24].

Next, international trade can be measured in terms of trade liberalization and trade openness, e.g. tariff rate and trade openness index [25]. Both measurements reflect similar characteristics of trade; however, trade openness measures the size of an economy's tradeable sector, while tariff rates are used to measure policies that reduce trade openness. Trade protections can also occur as non-tariff barriers, which include protections such as quota restrictions and labeling, and while measuring trade liberalization requires consideration of both tariff rates and non-tariff barriers, the difficulty in collecting and recording data on non-tariff barriers creates challenges in quantifying non-tariff barriers [16].

3. Material and Method

3.1. Model and Estimation Strategy

Referring to the baseline model developed in the previous studies [2,14,20] we specified the empirical model to estimate the relation between trade liberalization and food security. Thus, it is assumed that food security is a function of trade liberalization and other inputs such as social and economic factors.

Accordingly, we assumed that food security could be approximated by the following production function.

FS = f (TLIB, X)

FS = f (AGRI,MANUF,ECON,SOC)

FS denotes food security and TLIB denotes trade liberalization measurement, X denotes the other variables that may affect food security. Meanwhile, trade liberalization is proxy with de jure measurement which is import tariffs, split into two sectoral exposure such as AGRI for the agriculture sector and MANUF for the food manufacturing sector; FS is measured in food nutrition intake per capita calorie and protein; ECON is for the economic variables and SOC is for the social variables.

The study follows the research framework shown in Figure 4 below:

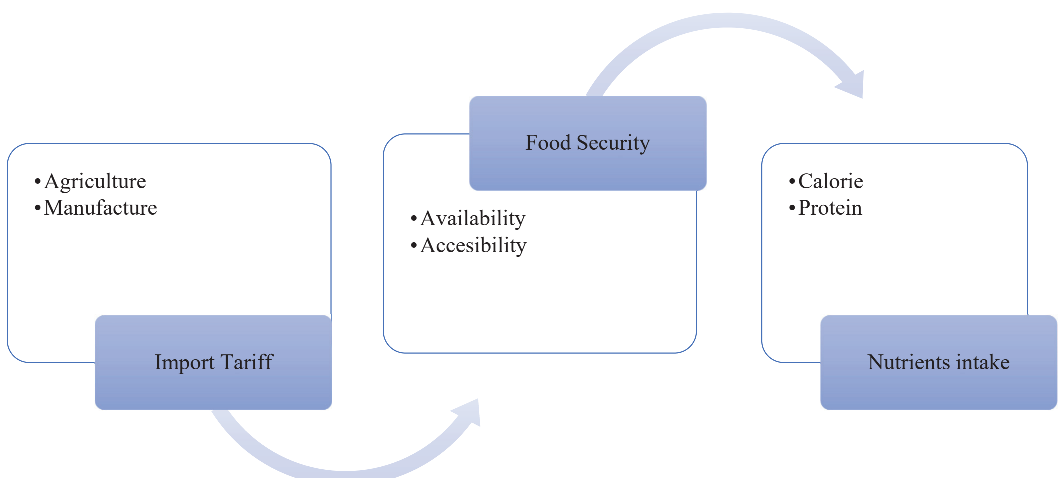

Figure 4. Research Framework. Source: authors.

We estimate the effect of trade on food security using energy intake and protein intake as a proxy for food security because food consumption is a key component in reducing food insecurity; it is determined by food availability and accessibility among the people in each district and is measured by daily per capita intake. Trade is measured by sectoral tariff exposure across districts in which the estimation is applied to all sample districts and differentiates between the districts in and outside Java and Bali.

Hence, we specified the model estimation to analyze the impact of trade liberalization on food security into several regression equations that are varied based on food security measurement such as calorie and protein per capita intake Further, based on the analysis of existing literature and to fulfill the purpose of this study, an empirical model using panel data fixed-effect regressions was constructed to determine the effect of trade liberalization on food security.

The model is as follows:

$$\mathrm{FS_{it}} = \alpha + \beta_1 \mathrm{TRAGF_{it}} + \varepsilon_{it} \quad (1)$$

$$\mathrm{FS_{it}} = \eta + \tau_1 \mathrm{TRMF_{it}} + \varepsilon_{it} \quad (2)$$

$$\mathrm{FS_{it}} = \lambda + \rho_1 \mathrm{TRAGF_{it}} + \rho_2 \mathrm{TRMF_{it}} + \varepsilon_{it} \quad (3)$$

$$\mathrm{FS_{it}} = \theta + \delta_1 \mathrm{TRAGF_{it}} + \delta_2 \mathrm{TRMF_{it}} + \sum_{k=3}^{K} \delta_k X_{3,\mathrm{it}} + \varepsilon_{it} \quad (4)$$

Because the study aims to examine trade liberalization across Indonesia at the district level, the model examines each individual district i in time period *t*. FS denotes food security, which is measured by calorie and protein intake. Tariffs are differentiated between agriculture tariffs (TRAGF) and food manufacturing tariffs (TRMF). Tariff that is used in this estimation is simple average tariff, in which we choose the all-duty codes tariff. Index X refers to the set of control variables that may influence food security; the selected control variables include for instance GRDP per capita, agriculture population density, household average size, women's education. These can be categorized into two groups:

1. Economic variables: GRDP per capita, poverty, household employment share, income share.
2. Social variables: Agriculture population density, aggregate household size, education.

The estimation method is developed further by adding interaction variables (INT) in the control variables that interacting tariffs with the share of household employment in agriculture (SA) and in manufacturing (SM), and the share of household income based on their field of employment, where income from employment in agriculture is denoted ISA and income from manufacturing is denoted ISM. The developed model is as follows:

$$\begin{aligned}\mathrm{FS_{it}} = \omega + \quad & \vartheta_1 \mathrm{TRAGF_{it}} + \vartheta_2 \mathrm{TRMF_{it}} \\ & + \vartheta_3 INT\_SA + \vartheta_4 \mathrm{INT\_SM} + \sum_{k=5}^{K} \vartheta_k \mathrm{X_{5,it}} + \varepsilon_{\mathrm{it}}\end{aligned} \tag{5}$$

$$\begin{aligned}\mathrm{FS_{it}} = \varphi + \quad & \pi_1 \mathrm{TRAGF_{it}} + \pi_2 \mathrm{TRMF_{it}} \\ & + \pi_3 INT\_ISA + \pi_4 \mathrm{INT}\_ISM + \sum_{k=5}^{K} \pi_k \mathrm{X_{5,it}} + \varepsilon_{\mathrm{it}}\end{aligned} \tag{6}$$

Moreover, we also divide the sample into two main geographic areas based on population density: the islands of Java and Bali and the other islands in the archipelago (Sumatera, Kalimantan, Sulawesi Papua and other small island groups). Thus, the model in Equation (4) is estimated in which the districts are grouped based on the island groups. This estimation is performed because the effect of tariff might be varied across districts on different islands.

In consideration to non-tariff barriers as the new form of tariff measurement, which is not considered in this study due to a lot of time and effort is needed in gathering and measuring the data. The same is true for openness data, which is limited to national data only. Hence, this study measures trade liberalization only using import tariff rates, with sectoral import tariffs being measured based on their exposure to each district in Indonesia. We use all-duty codes tariff, it is not only for MFN (Most Favor Nation) tariff. The tariffs are categorized into two sectors: agriculture and manufacturing that related to food sector.

Following the method developed by Kis Katos and Sparrow [26], tariff exposure is measured based on economic sector composition and is defined by weighting tariff lines according to the sectoral shares in each district's regional GDP [26]. Using the Equation (7), we convert the national tariff of agriculture sector and food manufacturing sector to district level.

The equation is as follows:

$$T_{k,t}^{GRDP} = \sum_{h=1}^{H} \left(\frac{GRDP_{h,k}}{GRDP_{h,2000}} \times T_{ht} \right) \tag{7}$$

where *T* represents the tariff in each district *k* and period *t* and is generated from the national tariff *T* per sector *h* weighted by the sectoral GRDP (Gross Regional Domestic Product) in each district *k*. To construct *T* (tariff exposure), the import tariff is weighed by the GRDP per district. We use the same procedure in calculating each tariff exposure of agriculture and food manufacturing sector. In this study, instead of using overall tariffs, we prefer to use the sectors that are related to food imports, i.e., the agriculture and food manufacturing sectors; hence, the overall tariff has been divided into two sectors. The separation of those sectoral tariffs is because the impact raised by each sector might be different. The tariffs are weighted by gross regional domestic product to account for variations in the exposure effect across different districts. Accordingly, each region has different economic composition, which may result in different tariffs exposure which can be expressed in terms of total output [26].

3.2. Data and Analysis

This study uses 2011 to 2018 consumption and GRDP data from Central Bureau of Statistics (BPS). We collected data beginning from 2011 because the yearly basis consumption data start from that year, before which the survey data was available only once in three years. Furthermore, the period between 2011 to 2018 was marked by relatively low tariff rates, making it an ideal time to examine the effect of trade liberalization on food security. The import tariffs of each district were calculated and categorized into two sectors according to the equation in the previous subsection.

SUSENAS (Indonesian National Socio Economic Survey) data from BPS were used to measure food security through total calorie and protein intake per capita per day. The total number of districts for which the data are available is 496, which are later split into districts from Java and Bali island and other districts outside Java. The quality of food consumed by people determines the nutrient status in which household food consumption depends on the income of household that defines its purchasing power. There are many nutrients in the food consumed such as calories, protein, fat and carbohydrates; however, only calories and protein are used as a proxy of food security in this case. These two nutrients are important for individual dietary needs. Calories are the expression of energy measurement and protein is related to enzyme and body immune. BPS (Statistic Indonesia) used the level of calorie and protein consumed to express the level of nutritional adequacy which is one of the indicators of population welfare.

In order to estimate the relationship between trade and food security, district fixed effect regressions were performed for the time period from 2011 to 2018. As a proxy for trade liberalization, we used the tariff import data gathered from UNCTAD Trade Analysis Information System (TRAINS). We also used data on GRDP per capita, poverty rate, agriculture population density and household size as control variables. The explanatory variables and control variables were based on the developed model, the construction of which was guided by past studies on trade and food security. As the estimation involves time series panel data, the model was regressed using the fixed effect panel data regression method, and comparisons are drawn between the sample of all districts and that of districts in islands outside Java and Bali. Three models were estimated, with the following specifications:

The first model estimates solely the effect of tariffs on food intake in which the effect of each tariff is estimated in different equation.

$$\mathrm{Cal}_{\mathrm{it}} = \alpha^{calagr} + \beta_1^{calagr}\mathrm{TARGF}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{8}$$

$$\mathrm{Cal}_{\mathrm{it}} = \alpha^{calmanu} + \beta_1^{calmanu}\mathrm{TRMF}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{9}$$

$$\mathrm{Prot}_{\mathrm{it}} = \alpha^{protagr} + \beta_1^{protagr}\mathrm{TRAGF}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{10}$$

$$\mathrm{Prot}_{\mathrm{it}} = \alpha^{protmanu} + \beta_1^{protmanu}\mathrm{TRMF}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{11}$$

In the second model, the effect of both tariffs is included in the estimation equation.

$$\mathrm{Cal}_{\mathrm{it}} = \eta^{cal} + \tau_1^{cal}\mathrm{TARGF}_{\mathrm{it}} + \tau_2^{cal}\mathrm{TRMF}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{12}$$

$$\mathrm{Prot}_{\mathrm{it}} = \eta^{prot} + \tau_1^{prot}\mathrm{TARGF}_{\mathrm{it}} + \tau_2^{prot}\mathrm{TRMF}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{13}$$

The third model estimates the effect of tariffs on food intake with control variables:

$$\begin{aligned}\text{Cal}_{\text{it}} = \ & \lambda^{cal} + \rho_1^{cal}\text{TARGF}_{\text{it}} + \rho_2^{cal}\text{TRMF}_{\text{it}} + \rho_3^{cal}\text{l\_gcap}_{\text{it}} + \rho_4^{cal}\text{hh}_{\text{sizeit}} \\ & + \rho_5^{cal}\text{pov}_{\text{it}} + \rho_6^{cal}\text{l\_popfis}_{\text{it}} + \varepsilon_{\text{it}}\end{aligned} \quad (14)$$

$$\begin{aligned}\text{Prot}_{\text{it}} = \ & \lambda^{prot} + \rho_1^{prot}\text{TARGF}_{\text{it}} + \rho_2^{prot}\text{TRMF}_{\text{it}} + \rho_3^{prot}\text{l\_gcap}_{\text{it}} + \\ & \rho_4^{prot}\text{hh\_size}_{\text{it}} + \rho_5^{prot}\text{pov}_{\text{it}} + \rho_6^{prot}\text{l\_popfis}_{\text{it}} + \varepsilon_{\text{it}}\end{aligned} \quad (15)$$

The fourth model estimates the effect of tariffs on food intake with interaction variables for tariffs in which the model construction of which was guided by the past studies on trade and food security.

$$\begin{aligned}\text{Cal}_{\text{it}} = \ \theta^{cal} + \ & \delta_1^{cal}\text{TARGF}_{\text{it}} + \delta_2^{cal}\text{TRMF}_{\text{it}} + \delta_3^{cal}\text{l\_gcap}_{\text{it}} + \delta_4^{cal}\text{hh}_{\text{sizeit}} \\ & + \delta_5^{cal}\text{pov}_{\text{it}} + \delta_6^{cal}\text{l\_popfis}_{\text{it}} + \delta_7^{cal}\text{TRAGF} * \text{SA} + \delta_8^{cal}\text{TRMF} \\ & * \text{SM} + \varepsilon_{\text{it}}\end{aligned} \quad (16)$$

$$\begin{aligned}\text{Prot}_{\text{it}} = \ \theta^{prot} + \ & \delta_1^{prot}\text{TARGF}_{\text{it}} + \delta_2^{prot}\text{TRMF}_{\text{it}} + \delta_3^{prot}\text{l\_gcap}_{\text{it}} + \delta_4^{prot}\text{hh}_{\text{sizeit}} \\ & + \delta_5^{prot}\text{pov}_{\text{it}} + \delta_6^{prot}\text{l\_popfis}_{\text{it}} + \delta_7^{prot}\text{TRAGF} * \text{SA} \\ & + \delta_8^{prot}\text{TRMF} * \text{SM} + \varepsilon_{\text{it}}\end{aligned} \quad (17)$$

$$\begin{aligned}\text{Cal}_{\text{it}} = \ \gamma^{cal} + \ & \sigma_1^{cal}\text{TARGF}_{\text{it}} + \sigma_2^{cal}\text{TRMF}_{\text{it}} + \sigma_3^{cal}\text{l\_gcap}_{\text{it}} + \sigma_4^{cal}\text{hh}_{\text{sizeit}} \\ & + \sigma_5^{cal}\text{pov}_{\text{it}} + \sigma_6^{cal}\text{l\_popfis}_{\text{it}} + \sigma_7^{cal}\text{TRAGF} * \text{ISA} + \sigma_8^{cal}\text{TRMF} \\ & * \text{ISM} + \varepsilon_{\text{it}}\end{aligned} \quad (18)$$

$$\begin{aligned}\text{Prot}_{\text{it}} = \ \gamma^{prot} + \ & \sigma_1^{prot}\text{TARGF}_{\text{it}} + \sigma_2^{prot}\text{TRMF}_{\text{it}} + \sigma_3^{prot}\text{l\_gcap}_{\text{it}} + \sigma_4^{prot}\text{hh}_{\text{sizeit}} \\ & + \sigma_5^{prot}\text{pov}_{\text{it}} + \sigma_6^{prot}\text{l\_popfis}_{\text{it}} + \sigma_7^{prot}\text{TRAGF} * \text{ISA} \\ & + \sigma_8^{prot}\text{TRMF} * \text{ISM} + \varepsilon_{\text{it}}\end{aligned} \quad (19)$$

We use natural log for certain variables, such as agriculture population density and GRDP per capita, in order to obtain better estimates. Tariff data is measured by sector due to the limited availability of data on import tariff per food product, particularly at the district level.

Table 1 presents the list of variables and measurement units used in the models:

Table 1. List of Variables and Measurement.

Variable	Description	Unit of Measurement
Tariff (Sectoral)	Import tariff - Agricultural Tariff - Food Manufacturing Tariff	Percentage (All duty codes)
Food Security	- Calorie Consumption - Protein Consumption	Average kilocalorie/capita/day Average gram protein/capita/day
Control Variables	GRDP per capita, Agriculture population density, Household average size, education, poverty rate	In natural log of GDP, natural log of agriculture population, share of the wife's education in the family (level junior high)
Interaction Variables 1 Interaction Variables 2	Share of people working in agriculture; Share of people working in manufacturing Share of household income in Agriculture and Manufacturing field	In percentage based on SUSENAS data

4. Results and Discussion

4.1. Descriptive Statistics

The following Figure 5 plots the national import tariff rates from 2011 to 2018 for the two sectors that are related to food imports.

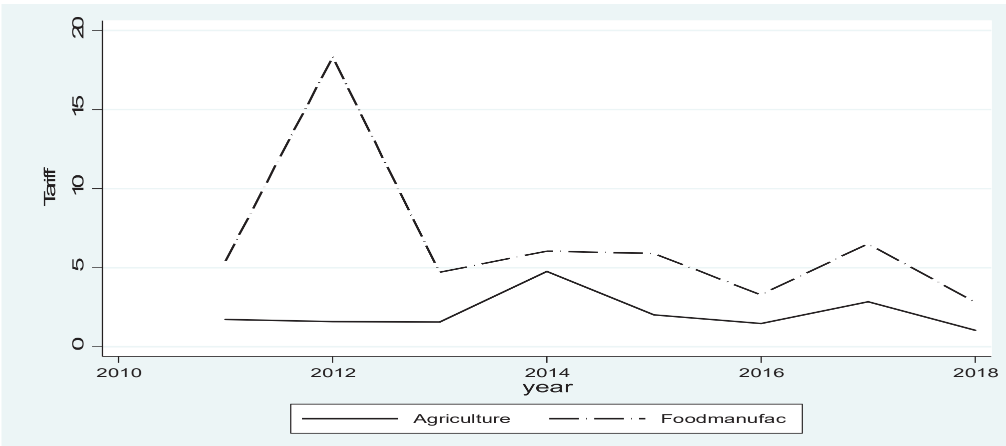

Figure 5. National sectoral tariff for agriculture and manufacturing sectors.

Despite some spikes and slight fluctuations in Indonesia's agriculture and manufacturing sector tariffs, both sectors exhibit a trend of declining tariffs at the national level. Yet, the graph in Figure 6 illustrates that overall tariff exposure at the regional level increased moderately between 2011 and 2018 for both sectors. Agriculture tariff exposure declined slightly after 2011 but fluctuated upwards between 2014 to 2018, whereas manufacturing tariff exposure saw greater fluctuations throughout the entire period of 2011 to 2018. This depicts the mean of both tariff exposure of regions per year, which in general fluctuate over the years.

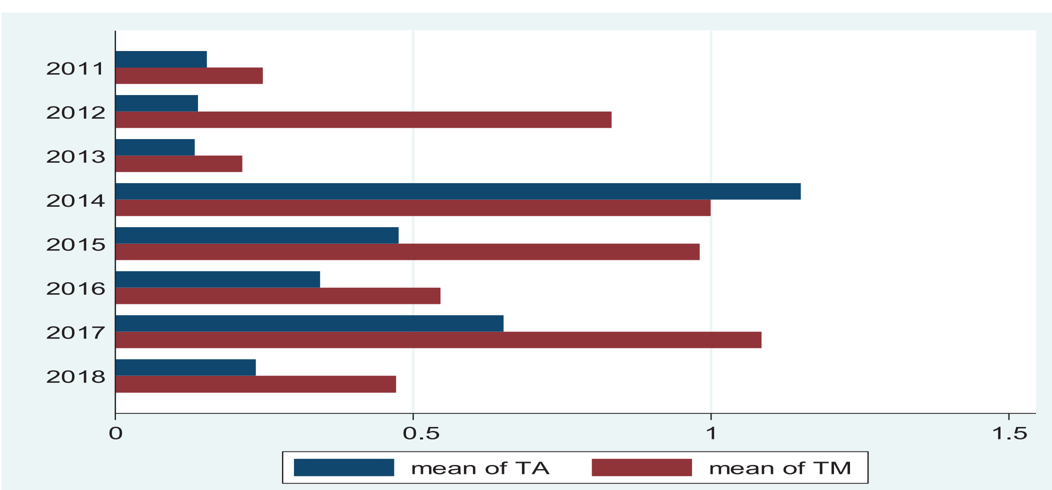

Figure 6. Mean of regional tariff exposure per year for the agriculture (TA) and food manufacturing (TM) sectors.

Next, the following map in Figure 7 presents the average consumption of calories (AkE-the threshold of calorie consumption) and proteins (AkP-the threshold of protein consumption) across districts in Indonesia in 2018. The map distinguishes regions according to whether average consumption in the region surpasses the level of sufficient nutrition intake as stipulated by the Ministry of Health: 2150 kcal for calories and 57 grams of protein.

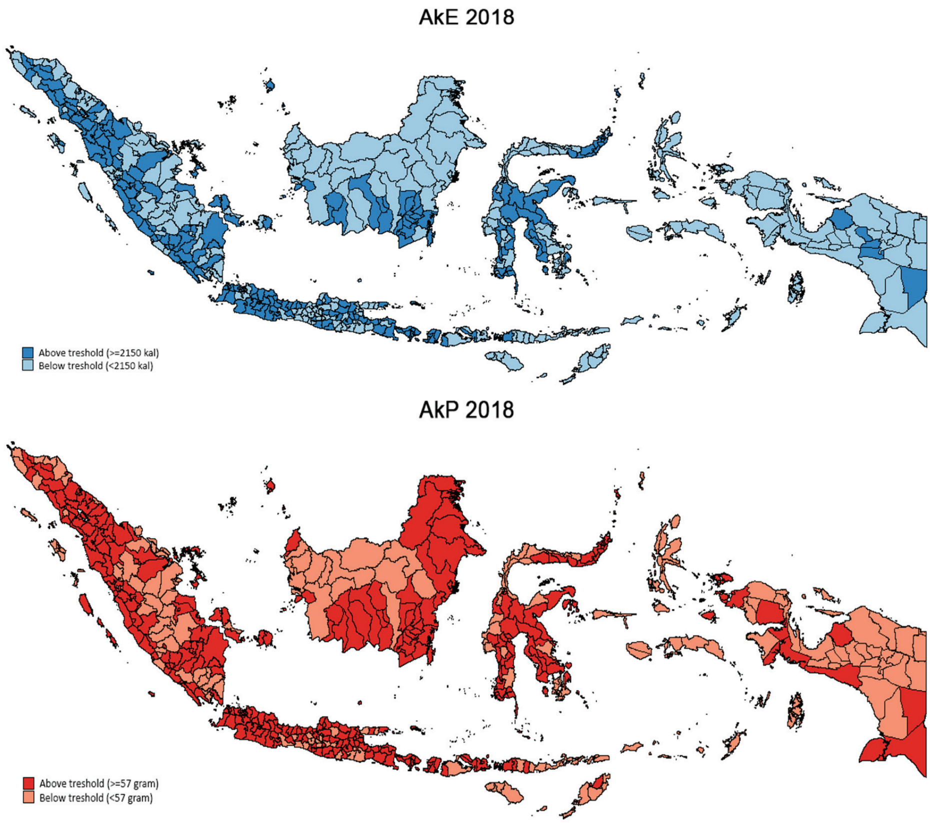

Figure 7. Map of Calorie and Protein threshold intake 2018.

The map (see Figure 7) reveals that most districts in Eastern Indonesia have not satisfied the minimum threshold of calorie and protein consumption. In contrast, most districts in Java and Bali have achieved the minimum threshold. The stark differences in nutritional intake between the two regions are among the reasons why we also provide separate estimates for the relationship between tariff exposure and food security in the sample that excludes Java and Bali.

In addition, the graph in Figure 8 illustrates the range of calorie and protein consumption between 2011 and 2018 for districts in each province. As mentioned, there are some regions that have not met the sufficient level of dietary need; however, the range of nutrition intake between those time period is slightly declining across provinces. This result is depicted in the graph in Figure 8.

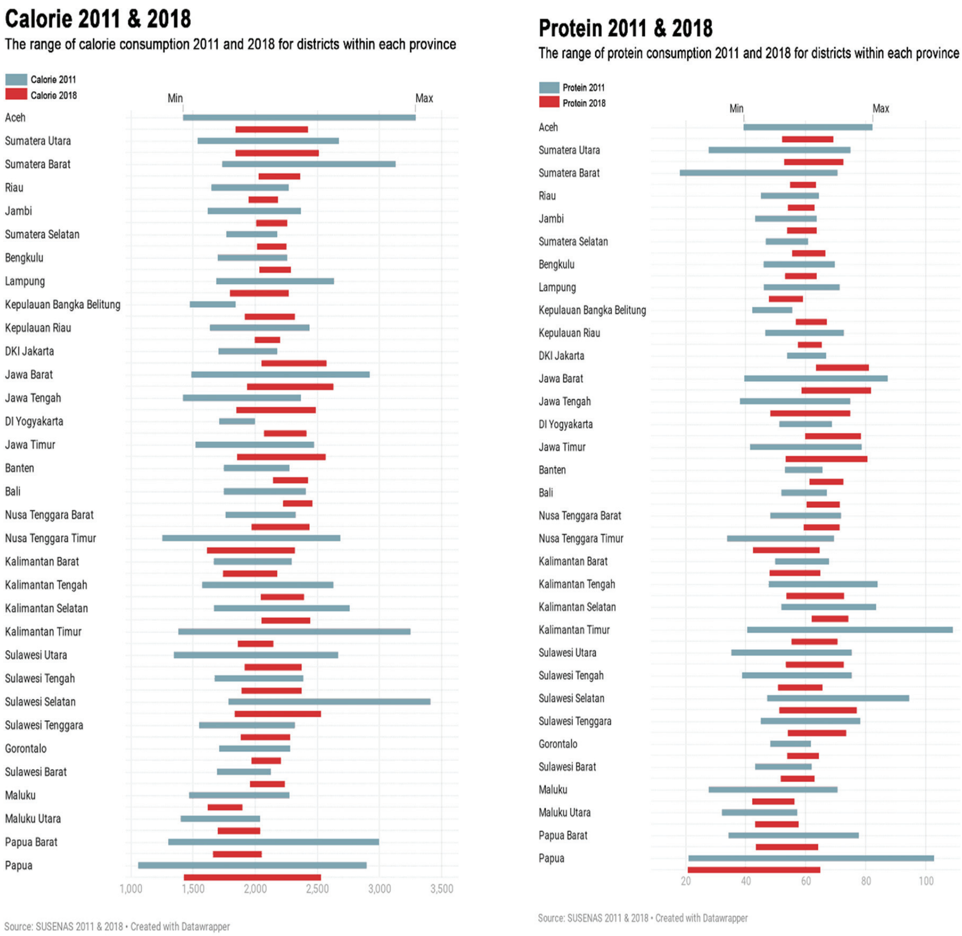

Figure 8. The range of calorie and protein consumption between 2011 and 2018 for districts within provinces.

It can be seen from the graphs (Figure 8) that most provinces saw a decrease in their calorie and protein consumption gap between 2011 to 2018. This is following the trend of national import tariffs that are also going down, as shown in Figure 5. Nonetheless, the relation between tariff and food security cannot be concluded solely from these graphs as there are many other factors that may have contributed to food security.

4.2. Estimation Results

The results in both Tables 2 and 3 show that tariff protection may negatively affect food security; an increase in both agriculture and manufacturing tariffs resulted in a decrease of average household nutrient intake, i.e., a decrease in calorie (see Table 2) and protein (see Table 3) consumption per capita. The interaction factors refer to the share of those who work in the agriculture and manufacturing sectors and the income share of household work in agriculture and manufacturing. Tariffs are estimated separately in the first and second column, while in the third to last column, both tariffs are included.

As can be seen from Table 2, the results in the first and second columns indicate that agriculture and manufacturing tariffs have negative and significant coefficients towards nutrient intake. The coefficients are consistently negative and significant even when both tariffs are considered jointly in the third column and when more control variables and interaction terms are included in the regression. The result indicates that an increase in tariff exposure is associated with a decrease in calorie consumption, but the size of the effect is different between agriculture and manufacturing sector tariffs.

The impact of manufacturing tariff exposure is stronger than that of agriculture tariff exposure: the results in column 3 imply that the increase of agriculture and manufacturing tariffs by a one-unit percentage will reduce calorie consumption by 31.26 kcal and 38 kcal, respectively. The coefficient of agriculture is less than that of manufacturing tariffs. There are slightly different results when interaction variables are included; agriculture tariff exposure has a larger impact on calorie consumption.

Table 2. Estimation results calorie model.

Dependent Variable: Calorie						
	Model 1		Model 2	Model 3	Model 4	
Independent Variables	(1) Agriculture Tariff	(2) Manufacture Tariff	(3) Both Tariffs	(4) No Interaction Variables	(5) Interaction Variables 1 Employment Share	(6) Interaction Variables 2 Income Share
TRAGF	−31.26 ***		−31.12 ***	−19.23 ***	−65.88 ***	−58.56 ***
	(4.839)		(4.749)	(4.688)	(13.88)	(12.77)
TRMF		−38.00 ***	−37.94 ***	−28.39 ***	−42.01 ***	−41.76 ***
		(3.346)	(3.325)	(3.296)	(5.589)	(5.615)
lgcap				70.87 ***	77.08 ***	76.01 ***
				(11.97)	(12.07)	(12.05)
hh_size				−220.1 ***	−210.9 ***	−210.4 ***
				(30.66)	(30.63)	(30.65)
povertyrate				−15.70 ***	−15.56 ***	−15.40 ***
				(3.175)	(3.165)	(3.167)
lpfis1				34.26 ***	33.87 ***	33.90 ***
				(8.290)	(8.270)	(8.277)
Women Educ (SMP)				290.7 ***	305.2 ***	302.9 ***
				(81.49)	(81.30)	(81.32)
TRAGF * AgricultureShare					181.6 ***	
					(51.13)	
TRMF * ManufactureShare					186.1 **	
					(60.88)	
TRAGF * AgriIncome						170.6 **
						(51.91)
TRMF * ManufacIncome						179.3 **
						(59.94)
_cons	2005.6 ***	2006.0 ***	2038.0 ***	2682.5 ***	2628.2 ***	2628.3 ***
	(5.869)	(4.203)	(6.421)	(153.9)	(153.9)	(154.0)
N	3851	3850	3850	3569	3569	3569
R^2	0.012	0.037	0.049	0.123	0.129	0.129

Standard errors in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3. Estimation result for protein model.

	Dependent Variable: Protein					
	Model 1		**Model 2**	**Model 3**	**Model 4**	
Independent Variables	(1) Agriculture Tariff	(2) Manufacture Tariff	(3) Both Tariffs	(4) No Interaction Variables	(5) Interaction Variables 1 Employment Share	(6) Interaction Variables 2 Income Share
TRAGF	−0.729 ***		−0.726 ***	−0.508 ***	−1.554 ***	−1.338 **
	(0.153)		(0.151)	(0.151)	(0.449)	(0.413)
TRMF		−0.892 ***	−0.891 ***	−0.694 ***	−0.990 ***	−0.978 ***
		(0.106)	(0.106)	(0.106)	(0.181)	(0.182)
lgcap				1.298 ***	1.437 ***	1.406 ***
				(0.386)	(0.390)	(0.390)
hhsize				−4.124 ***	−3.922 ***	−3.919 ***
				(0.989)	(0.990)	(0.991)
povertyrate				−0.585 ***	−0.582 ***	−0.578 ***
				(0.102)	(0.102)	(0.102)
lpfis				1.351 ***	1.343 ***	1.343 ***
				(0.267)	(0.267)	(0.268)
Women Educ (SMP)				17.96 ***	18.28 ***	18.22 ***
				(2.629)	(2.628)	(2.629)
TRAGF * AgricultureShare					4.073 *	
					(1.653)	
TRMF * ManufactureShare					4.047 *	
					(1.968)	
TRAGF * AgriIncome						3.605 *
						(1.678)
TRMF * ManufacIncome						3.819 *
						(1.937)
_cons	55.92 ***	55.94 ***	56.69 ***	67.91 ***	66.71 ***	66.76 ***
	(0.186)	(0.134)	(0.205)	(4.966)	(4.975)	(4.978)
N	3851	3850	3850	3569	3569	3569
R^2	0.007	0.021	0.027	0.087	0.090	0.090

Standard errors in parentheses * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The tariff has a greater effect on consumption for households working either in the agriculture or manufacturing sector. The minimizing tariff effect on consumption is slightly larger for those who work in agriculture.

Table 3 explores the effect of tariffs on protein consumption. The baseline model is presented in column 4, while columns 1 and 2 show the individual effect of each tariff and column 3 shows their effects when they are included jointly. Columns 5 and 6 show results that include interaction variables between tariff exposure and employment and income shares. The results show that agriculture and manufacturing tariffs have negative impacts on protein consumption, with the baseline model predicting that protein consumption declines by 0.5 grams and 0.7 grams when tariffs for agriculture and manufacturing sectors are increased by one percentage point respectively.

These results are consistent with the tariff effects on calorie consumption, where the impact of manufacturing tariffs is greater than that of agriculture tariffs. Meanwhile, the regressions in columns 5 and 6 show that the impact of the tariff is larger when there is an interaction factor of people working in those sectors. The effect of the interaction factor towards consumption may minimize the negative effect of tariff raises, although the coefficient of interaction becomes less significant, falling to the 5 percent level.

Overall, the results in Tables 2 and 3 show that the effect of tariffs on calorie and protein consumption is negative, which implies that when tariffs increase, consumption decreases. We also find that when tariffs interact with the share of employment and the share of income, the effect of tariffs on calorie and protein intake is higher than the result without interaction variables. It also indicates that the effect of interaction variables itself have minimized the decline of consumption. As for the control variables, the effect on food consumption corroborates the theoretical framework and results from previous studies.

Next, referring to the control variables included in the regressions, Figure 4 has demonstrated that geographical aspects such as location and the remoteness of the area may also affect the resource endowments of each district and therefore contribute to the level of food security in the area [27]. Hence, to explore those variations and to ensure that the results from the overall sample are not driven only by the socioeconomic characteristics of the large metropolitan areas in Java and Bali, we divide the sample into five subgroups based on the major island groups in Indonesia: (1) Sumatera; (2) Jawa and Bali; (3) Kalimantan; (4) Sulawesi; and (5) Nusa Tenggara, Maluku and Papua, which we take as the reference group. The estimation result is presented in Table 4.

Table 4. Estimation based on sample composition of five islands.

Sub Group	Sumatera		Jawa/Bali		Kalimantan		Sulawesi		NTB/NTT/Maluku/ Papua	
	(1)		(2)		(3)		(4)		(5)	
	Calorie	**Protein**	**Calorie**	**Protein**	**Calorie**	**Protein**	**Calorie**	**Protein**	**Calorie**	**Protein**
TRAGF	−7.759	−0.364	−2.384	0.378	−45.56 *	−1.447 *	−8.274	−0.163	−67.00 ***	−1.515 ***
	(7.002)	(0.220)	(10.99)	(0.377)	(22.08)	(0.714)	(10.45)	(0.331)	(14.23)	(0.457)
TRMF	−29.59 ***	−0.635 **	−20.99 ***	−0.527 ***	−38.69 ***	−1.076 **	−46.30 **	−1.064 *	−23.20	−0.219
	(6.705)	(0.211)	(3.648)	(0.125)	(10.49)	(0.339)	(17.02)	(0.539)	(20.14)	(0.647)
lgcap	95.23 ***	1.794 *	103.3 ***	2.587 ***	−31.87	−3.285 **	86.86 **	1.992 *	7.780	0.427
	(23.11)	(0.727)	(21.60)	(0.740)	(39.11)	(1.265)	(29.88)	(0.945)	(32.80)	(1.054)
hhsize	−235.7 ***	−4.005 *	−387.9 ***	−10.20 ***	−254.8 *	−5.899	−289.0 ***	−5.278 ***	3.665	1.914
	(55.78)	(1.755)	(61.08)	(2.093)	(101.7)	(3.288)	(78.29)	(2.477)	(73.40)	(2.359)
povertyrate	−14.83 *	−0.764 ***	−27.67 ***	−0.994 ***	−20.06	−1.356 *	13.30	0.303	−13.29 *	−0.244
	(5.921)	(0.186)	(5.681)	(0.195)	(18.84)	(0.609)	(13.23)	(0.419)	(6.063)	(0.195)
lpfis	34.45 *	0.878 *	4.355	−0.189	19.48	1.077	45.91	1.816	32.53	1.895 **
	(14.09)	(0.443)	(23.03)	(0.790)	(20.36)	(0.658)	(36.39)	(1.151)	(17.79)	(0.572)
Women Educ	65.84	11.69 **	429.1 **	18.90 ***	142.9	17.19 *	289.5	17.39 *	578.7 *	26.38 ***
	(137.8)	(4.335)	(139.1)	(4.768)	(255.0)	(8.246)	(234.2)	(7.410)	(232.4)	(7.470)
_cons	2712.8 ***	70.14 ***	3324.5 ***	95.71 ***	3212.2 ***	97.24 ***	2603.9 ***	60.27 ***	1965.6 ***	35.59 **
	(291.7)	(9.175)	(292.2)	(10.01)	(459.1)	(14.84)	(426.3)	(13.49)	(402.3)	(12.93)
N	1148	1148	968	968	409	409	560	560	484	484
R^2	0.137	0.090	0.287	0.219	0.085	0.086	0.095	0.052	0.090	0.091

Standard errors in parentheses* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The sign of the tariff coefficients remains the same for all groups, albeit with a markedly greater effect for the NTT/NTB/Maluku and Papua islands and with different significance across other islands. Agriculture tariffs are only significant in Kalimantan and Nusa Tenggara/Maluku and Papua, whereas the manufacturing tariff coefficient is significant in all islands except Nusa Tenggara/Maluku and Papua. Thus, tariff effects in and Nusa Tenggara/Maluku and Papua are driven by agriculture tariffs, whereas manufacturing tariffs drive most of the effects in Sumatera, Java/Bali and Sulawesi. These differences might be due to a variety of local conditions and cultures in each district, which can induce different responses to tariff changes.

Thus, this study confirmed some findings from previous studies [14,16]; for example, it is found that trade openness and dietary energy consumption are positively associated, and the latter concludes that lower trade barriers positively impact calorie and protein intake. Furthermore, this study also finds that trade liberalization can have negative effects on calorie and protein intake, with varying effects across different districts and islands.

Some control variables in this study are also worth noting. For example, the education level of women in the family positively influences food consumption, as women often play a larger role in providing the food and dietary needs of households. It is also found that employment in agriculture and manufacture is helpful in minimizing the negative influence of rising tariffs, especially as the agriculture sector is still a key employment sector in Indonesia, with 31.86% of Indonesians in 2017 being employed in the sector and therefore relying on agriculture for their livelihoods [28]

Thus, if tariffs in both sectors rise, calorie and protein consumption may decrease and adversely affect the welfare of households. This study found evidence that the coefficients for both tariffs are negative and significant, indicating that higher sectoral tariffs are associated with lower food consumption. These effects vary across islands; in remote islands such as Nusa Tenggara, Maluku and Papua, agriculture tariffs have a greater impact than manufacturing tariffs, and the reverse is true in more populated and urban islands such as Java, Bali and Sumatera.

5. Conclusions

This study examined the relationship between food security (which is defined as calorie and protein intake) and trade liberalization (which is defined as the tariffs in the agriculture and food manufacturing sectors). This study found that calorie and protein consumption as a measurement of food security is affected by tariff protection. Import tariffs in food are negatively associated with calorie and protein consumption, but the effect of trade liberalization—i.e., the effect of agriculture and manufacture sectoral tariff exposure—on food consumption may be minimized if households work in the agriculture and/or manufacturing sectors. It can also be said that tariffs, particularly agriculture tariffs, are likely to have a greater impact on households living in remote or rural areas—areas in which poor households are often concentrated. Thus, trade liberalization may exacerbate the vulnerability that poor households have towards food insecurity, in which from the data Indonesia's food security index is increasing nowadays.

We find that the impact of tariffs on food consumption is lower in Java's districts compared to those outside Java. It is also found that food consumption in the districts in Sumatera, Bali/Jawa and Sulawesi are driven more by food manufacturing tariffs, while those in the other islands are affected by agriculture tariffs. Therefore, decisions with regard to tariff hikes should ideally consider the subsequent effect on people and varying effects of tariff exposure that may widen the inequalities between urban and rural districts. From a policy perspective, this calls for greater consideration of geographic locations, local economic conditions, and the share of employment in each district in order to design better tariff policies.

This study differs from previous studies in two ways. First, we derived tariff exposure into two sectors that are related to food consumption. Second, we identified the association between tariffs and food security by looking into subgroups based on geographic locations. Our main results confirm that tariffs on agriculture and food manufacturing negatively impact food security. We also interact tariff variables with the employment and income share in each sector to show that the negative effects of tariffs toward calorie and protein intake might be outweighed by the positive effects from the employment share of each sector, which are rooted in the income that households earn from working in those sectors.

This study has several limitations and can be further developed to consider tariffs for certain food products that are consumed by a majority of households in Indonesia and to consider other forms of tariff and non-tariff measurements. Another limitation is that consumption data are not available on a yearly basis before 2011, thereby restricting the years available for our analysis. Further insight may also be garnered by estimating the effect of trade openness on food security if export–import data at the district level are available. This might be a more sensible measurement of trade; however, it is also challenging to gather the data at the district level. Nonetheless, this study has contributed to the debate regarding the relationship between import tariffs and food insecurity at the sub-national level, particularly in Indonesia, and this study has highlighted the need for governments to consider more closely the protection of vulnerable households from the effect of tariffs and the possibility of using tariffs as a channel to reduce food insecurity. By supporting investment in domestic agriculture and food manufacturing sectors, governments may reduce the harmful effects of tariffs through the boosting of household incomes, especially for households in remote areas.

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An Analysis of the Determinants of Irrigation Farmworkers' Food Security Status: A Case of Tshiombo Irrigation Scheme, South Africa †

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Abstract: Food insecurity is a comprehensive challenge. Food, being one of the most basic human needs, has become one of the most important concerns in the world, as more people are living in poverty and are vulnerable to food insecurity. Food insecurity levels vary across sectors, meaning that policy recommendations to address the problem have to be in specific contexts. Farmworkers in irrigation schemes are a sub-group that has received little attention in research regarding food security outcomes. This paper provides evidence of a study that was carried out to analyze food security among irrigation scheme farmworkers who either rent or do not rent irrigation plots from their employers in the Tshiombo Irrigation Scheme, Limpopo Province. Data were collected from 191 randomly selected farmworkers. The Household Food Insecurity Access Scale (HFIAS) was utilized to determine the extent of food security among the irrigation scheme farmworkers. Data were analyzed using the ordered probit model. Among the variables considered in the model, land size ($p < 0.05$), land leasing ($p < 0.01$), total household expenditure ($p < 0.05$), and food stored by farmworkers ($p < 0.1$) were found to significantly influence irrigation farmworkers' food security status. These findings suggest that policymakers should design policies that encourage stakeholders from NGOs, and private and public sectors to train and provide resources that will enable and develop livelihood skills among farmworkers.

Keywords: ordered probit model; Limpopo Province; farmworkers' food security status; livelihood

1. Introduction

There are various definitions of food security. The most recognized is that by FAO [1], which denotes that food security exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life [2]. The four pillars of food security are food availability, food access, food utilization, and food stability [3]. Food availability refers to an effective or continuous supply of food at both national and household levels. Food availability is affected by the production capabilities of the agricultural sector, and input and output market conditions [1]. Food access refers to the ability of households to acquire enough nutritious food [4]. This pillar reflects the demand side of food security and highlights the uneven inter and intra-household food distribution and sociocultural limits on food choices [5]. Food access is determined by two factors: economic and physical access. Economic access is determined by disposable income, food prices, and accessibility to social support, while physical access depends on the physical infrastructure that supports access such as paved roads, railways, electricity, and irrigation facilities [5]. Food utilization refers to a process through which the body utilizes various nutrients in the food. It also requires proper food preparation and hygiene practices, wide-ranging eating habits, and a diverse diet that necessitates the availability of all essential nutrients and the proper intra-household distribution of food [4]. Food stability strives to secure the dimensions of food availability, food access, and food utilization over time; therefore, access to food should remain unaffected even during sudden shocks such as economic crises [4]. FAO [1] points out that the variables in this pillar measure the dependence on food imports, domestic price variability, and variation in land equipped with irrigation. To achieve food security, all four dimensions must be fulfilled simultaneously [4]. Food insecurity is considered to occur when one or more of these factors are affected [6]. Vorster, et al. [7] agreed that South Africans, particularly those with a low income, may select a relatively less healthy diet that is associated with malnutrition. McLaren, et al. [8] stated that the right to food is highlighted in the international human rights documents and in section 27(1) (b) of the Constitution of the Republic of South Africa, which states that everyone has the right to have access to sufficient food and water; this is often violated. One of the challenges for the South African government is aligning policies and programs to reach and maintain food security status for all [9]. South Africa still lacks specific and accepted methods to measure food security and has no regulated way of monitoring the food security status of its population [10].

Smallholder and commercial farming are the pillars of South Africa's primary agricultural production and food security. South Africa has an impressive level of food self-sufficiency. However, large numbers of households in South Africa are food-insecure [11]. One in four South Africans experiences hunger due to poverty, low wage, and high food prices [12]. Farmworkers in irrigation schemes earn the lowest wage in the agricultural sector in South Africa [13]. The government promotes and supports smallholder irrigation in former homelands to create jobs, reduce poverty, and enhance economic growth [11]. Ironically, food insecurity is rising among farmworkers in South Africa.

In Western Cape, many farmworkers lost their jobs after the farmworkers' strike of 2013. Many describe how their food supplies are exhausted by mid-week, forcing them to skip meals due to low wages and, during tough periods, ending up eating porridge twice a day [14]. Countrywide, the agricultural labor force has shifted from workers with permanent contracts to seasonal or casual workers [13]. Seasonal and casual farmworkers are more vulnerable to food insecurity than permanent farmworkers because the former are employed only during the agricultural season and often earn below the legislated minimum wage rate [13]. Several studies in Africa have assessed the livelihood, labor, and employment status of farmworkers in rural areas, and these include Zimbabwe [15], Nigeria [16], and South Africa [17]. However, the recent literature of studies that can guide policymakers on food security and nutrition among farmworkers in an irrigation scheme in South Africa is scarce. Hence, this study analyzed the determinants of food security status among irrigation scheme farmworkers in the Limpopo Province of South Africa. The hypothesis is that irrigation scheme farmworkers who rent land from landlords are more food-secure than nonland-renting irrigation scheme farmworkers. To test our hypothesis, we used parametric ANOVA for continuous variables and a chi-square test for categorical variables to indicate the association between the irrigation scheme farmworkers' food security status with different economic parameters. Furthermore, the ordered probit model was used to analyze factors that influence irrigation farmworker food security status.

2. Review of Food Security Measurements

2.1. Major Indicators Utilized to Measure Food Security Dimensions

The following indicators have been identified, their robustness and validity have proven to be cost-effective, time-sensitive, and effective in identifying those that lack access to adequate food, and these have been used across different geographical locations and cultures [18]. Each of these measures has been confirmed to be valid by the following authors: The Household Food Insecurity Access Scale by [18]; CSI Coping Strategies Index by Maxwell, et al. [19]; Household Dietary Diversity Score HDDS by Maxwell et al. [19].

2.1.1. Household Dietary Diversity

The Household Dietary Diversity Score (HDDS) was released in 2006 as part of the Food and Nutritional Technical Assistance (FANTA) II project as a population-level indicator of household food access [20]. Household dietary diversity can be described as the number of food groups consumed by a household over a given period and is an important indicator of food security dimensions. A more diversified household diet is correlated with caloric and protein adequacy, the percentage of protein from animal sources, and household income. The HDDS indicator indicates a household's ability to access food as well as its socioeconomic status based on the previous 24 h [21]. The dietary diversity questionnaire is based on a set of food group questions and can be used to find a household's dietary diversity score by categorizing different types of food based on the nutrients they comprise.

Few households in South Africa are making use of wild foods as part of their nutrient diet [22]. Wild foods are important for food security and poverty alleviation, and they are often cost-efficient and time-efficient to collect, saving households time and money [23]. Wild foods are especially important for the more disadvantaged members of the communities; those that are at most risk of food insecurity rely on these products for food, while others consume these because of cultural and taste preferences [23]. According to Bvenura and Afolayan [24], the consumption of wild vegetables is on the decline. Their economic importance is not fully realized by most South African citizens, unlike in other Sub-Saharan countries such as Zimbabwe, Zambia, Kenya, Botswana, Nigeria, and Swaziland, whose citizens continue to cultivate wild vegetables in abundance. Some of the vegetables grown are C. olitorius, C. gynandra, and some Amaranthus species that are also sold to supplement household income. The species mentioned above are also still cultivated on a small scale in some parts of Limpopo and KwaZulu Natal provinces [24]. Rural households also supplement their dietary needs with a variety of insects and wild meats and also collect wild fruits for consumption and sale.

2.1.2. Coping Strategies Index

The coping strategy index (CSI) is a group of questions that are asked in a household to find out how they manage to cope with the shortage of consuming enough food. The coping strategy index is estimated by measuring behavior, such as the alternative actions individual households use when they cannot acquire sufficient food [25]. The coping strategies are often identified by the person who is responsible for preparing or consuming the food. The coping strategies observed are usually linked to food practices in the short-term [26]. Chagomoka, et al. [27] observed that the gathering of wild food and selling of firewood was widely practiced in the rural parts of Limpopo Province, and they identified five coping strategies in the rural areas as the most severe in times of food insecurity, namely skipping a whole day without food, borrowing, buying food on credit, consuming seed stock, and restricting adult intake in favor of children. A study conducted by Oldewage-Theron, et al. [28] in Gauteng (Vaal triangle) revealed that most female-headed households experienced incidences of money shortfall as their money was used for food the month preceding the study. The coping strategies employed by these households were cooking a limited variety of foods during the previous month and limiting portion sizes [28].

2.1.3. The Household Food Insecurity Access Scale

The HFIAS is a continuous measure for investigating the incidents of household food insecurity in the previous month [18]. The scale is based on the principle that the occurrence of food insecurity can be established, quantified, and examined by classifying individual households using the food insecurity level. According to Carletto, et al. [29], the HFIAS highlights three broad aspects of household food insecurity access, which include: worrying about the likelihood of food insecurity, inadequate quality of food, and inadequate food supplies. The HFIAS is an advanced tool for measuring household food insecurity and it consists of a set of nine generic questions [18]. The first question addresses the anxiety and uncertainty of household food supply, Q2–Q4 address food quality variety and preference, and Q5–Q9 address insufficient food intake and its physical consequences. Q2–Q4 and Q5–Q9 are organized in order of increasing severity of the food insecurity condition [18]. Based on the response to the nine questions and frequency of occurrence over the past 30 days, households are assigned a score that ranges from 0 to 27 [30]. A study by Kabalo, et al. [31] indicated that the HFIAS method produces accurate results because of its internal consistency, criterion validity, and reliability for analyzing household food insecurity. Therefore, the Household Food Insecurity Access Scale (HFIAS) was utilized to determine the extent of food security among the irrigation scheme farmworkers in Tshiombo Village.

3. Materials and Methods

3.1. Description of the Study Area

We carried out the study in the Tshiombo Irrigation Scheme located 40 km north of Thohoyandou Service Centre, Vhembe District in Limpopo Province of South Africa (Figure 1). The scheme is 1195 hectares with 930 plots and each farmer owns an average of 1.286 hectares. Project beneficiaries of the Tshiombo Irrigation Scheme are from seven villages [32]. The average rainfall is ±500 mm/annual, with most of it falling during summer (October to March) [33]. The irrigation scheme offers the local community an opportunity to increase income and participate in the local economy. Irrigation development benefits the rural poor in various ways including (a) reduced food prices resulting from increased production and (b) increased on-farm and off-farm employment, leading to income generation for the poor [34]. About 50% of the farmers also sell crops in the formal markets with maize, cabbages, potatoes, tomatoes, onions, beans, spinach, and butternut being the most commonly produced in the irrigation scheme [35].

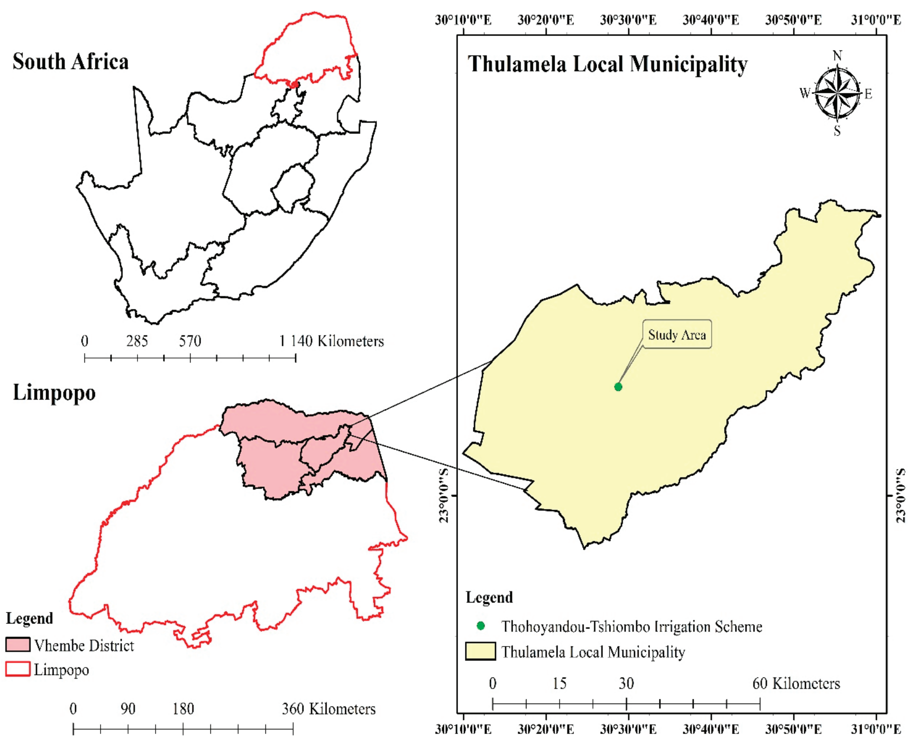

Figure 1. Study site, Limpopo Province (Source: Author).

3.2. Sampling Size and Sample Technique

To obtain a representative sample, the study used the sample size determination formula given by [36]:

$$n = \frac{N}{1 + (e^2)}$$

where n is the sample size, N is the population size, and e is the level of precision of 0.005. A total of 114 land-leasing farmworkers were selected from a population of 160, while a total of 77 nonland-leasing farmworkers were selected from a population of 95.

A probability sampling method involving a simple random technique was used to select a total of 191 farmworkers with the aid of information obtained from the extension farmworker. Both males and females had an equal chance of being selected for the study.

3.3. Method of Data Collection

A pre-tested questionnaire was used as a primary data collection tool. The questionnaire was administered by well-trained enumerators. The data were collected on the characteristics of the irrigation farmworkers, food access or availability, and the availability of resources.

3.4. Method of Analysis

Data were captured and analyzed using Statistical Package for Social Scientists (SPSS) and STATA. Before the analysis of the variables, the Shapiro–Wilk test was applied to test the normality of the explanatory variables using SPSS. From the test conducted, if the p-value of the Shapiro–Wilk test was greater than 0.05, the data were considered normal. A one-way Analysis of Variance (ANOVA) parametric test was used to analyze the descriptive statistics for continuous variables. The p-values were generated by SPSS for a one-way Analysis of Variance (ANOVA) parametric test. The ANOVA parametric test was validated by the following assumptions: the variables were checked for normality and it was satisfied, the variance in the samples was approximately equal, and the data were randomly and independently sampled from the population. The chi-square test was used to analyze the descriptive statistics of categorical variables through SPSS. The SPSS generated the p-values throughout the study. The significant levels for the coefficients in the study were categorized into three levels: 1%, 5%, and 10%. STATA was used for econometrics modeling.

3.5. Household Food Insecurity Access Scale (HFIAS)

To determine food insecurity among irrigation farmworkers, a Household Food Insecurity Access Scale (HFIAS) of nine questions was used, as detailed in the HFIAS Indicator Guide v3 (Appendix A) [18]. The HFIAS represented a generally increasing level of severity of food insecurity and how often the condition occurred [18]. If the response to the condition described in the corresponding occurrence question was yes, the farmworker household-head was asked to describe how often a condition had occurred in the past 30 days. The four categories of food security status comprise the following as detailed in the HFIAS Indicator Guide v3 [18]:

1. A food-secure household experiences none of the food insecurity (access) conditions or just experiences worry, but rarely. HFIA category = 1 if ((Q1a = 0 or Q1a = 1) and Q2 = 0 and Q3 = 0 and Q4 = 0 and Q5 = 0 and Q6 = 0 and Q7 = 0 and Q8 = 0 and Q9 = 0).
2. A mildly food-insecure household sometimes or often worries about not having enough food and is unable to eat preferred foods, or eats a more monotonous diet than desired, or, however rarely, eats some foods considered undesirable. HFIA category = 2 if ((Q1a = 2 or Q1a = 3 or Q2a = 1 or Q2a = 2 or Q2a = 3 or Q3a = 1 or Q4a = 1) and Q5 = 0 and Q6 = 0 and Q7 = 0 and Q8 = 0 and Q9 = 0).
3. A moderately food-insecure household sacrifices quality more frequently, by eating a monotonous diet, or, sometimes or often, undesirable foods. They sometimes,

however rarely, start cutting back on quantity by reducing the size or number of meals, although they do not experience any of the three main severe conditions. HFIA category = 3 if ((Q3a = 2 or Q3a = 3 or Q4a = 2 or Q4a = 3 or Q5a = 1 or Q5a = 2 or Q6a = 1 or Q6a = 2) and Q7 = 0 and Q8 = 0 and Q9 = 0).

4. A severely food-insecure household goes further to cut down on meal size or the number of meals, and/or experiences any of the three most severe conditions (running out of food, going to bed hungry, or going the whole day and night without eating). HFIA category = 4 if (Q5a = 3 or Q6a = 3 or Q7a = 1 or Q7a = 2 or Q7a = 3 or Q8a = 1 or Q8a = 2 or Q8a = 3 or Q9a = 1 or Q9a = 2 or Q9a = 3) [18].

3.6. Estimating Determinants of Farmworkers' Food Insecurity: Ordered Probit Model

The Ordered Probit is suitable for modeling with an ordered categorical dependent variable and determines factors that influence farmworkers' food security status. The dependent variable in this study was farmworkers' food security, grouped into four ordered categories. The four categories were formulated such that a household can fall into any one of the four categories during a survey depending on the household's socioeconomic condition. The categories were Q_1 (food-secure), Q_2 (mildly food-insecure), Q_3 (moderately food-insecure), and Q_4 (severely food-insecure).

The respective category for food security is unobserved and is denoted by the latent variable $\boldsymbol{Q_i}$*. The latent equation below models how $\boldsymbol{Q_i}$* varies with personal characteristics.

$$\boldsymbol{Q_i}* = \boldsymbol{X_i} \tag{1}$$

where $\boldsymbol{Q_i}$* measures the difference in the value derived by individual *i* from either food-secure, mildly food-secure, moderately food-insecure, or severely food-insecure. *i* = 1, 2, 3 ... n; n represents the number of respondents. Each individual *i* belongs to one of the four groups. *X* is a vector of exogenous variables.

Following [37], and taking the value of 4 if the household was severely food-insecure and 1 if a household was food-secure, the implied probabilities are as follows:

$$\begin{gathered}
\Pr\{\boldsymbol{Q_i} = 1|\boldsymbol{X_i}\} = \Phi\,(-\boldsymbol{X_i}\beta), \\
\Pr\{\boldsymbol{Q_i} = 2|\boldsymbol{X_i}\} = \Phi\,(\mu_2 - \boldsymbol{X_i}\beta) - \Phi\,(\mu - \boldsymbol{X_i}\beta), \\
\Pr\{\boldsymbol{Q_i} = 3|\boldsymbol{X_i}\} = \Phi\,(\mu_3 - \boldsymbol{X_i}\beta) - \Phi\,(\mu_2 - \boldsymbol{X_i}\beta), \\
\Pr\{\boldsymbol{Q_i} = 4|\boldsymbol{X_i}\} = 1 - \Phi\,(\mu_3 - \boldsymbol{X_i}\beta).
\end{gathered} \tag{2}$$

where μ_i is the unknown parameter that is estimated jointly with β. Estimation is based upon the maximum likelihood, where the above probabilities enter the likelihood function. The interpretation of the β coefficients is in terms of the underlying latent variable model in the equation.

The probability of households being found between 1 and 4 can be written as:

$$\Pr\,(\boldsymbol{Q_i} = 1) = \Phi\,(\boldsymbol{X_i}\beta_1) \tag{3}$$

where Φ (·) is the cumulative distribution function (cdf) of the standard normal.

3.7. Definitions of Variables

The ordered probit model was used to determine farmworkers' characteristics that predict their food security status. The farmworker food security determinants were obtained through a review of the literature. A description of the explanatory variables used in the ordered probit model and the expected signs of the potential explanatory variables are provided in Table 1. The "+" means the variable is expected to have a positive effect on the dependent variable "−"means the variable is expected to have a negative effect on the dependent variable.

Table 1. Description of independent variables used in the model.

Variables	Measures	Expected Sign
Age	Years	−
Gender	Male = 1; Female = 0	−
Marital status	Married = 1; Single = 0	+
Level of education	1 = Formal education; 0 = Non-formal education	−
Number of dependents	Number of dependents	−
Leasing land from employer	Yes = 1; No = 0	−
Land size	Hectares	−
Food storage	Yes = 1; No = 0	−
Total monthly income	Rand (R)	−
Total monthly household expenditure	Rand (R)	+

Source: Research survey, 2020. + means the variable is expected to have a positive effect on the dependent variable; − means the variable is expected to have a negative effect on the dependent variable.

The coefficients of the ordered probit model did not represent the magnitude of the effects of the explanatory variables. A positive value indicates an increase in the food insecurity prevalence, which implies an increase in the likelihood that a household would be food-insecure. In contrast, a negative coefficient implies a likelihood that a household would be more food-secure.

The age of the household head is a continuous variable measured in years. Age is expected to influence farmworkers' food insecurity negatively. The more experienced the household head is, as expressed in the age of the head of household, the fewer chances for a household to be food-insecure [38].

The gender of the household head is a dummy variable that takes the value of 1 if the respondent is male and 0 if the respondent is female. Females have a high dependency and are likely to have fewer chances of participating in other income-generating activities [39]. A negative effect on food insecurity is expected.

Female household heads have fewer years of education and resources than male household heads. A negative effect on food insecurity is expected [40].

The marital status of the household head is a dummy variable that takes the value 1 if the household head is married and 0 if otherwise. Married household heads may have a larger household size and are liable to feed more mouths in the household. A positive effect is expected in the study [41].

The level of education is a dummy variable that takes the value of 1 if the household head has acquired formal education and 0 if otherwise. A negative effect is expected between the level of education and household food security. Food insecurity decreases with higher levels of education achieved by a household head. Education positively influences the household head's production and nutritional decisions [40].

The number of dependents is a continuous variable. A positive effect is expected as a household head with a small household is likely to be food-secure and feed fewer mouths compared to a large household [40].

Land leasing is a dummy variable that takes the value of 1 if the household head leases land from an employer and 0 if otherwise. Irrigation farmworkers' households who lease irrigation scheme plots from their employers are expected to be more food-secure than those who do not lease. Leasing land is often used to generate quick cash in response to emergency needs [42]. Therefore, a negative effect is expected in the study.

Food storage is a dummy variable that takes 1 if the household head stores food for emergencies to alleviate future malnutrition shocks, drought, or high food prices. A negative effect is expected between food storage and household head food security. Land size is a continuous variable. In this study, farm size is expected to affect household head food insecurity negatively. More food storage can alleviate any future shocks such as droughts and high food prices [37].

Total monthly income is a continuous variable measured in Rand (R). According to income determines the quantity and quality of food that a household can access, taking into account the size of the household. High incomes can increase household purchasing power and food security. Conversely, low incomes can adversely affect food security because households cannot buy food [39]. A positive effect was expected in the study.

Total monthly household expenditure is a continuous variable measured in Rand (R). Households with a higher proportion of their total income spent on food are more vulnerable to the dynamics of food prices than households with a lower proportion of food [43]. A negative effect was expected in the study.

4. Result

4.1. Descriptive Statistics

The explanatory variables were checked for normality and were deemed normal. The sample of 191 irrigation farmworkers was dominated by female farmworkers (62.8%). Middle-age irrigation farmworkers dominated in the Tshiombo Irrigation Scheme with an average of 46 years for both males and females. Most of the respondents surveyed resided in households with more than five members. About 55.5% of the respondents had acquired formal education and 44.5% had no formal schooling. While 51% of the irrigation farmworker households were food-secure, 7.3% were mildly food-insecure, 19.9% were moderately food-insecure, and 20.9% were severely food-insecure.

Table 2 presents the parametric one-way Analysis of Variance (ANOVA) test results of continuous variables. The land size was statistically significantly different between food-secure, mildly food-insecure, moderately food-insecure, and severely food-insecure. The ANOVA test indicated that recipients of land who were food-secure received 1.94 plots, those who were mildly food-insecure received 2 plots, those who were moderately food-insecure received 1.34 plots, and those who were severely food-insecure received 4 plots. There was a statistically significant difference in the total household monthly expenditure between food-secure, mildly food-insecure, moderately food-insecure, and severely food-insecure. Table 2 shows that every month, a food-secure irrigation farmworker spent R2222, a mildly food-insecure farmworker spent R1894 a month, a moderately food-insecure irrigation scheme worker spent R2306, and a severely food-insecure irrigation scheme farmer spent R2613.

Table 2. Parametric One-Way ANOVA results for farmworkers' food security determinants.

Variables (Mean)	Food-Secure	Mildly Food-Insecure	Moderately Food-Insecure	Severely Food-Insecure	*p*-Value
Age (Years)	44.98	51.50	46.42	47.63	ns
Number of dependents	4.96	5.57	5.02	5.57	ns
Land size (ha)	1.94	2.00	1.34	4.00	***
Total household monthly expenditure (ZAR)	2222.82	1894.28	2306.32	2613.75	*
Total household monthly income (ZAR)	2026.36	1557.14	1744.47	1817.30	ns

Note: *** and * mean the coefficient is statistically significant at 1% and 10% levels, respectively. ns = not statistically significant. Source: Research survey, 2020.

Table 3 presents the chi-square test results of categorical variables. A statistically significant relationship exists between irrigation farmworker food security status and leasing of land from the employer ($p < 0.01$). These results were in line with our hypothesis. Table 3 shows that 64.5% of the irrigation farmworkers who leased land from employers were food-secure, 22% were mildly food-insecure, 7.8% were moderately food-insecure, and 5.3% were severely food-insecure. In the category of irrigation farmworkers who could not lease land from employers, 32.5% were food-secure, 7% were mildly food-insecure, 22.8% were moderately food-insecure, and 37.7% were severely food-insecure.

Table 3. Association between food security and socioeconomic parameters.

Variable	Measure	Food-Secure (n = 99) (%)	Mildly Food-Insecure (n = 14) (%)	Moderately Food-Insecure (n = 38) (%)	Severely Food-Insecure (n = 40) (%)	n	X^2 Sig. Level
Marital status	Single	45.0	8.0	20.0	27.0	100	ns
	Married	59.3	6.6	19.8	14.3	91	
Gender	Female	46.7	6.7	23.3	23.3	120	ns
	Male	60.6	8.5	14.1	16.9	71	
Leasing land from employer	No	32.5	7.0	22.8	37.7	77	***
	Yes	64.9	22.0	7.8	5.3	114	
Level of education	No form education	50.20	8.2	14.1	27.1	85	ns
	Formal education	52.8	6.6	24.5	16.0	106	
Food stored	No	4.6	7.1	42.4	45.9	66	***
	Yes	89.7	7.5	1.9	0.9	125	

Note: *** means the coefficient is statistically significant at 1%. ns = not statistically significant. n = sample size. X^2 = chi-square. Source: Research survey, 2020.

A statistically significant relationship was found between irrigation farmworkers' food security status and food storage ($p < 0.01$). The results indicated that 89.7% of irrigation farmworkers who stored food were food-secure, 7.5% were mildly food-insecure, 1.9% were moderately food-insecure, and 0.9% were severely food-insecure. In the comparison of irrigation farmworkers who did not store their food, 4.6% were food-secure, 7.1% were mildly food-insecure, 42.4% were moderately food-insecure, and 45.9% were severely food-insecure.

4.2. Determinants That Influence Irrigation Scheme Farmworkers' Food Security Status

The ordered probit model was used to determine household characteristics that influence irrigation farmworker households' food security status (Table 4). The results indicate that all estimated coefficients are statistically significant as the LR X^2 statistic is statistically significant ($p < 0.01$). The coefficients of the ordered probit model do not represent the magnitude of the effects of the explanatory variables. Instead, the marginal effects are discussed. It follows that a positive coefficient implies an increase in the likelihood that a household would be food-insecure. In contrast, a negative coefficient implies a likelihood that a household would be food-secure. The results indicate that irrigation farmworkers' characteristics such as land leasing, food storage, land size, and total household expenditure are statistically significant determinants of food security.

Table 4. Ordered probit results of determinants of household food insecurity.

Independent Variables				Marginal Effects			
	Coefficients	Robust St. Error	$p > z$	Food-Secure	Mildly Food-Insecure	Moderately Food-Insecure	Severely Food-Insecure
Gender	−0.051	0.233	0.826	0.020	−0.002	−0.015	−0.003
Marital status	−0.206	0.219	0.345	0.081	−0.009	−0.060	−0.012
Level of education	0.240	0.261	0.359	−0.095	0.011	0.070	0.013
Leasing land from employer	−0.691	0.259	0.008 ***	0.266 ***	−0.018 ***	−0.199 ***	−0.048 ***
Total monthly income	−0.0001	0.0001	0.159	0.0068	-7.45×10^{-6}	−0.0051	−0.0001
Food storage	−3.028	0.273	0.000 ***	0.854 ***	−0.005 ***	−0.460 ***	−0.388 ***
Land size	0.144	0.057	0.012 **	0.002 **	0.006 **	0.042 **	0.008 **
Total monthly household expenditure	0.0002	0.0001	0.035 **	−0.0091 **	9.99×10^{-6} **	0.0068 **	0.0013 **

Note: Number of observations = 191. LR X^2 = ***. Pseudo R^2 = 0.48; Log likelihood = −116.57. ** and *** mean the coefficient is statistically significant at 5% and 1% levels, respectively. Research survey, 2020.

5. Discussion

The study hypothesis was that irrigation scheme farmworkers who rent land from landlords are more food-secure than nonland-renting irrigation scheme farmworkers. In agreement with the results in Table 3, the results show that there is a statistically significant and positive relationship between leasing land and food security among irrigation farmworkers. Similarly, the results in Table 4 also show that leasing land is statistically significant and, as expected, has a negative influence on farmworkers' food insecurity status. This implies that when an irrigation farmworker can lease land from their employer, they have lower chances of becoming food-insecure. The results indicate that if a household head leases land from an employer, the household will have a 26.6% chance of becoming food-secure and about a 1.8% worse probability of becoming mildly food-secure. Similarly, suppose an irrigation farmworker has no access to leasing land, then the household has a 19.9% chance of moving into the moderately food-insecure and another 4.8% chance of dropping into the severely food-insecure category. The results build on the existing evidence by [44] that land rental markets play an important role in enhancing income in the short run and can effectively eradicate poverty and food insecurity in rural households as a safety net from food insecurity shocks. The land is the most productive asset for rural residents in developing countries to curb food insecurity and unemployment [45]. African countries such as Malawi, Zambia, Kenya, and Ethiopia are involved in land rental markets [46], but the land market contract arrangements vary considerably across countries. The majority of the land African smallholder farmers use is under a customary system, making the sale of land prohibited. Land rental markets are a significant way of re-adjusting land-labor ratios among farming households [42]. Leasing land is often used to generate cash in response to emergency needs. Poor households cannot afford to rent land, and having an unstable income makes it difficult to have the financial security needed to rent land [47]. The Government of Ethiopia allows land leasing and informal transfers of irrigable land, but not land sales, to avoid the issues of land redistribution.

Table 3 shows that land size is statistically significant and has a relationship with farmworkers' food security status. However, contrary to expectations, the ordered probit model in Table 4 shows that land size is statistically significant and positively influences farmworkers' food insecurity. This suggests that when land size increases, food insecurity also increases among farmworkers. The results indicate that a one-hectare increase in the land household has resulted in a 0.2% increase in the chance of becoming food-insecure from food-secure and about a 0.6% increase in the chance of becoming mildly food-insecure. Similarly, a hectare in area access increases the chances of a household moving from mildly food-insecure to moderately food-insecure by 4.2%, and a 0.8% chance of falling under the severely food-insecure category. However, our results do not support the existing evidence by Nkomoki, et al. [48,49]. A possible explanation is that household heads might have resource constraints for investing in their land. Nkomoki, Bavorová and Banout [48] studied the influence of land size on household food consumption score (FCS) and household hunger score (HHS) in Zambia. Their findings showed that land size is associated with households being less likely to be in the poor FCS. Furthermore, our finding is not in agreement with [49], who used a model similar to ours to estimate if the land size was a determinant of household food and nutrition security in Myanmar. Their result indicated that an increase in land size enhanced household food security status. Similarly, our result is not aligned with that of [50], who analyzed the relationship between land access and food security in Kenya. They demonstrated that an increase in land size resulted in a rise in household food security.

In agreement with the results in Table 3, the results show that there is a statistically significant and positive relationship between total monthly farmworker household expenditure and food security among irrigation farmworkers. Similarly, the results in Table 4 also show that the total monthly farmworker household expenditure is statistically significant and is positively related to household food insecurity. This implies that a one-Rand increase in monthly expenditure on basic household needs has a 0.9% chance of remaining food-secure. The same households have a 0.68% chance of moving into moderately food-insecure and 0.13% probability of falling into severely food-insecure categories if there is a Rand short in their total monthly expenditure. A possible explanation would be that there is no direct relationship between monthly income and monthly expenses. Irrigation farmworkers could be vulnerable to food insecurity due to monthly expenditures exceeding their monthly income. The findings are consistent with the findings of [51].

In agreement with Table 3, the descriptive statistic results show that the variable food stored is statistically significant and has a relationship with farmworkers' food security status. Similarly, Table 4 shows that the food stored by irrigation farmworkers is statistically significant and negatively related to food insecurity. This suggests that the probability of a household being food-secure increases as the household head stores food for long-run purposes, such as future shocks due to loss of employment for farmworkers during off-seasons. The results indicate that if a household head stored food, the household will have an 85.4% chance of becoming food-secure and about a 0.5% worse chance of becoming mildly food-secure. In a similar year, if a household head does not store food for future shocks, the household has a 46% chance of moving into moderately food-insecure and a 38.8% chance of falling under the severely food-insecure category. A study by [52] pointed out that despite the abundant food supply in South Africa, food storage is needed as it plays a significant role in ensuring food availability at a household level.

6. Conclusions

The main aim of the study was to determine the food security status among farmworkers. Food security was measured by a Household Food Insecurity Access Scale. From the study sample, the ordered probit model revealed that the total household monthly expenditure and land size lower the probability of a household being food-insecure. On the other hand, leasing land and food storage increase the probability of a household being food-secure. Based on the study's findings, the total household expenditure lowered the probability of farmworkers being food-secure. The study recommends that stakeholders should encourage farmworkers to engage in nonfarm activities to reduce food insecurity. Regarding the study's hypothesis, the results showed that irrigation farmworkers who leased land had a better chance of becoming food-secure and had a worse chance of becoming mildly food-insecure, moderately food-insecure, and severely food-insecure than those who do not lease land. Based on the findings, the study recommends an involvement of private and public stakeholders to provide training that will promote livelihood skill development and the provision of resources to lessen the chances of recipients falling into the severe food insecurity category.

Encouraging farmworkers on irrigation schemes to rent land from their employers will reduce household food insecurity. These findings suggest that policymakers should design policies that enhance irrigation farmworkers' food security through engagement in informal land lease contracts to enable land rental market participation by farm employers and farm workers in rural areas such as Tshiombo Village.

Food security is a complex subject whose accomplishment can be measured in various ways such as HDD, CSI, and HFIAS. This study only used the HFIAS tool for measuring food security among irrigation scheme farmworkers in Tshiombo. Therefore, the study's findings should not be generalized to all irrigation schemes, as circumstances may be different. The study should be supplemented with studies that use other tools for measuring food security so that a more comprehensive conclusion can be drawn. It is vital to note that ongoing research on the issue of food security status among farmworkers in irrigation schemes is needed. To fully understand the complex dynamics of this issue and to acquire more information on the diverse conditions regarding food and nutrition insecurity among farmworkers laboring in smallholder farms, this would include:

- An examination of income inequality among farmworkers could provide further insight into the welfare of rural farmworker households. Income inequality was not examined in this study.

- A comparative investigation of a seasonal hunger analysis among farmworkers in rural households needs to be investigated through monthly to yearly monitoring indicators, which measure different aspects of food insecurity and determine to what extent food security fluctuates.

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Appendix A

Household Food Insecurity Access scale
In the past four weeks . . .

a. Did you worry that your household would not have enough food?
b. Were you or any household member not able to eat the kinds of foods you preferred because of a lack of resources?
c. Did you or any household member have to eat a limited variety of foods due to a lack of resources?
d. Did you or any household member have to eat some foods that you did not want to eat because of a lack of resources to obtain other types of food?
e. Did you or any household member have to eat a smaller meal than you felt you needed because there was not enough food?
f. Did you or any household member have to eat fewer meals in a day because there was not enough food?
g. Was there ever no food to eat of any kind in your household because of a lack of resources to get food?
h. Did you or any household member go to sleep at night hungry because there was not enough food?
i. Did you or any household member go a whole day and night without eating anything because there was not enough food?

Respondents indicate whether the response is Yes, or No. If the response is "Yes", then they are asked to indicate the extent to which they agree with the statement. The responses of frequency are coded 0, 1, and 2, where (0) Rarely (once or twice in the past four weeks), (1) Sometimes (three to ten times in the past four weeks), and (2) Often (more than ten times in the past four weeks) [18].

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Review

A Systematic Review of Indigenous Food Plant Usage in Southern Africa

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Abstract: Indigenous food plants provide various social functions; they are crucial to food supply diversification efforts, and they improve food and nutrition security. Research has shown that indigenous foods' nutritional potential and advantages have yet to be adequately appreciated and explored. This systematic review discusses the various elements contributing to IF promotion, which may help increase their intake. Therefore, a systematic literature review was conducted to determine the availability, regularity of consumption, utilisation, preparation, harvesting, and preservation of indigenous foods. Additionally, this review details the knowledge, perceptions, and beliefs of IFs under these themes. The findings of this systematic review highlight the importance of promoting IFs through policies, the development of capabilities and skills, in-depth research, and an extensive indigenous food plant composition. The fact that Southern African populations do not value indigenous foods and their potential advantages appears to be a significant barrier. Furthermore, the younger generation has lost access to the older generations' indigenous food knowledge. Thus, the preservation of indigenous food knowledge in books and continuing education of the younger generation about the importance of consuming indigenous foods and the nutrition content they contain may help with its uptake.

Keywords: indigenous food plants; indigenous foods; indigenous food knowledge; promotion

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1. Introduction

Approximately 820 million people globally are undernourished [1]. The Food and Agriculture Organization (FAO) estimates that 239 million of the 820 million malnourished people are from Sub-Saharan Africa (SSA). Hunger has been reported as rising in almost all sub-regions of Africa, Latin America, and Western Asia, with approximately 11 million annual deaths attributed to dietary risk factors [1]. Approximately two million deaths were reported to be associated with an inadequate intake of fruit and vegetables. South Africa was said to have accounted for approximately one-half million of these deaths, with a deficient intake of fruits and vegetables [2]. Okop et al. [3] asserted that an inadequate intake of fruits and vegetables contribute to a burden of diseases, resulting in death from gastrointestinal cancer, ischaemic cardiac disease, and strokes. However, there is a significant proportion of diverse indigenous foods (IFs) available in Southern Africa that has been neglected, resulting in food insecurity in the countries [4–6]. Historically, these foods were once the sole dietary components of humankind in Africa, serving as food and medicine [7,8].

IFs have been receiving worldwide attention recently due to their ability to contribute to higher-quality nutrition, more sustainable diets, and food and nutrition security [8,9]. A study conducted in India found that communities consuming diverse IFs had an increase in macro-nutrients (protein) and micro-nutrients (calcium, vitamin A, iron, thiamine, riboflavin, and folate) [10]. Their study was supported by other studies conducted in Africa (Kenya, Botswana, South Africa, Eswatini, and Zimbabwe) [11–13], where IFs were reported to be rich in macro-nutrients (protein) and micro-nutrients (calcium, vitamin A, potassium, magnesium, zinc, and iron). These foods were said to have the ability to improve food security through their availability, accessibility, sustainability, and utilisation [11–13]. The nutritional superiority of these foods over exotic foods has been established [14–16].

Other essential contributions of indigenous food plants (IFPs) to local economies and diets compared with exotic foods are drought resistance [6], conservation of biodiversity [17], indigenous food knowledge (IFK) [18], and provision of household income [19]. These findings contradict the assumption that Africans have little interest in traditional foods.

However, despite the benefits and knowledge mentioned above, IF production and consumption have declined since the olden days. Commercial farming, research, and development have significantly ignored these foods, making them less competitive than established major crops [20]. They are "usually excluded from official statistics on economic values of natural resources" [16]. This under-utilisation of IF stems from limited knowledge of these foods' nutritional content and health benefits, loss of IFK, and paucity of knowledge transfer across generations. This may be due to IF being associated with poverty in communities where they are grown and low self-esteem by those consuming them in these communities. Additionally, the lack of cultivation of these plants at a larger scale in modern commercialised and industrialised economies, i.e., the westernisation of agriculture, has significantly impacted the exclusion of these crops from commercial farming. Lastly, the shifting of dietary ideals and attitudes, cultural changes among African people, or lack of research and development of traditional recipes that are easy to prepare has also contributed to the disappearance of these crops from the everyday diet [6,16,21].

Crane et al. and Van Wyk [22,23] stressed the need for a comprehensive and systematic reference source for IF use. These authors highlighted the need for scholars to value, document, and protect IFs and IFK about plants and nature. There has yet to be a known comprehensive study on an ethnobotanical survey of indigenous or traditional plants of Southern Africa. Welcome and van Wyk [24] conducted the most recent extensive inventory on this topic. However, the authors focused only on the Southern African flora, excluding other Southern African countries, such as Angola, Malawi, Mozambique, Zambia, and Zimbabwe.

This paper aims to systematically review existing empirical studies and synthesise the findings regarding the availability of IFs in Southern Africa, including factors leading to their utilisation. We explore and reveal the current ethnobotanical information regarding the availability, accessibility, consumption, utilisation, preparation, preservation, knowledge, and perception patterns of IF. Specifically, we use this systematic review to answer two key questions: (1) which IFs are available in Southern Africa and what is their usage? and (2) what are rural communities' perceptions regarding factors contributing to the barriers leading to the availability, accessibility, consumption, utilisation, preparation, preservation, knowledge, and perception patterns of IF in Southern Africa?

The lens utilised for this research is an indigenous knowledge system (IKS). It is understood that IFK is a significant part of Africa's cultural heritage [25]. The use of IFK in the African continent goes back to the history of humankind. Ghosh-Jerath et al. [26] asserted that, for millennia, indigenous plants have served humanity as food and medicine in almost all societies. Therefore, it is essential to retain IFK, as there is a fear of losing this knowledge reservoir. It is reported that older generations, who are the carriers of indigenous knowledge, may only die by passing this reservoir of knowledge to the younger generation [27]. We posit that the IFK transfer may assist in promoting IFs' utilisation through consumption, preparation, and preservation. For this review, "indigenous foods" refers to indigenous/traditional vegetables and fruit.

2. Review Author's Reflexivity

All systematic review authors have extensive knowledge of IF. They grew up consuming these foods and are still consuming some of them (Zoe Nomakhushe Nxusani (Z.N.N.)

of Eastern Cape; Xikombiso Gertrude Mbhenyane (X.G.M.) of Limpopo, and Mthokozisi Kwazi Zuma (M.K.Z.) of KwaZulu Natal. X.G.M. has conducted numerous types of research on the health benefits of these foods [16,28–30]. They all believe in their promotion to combat food insecurity and malnutrition. All these factors may influence how the review was conducted and how findings were interpreted. However, we kept reflecting on our disciplinary backgrounds, past knowledge, and pre-conceived assumptions and opinions throughout the study. We encouraged each other to think critically about how these might influence the review procedures. The team discussed preliminary findings regularly to identify assumptions in the data synthesis, explore different perspectives among review authors, and document judgments made during the review process.

3. Methodology

A systematic review approach was employed to acquire and synthesise information on IFs in the Southern African context. Our review qualifies as a systematic map that summarises the existing data regarding the different aspects of a particular subject and identifies knowledge gaps since we have broad research questions.

3.1. Eligibility Criteria

The SPIDER (Sample [S], Phenomenon of Interest [PI], Design [D], Evaluation [E], and Research type [R]) tool was utilised to conduct a non-interventional review of existing studies to describe the eligibility criteria [31]. The framework was employed to expand thinking beyond the PICO (Problem [P], Intervention [I], Comparison [C], and Outcome [O]) framework, as it is more appropriate when exploring a non-intervention question and has practical application to qualitative and mixed-methods research [31]. We captured the topic of the review by adhering to the critical aspects of the SPIDER tool; thus, in the sample, we focused on studies conducted in rural communities of Southern African countries. Communities included, but were not limited to, elders, men and women, youth, traders, and farmers. The PI was studied by investigating the availability, accessibility, consumption, preparation, preservation, and utilisation of IFs. Perceptions, views, experiences, and practices were included in the selection. Qualitative, quantitative, and mixed research methods were included in the review process (see Table 1). The SPIDER tool has been used in several systematic reviews [32–34], making it an appropriate tool for this specific review.

Table 1. Systematic review eligibility criteria according to SPIDER criteria.

Spider Tools [1]	Search Terms
S	Southern African rural communities
PI	Studies investigating the availability, accessibility, consumption, preparation, preservation, and utilisation of indigenous foods
D	All study designs
E	Perceptions, views, experiences, and practices of the participating groups
R	Qualitative, quantitative, and mixed-methods

[1] S: Sample; PI: Phenomenon of Interest; D: Design; E: Evaluation; R: Research type.

3.2. Literature Search

The literature search for this review encompassed electronic resources, such as Medline/PubMed, ScienceDirect, African Digital Research Repositories, Google Scholar, and Ebscohost. In total, 14,111 studies were identified from the search process. These include Google Scholar (*n* = 5180), ScienceDirect (*n* = 157), Africa-Wide Information (*n* = 1405), CINAHL (*n* = 1224), Medline (*n* = 3160), African Digital Research Repositories (*n* = 669) and Registers (*n* = 2316). Both published and unpublished scientific articles (papers, conference proceedings, and theses) and public articles (government and non-government gazettes and reports) formed part of the search. The keywords used to search for relevant studies included: ((rural*) AND (youth* or children* or adolescence*) AND (elders* or seniors*) AND (farmers* or agriculturalists* or growers* or cultivators*) AND (indigenous foods* or traditional foods* or underutilized* plants* or neglected foods* or African vegetables*) AND (availability* or accessibility* or access*) AND (preparation* or preparedness* or readiness*) AND (consumption* or intake* or eating*) AND (utilization*) AND (perceptions* or views* or opinions*) AND (experiences* or practices* or knowledge*)). A string of several combinations of search terms were used to provide a wide variety of searches in the database (see Table 2). These terms were searched for and identified in abstracts and subject descriptors. A combination of databases that included electronics, books, and hand-searched journals were explored using the specified keywords. Only papers published from 2011 to 2021 were included in the search criteria. Additionally, documents from reference lists and bibliographies were searched.

Table 2. Search algorithm.

Variation	**Setting**		**Population**			**Phenomenon of Interest**	**Evaluation**	
Indigenous foods	Rural communities	Southern Africa	Youth	Elders	Farmers	Availability	Perceptions	Experience
Traditional foods	Rural areas	Angola	Children	Seniors	Agriculturist	Accessibility	Views	Practices
Underutilised plants		Botswana	Adolescent	Older people	Growers	Consumption	Opinions	Knowledge
Neglected foods		Lesotho	Young people		Cultivators	Preparation	Attitude	Awareness
African foods		Mozambique	Young adults		Ranchers	Preservation	Beliefs	
Native foods		Namibia				Utilisation		
		South Africa						
		Swaziland						
		Zambia						
		Zimbabwe						

3.3. Inclusion and Exclusion Criteria

Several inclusion and exclusion criteria had to be met for the studies to be included in this review.

(a) Inclusion criteria

The inclusion criteria for the review were: qualitative, quantitative, and mixed-methods articles published between 2011 and 2021, articles exploring barriers, and knowledge of rural communities of indigenous plants in Southern Africa. Southern Africa consists of nine countries: Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Eswatini, Zambia, and Zimbabwe (see Figure 1). All IFPs found in these Southern African countries, along with their uses, were included in the review.

This study defines the following terms:

- Rural inhabitants: includes elders, women, youth, food traders, and farmers.
- Barriers: includes preparation, preservation, availability, acceptability, and consumption of IFs.
- Knowledge: refers to perceptions, beliefs, attitudes, and practices.

Figure 1. The map of Southern African countries with indigenous food plants and knowledge discussed in this review [35].

(b) Exclusion criteria

Studies were excluded if they were (1) published outside the 2011 to 2021 study period; (2) reported findings on communities residing in urban areas; (3) reported on indigenous birds, insects, and sea mammals; (4) reported findings from countries outside the Southern African region; (5) published in languages other than English or IsiXhosa; and lastly,(6) were conducted on children aged 13 or less.

3.4. Data Collection

Title and abstract screening were carried out to retrieve relevant articles for the review. A single reviewer selected relevant articles (Z.N.N.), and they were double-checked by another reviewer (M.K.Z.). The chosen studies underwent the full-text screening stage, where extensive study screening occurred. Both screening processes were duplicated to ensure the synthesis process's reliability and eligibility (Z.N.N. and M.K.Z.). After screening completion, data were presented in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow chart diagram [36]. The PRISMA Statement included a 27-item checklist and a 5-phase flow diagram representing the review's search process [36].

3.5. Definition of Key Terms

Indigenous food: These crops originate in South Africa, either in that particular country or region. These foods were introduced into the country over centuries and are now known as naturalised or conventional harvests mentioned by the Department of Agriculture cited in van Rensburg [37]. For this review, "indigenous foods" is defined as native fruits and vegetables, those introduced to a region a long time ago, and traditional recipe foods.

Exotic food: These plants are imported from one country to another. They are not naturally found in the environment in which they currently exist [38].

Food utilisation: This is defined by the United States of International Development (USAID) as "food is properly used, proper food processing and storage techniques are employed, adequate knowledge of nutrition and childcare techniques exists and is applied, and adequate health and sanitation services exists. Thus, utilisation includes food storage, processing, health and sanitation, and related to nutrition" [39].

Food preservation: This is characterised as the procedures or methods used to control internal and external elements that could lead to food spoilage [40].

Indigenous knowledge system: Indigenous knowledge systems provide a knowledge system and know-how relevant to a particular community or culture that combines local people's cultural customs, morals, views, and worldviews [41].

3.6. Quality Appraisal

A quality appraisal tool was adapted from qualitative and quantitative research studies tools [42]. According to the authors, a critical quality appraisal is empirical in systematic reviews, as it emphasises the high-calibre quality of the included studies.

The reason for this adaptation is that the review did not focus only on one research type but covered all three (qualitative, quantitative, and mixed methods). Therefore, a critical appraisal tool that covers all research designs needed to be developed (see Table 3). During the adaptation process, specific components were either omitted or merged. These concepts expressly referred to each methodological framework (qualitative or quantitative). For instance, features such as time scale, group comparability, and outcome measures in the quantitative and theoretical framework in qualitative were removed, and other sections, such as sample, were merged.

Table 3. GRADE-CERQual approach to systematic reviews.

Number	Themes	Confidence in Findings	Explanation in Confidence
1	Availability of indigenous foods	Moderate	Findings were reported by 26 studies with minor adequacy concerns on limited richness of data and moderate methodological limitation concerns.
2	Consumption of indigenous foods	High	Finding supported by 28 studies with rich data, and minor methodological and coherence concerns.
3	Utilization and consumption of indigenous foods	High	Findings were reported by 21 studies with rich adequate and relevant data with minor methodological limitations concerns.
4	Accessibility of indigenous foods	High	Only 9 studies reported this component. However, the data from these studies was rich, relevant and from a diverse population.
5	Harvesting and preservation of indigenous foods	Low	Only 6 studies reported this component with moderate adequacy concerns on limited richness of data, coherence of data and methodological limitation concerns.
6	Preparation of indigenous foods	Moderate	Findings reported by 13 studies with minor data richness and relevance concerns, and moderate methodological and coherence concerns.
7	Knowledge of indigenous foods	High	Finding supported by 20 studies with rich data and minor methodological concerns.
8	Beliefs and values towards indigenous foods	Low	Finding supported by 4 studies with limited richness in data, and some relevance, coherence, and methodological concerns.

Table 3. *Cont.*

Number	Themes	Confidence in Findings	Explanation in Confidence
9	Perceptions and attitudes regarding indigenous foods	High	Finding supported by 13 studies with rich data, and minor methodological and coherence concerns.
10	Frequency and acceptance and preference of indigenous foods	Moderate	Finding supported by 6 studies with rich data and minor methodological concerns, but with moderate coherence concerns.

This tool rated each study on the basis of two criteria. For each measure, a score was assigned. For instance, 2 denotes "Yes", and 1 denotes "No". A study-specific goal score ranging from 1 to 40 was calculated by summing up scores across all criteria. However, a comment section was provided to elaborate on the reasoning for scoring. This section provided a detailed and transparent assessment where methodological strengths and limitations were reported—these tools provided assessment of the methodological limitation component of the CERQual approach.

Studies that scored 80% and above were deemed high-quality papers. In contrast, those that scored between 60% and 80% were categorised as medium-quality papers. Those that scored below 60% were considered low-quality papers. Figure 2 summarises the quality assessment on the basis of the information reported in each study. The majority (30/34) of the selected studies scored above 80%, 3/34 scored medium to high, and only one study scored low (<60%). Of the eleven concepts, most studies indicated the bibliographic details, purpose, key findings, type of study, study settings, population, data collection, and data analysis. Most studies' other poorly reported concepts were ethics approval, issuing informed consent addressing validity or reflexivity, and outlining the researcher's potential biases. Two reviewers (Z.N.N. and M.K.Z.) conducted the assessment in duplicate.

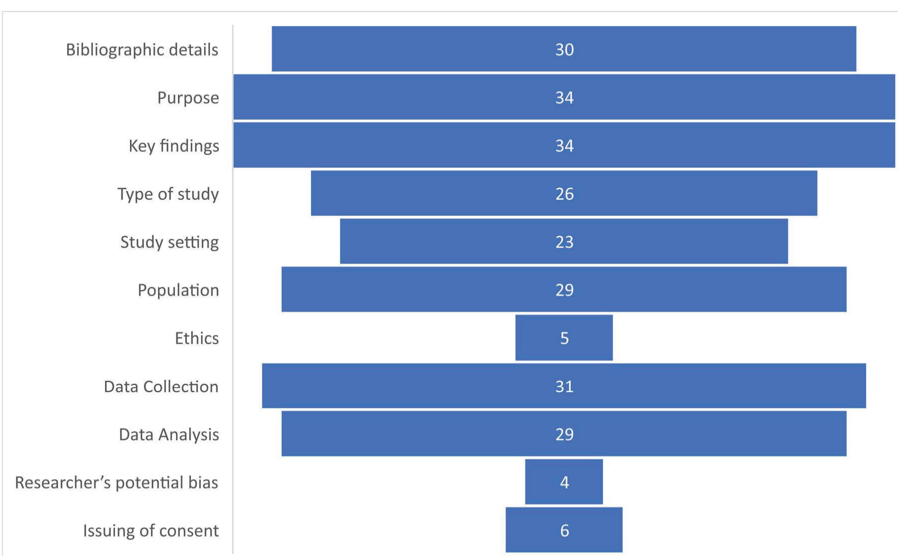

Figure 2. Quality appraisal concepts.

3.7. Assessment of Confidence in the Review Findings

The Confidence in the Evidence from Reviews of Qualitative Research (CERQual) technique was used to establish how much confidence to place in each review conclusion [43]

The Grade-CERQual approach includes four components: methodological limitations, coherence, adequacy, and relevance of data in assessing how much confidence to place in qualitative evidence synthesis.

Each criterion was assessed on three levels: (1) high (the phenomenon of interest is fully represented), (2) moderate (the phenomenon of interest is reasonably defined), and (3) low (the phenomenon of interest is not adequately represented). Of the seven phenomena of interest, utilisation and consumption, accessibility, and cultivation or production of IFs were adequately described. Likewise, the identification, availability, and preparation of IFs were reasonably represented. In contrast, the preservation of IFs could have been better defined. This shows that more research needs to be conducted on preserving these foods, as this is one of the components that will assist in the accessibility and stability of utilising IFs.

3.8. Data Extraction

Studies included in this systematic review underwent a rigorous data extraction phase. A standardised Google form was developed to systematically extract information from the articles (see Table 4).

The forms included the following key areas:

- Authors;
- Publication year;
- Study setting;
- Study design;
- Study population;
- The phenomenon of interest (availability, accessibility, cultivation, preparation, preservation, consumption, and utilisation);
- Evaluation (beliefs, acceptance, knowledge, frequency, and experience);
- Research type (qualitative, quantitative, or mixed methods).

This form was used for the synthesis and analysis of the impact of the evaluation on the phenomenon of interest. This process entails discovering patterns in data, with themes emerging as categories to aid analysis. Therefore, not all variables were applied to all studies represented in each work.

Table 4. Summary of the characteristics of the reviewed data.

Authors	Year of Publication	Study Period	Geographic Focus	Research Design	Sampling	Age		Sample Size	Availability	Consumption Frequency	Utilization	Accessibility	Harvest & Preservation	Preparation	Knowledge	Beliefs & Values	Perceptions & Attitudes	Frequency& Acceptance
Maroyi, A. [44]	2011	8 months	Zim	Qualitative	n/p	13–82	males, females, youth & community leaders	87		x	x			x				
Maroyi, A. [45]	2013	2 months	Zim	Qualitative	n/p	n/p	Households	147	x	x				x				
Bvenura, C., et al. [46]	2015	n/p	SA	Review	n/a	n/a	n/a	n/a	x	x				x				
Cloete, P., et al. [6]	2013	6 months	SA	Qualitative & quantitative	n/p	n/p	Households	600	x	x							x	
Kasimba, S., et al. [11]	2019	3 months	Bots	Qualitative	Random	18–49	253 females	253		x	x	x					x	
Taruvinga, A., et al. [47]	2015	n/p	SA	Quantitative	n/p	n/p	n/p	100	x	x				x			x	x
Kwinana-Mandindi, T.N. [48]	2014	12 months	SA	Qualitative & quantitative	Convenience	>18	Males and females	100	x	x	x	x	x	x	x	x	x	
Bruschi, P., et al. [49]	2019	7 months	Moz	Quantitative	n/p	16–90	30 males & 22 females	55	x		x				x			
Job, M. [7]	2018	n/p	Zim	Qualitative	Snowballing	60–90	females	n/p	x		x		x	x	x			
USAID [50]	2017	5 years	Mal & Zam	Qualitative	n/p	n/p	Mothers, fathers, health promoters, community leaders, health ministries & marketers	248,200	x	x			x				x	x
Welcome, A.K. and Van Wyk, B.E. [24]	2019	n/p	Bots, Les, SA, Swaz and Nam	Review	n/a	n/a	n/a	n/a	x	x								
van der Hoeven, M., et al. [51]	2013	n/p	SA	Qualitative & quantitative	Purposive	>18	Males and females	120	x	x	x	x	x	x	x	x	x	
Mbhenyane, X.G., et al. [29]	2013	n/p	SA	Quantitative	Convenience	>18	380 females & 323 males	703		x					x			

Table 4. *Cont.*

Authors	Year of Publication	Study Period	Geographic Focus	Research Design	Sampling	Age		Sample Size	Availability	Consumption Frequency	Utilization	Accessibility	Harvest & Preservation	Preparation	Knowledge	Beliefs & Values	Perceptions & Attitudes	Frequency& Acceptance
Mahgoub, S.A., et al. [52]	2013	n/p	Bots	Qualitative	Convenience	21–60	106 males & 106 females	212		x	x				x			
Dlamini, V.V. [5]	2017	n/p	Swaz	Mixed method	Convenience	>24	females	102	x	x	x	x	x	x	x			
Matenge, S.T., et al. [53]	2011	n/p	SA	Qualitative & quantitative	n/p	>20	Males & females	400	x	x	x				x	x		x
Mavengahama, S. [15]	2013	2 months	SA	Mixed method	Purposive	n/p	Males & females	99		x	x	x					x	
Nengovhela, R. [54]	2018	n/p	SA	Quantitative & qualitative	Random	n/p	Households	200	x	x	x	x			x		x	
Kasimba, S.N. [14]	2018	3 months	Bots	Qualitative & quantitative	Random	18–49	400 HH; 253 women; 18 street vendors	671	x	x	x	x					x	
Mungofa, N., et al. [55]	2018	3 months	SA	Qualitative	Random	18	Households	854	x	x		x			x		x	x
Masekoameng, M.R. and Molotja, M.C. [56]	2019	4 months	SA	Qualitative	Purposive	n/p	Households	168	x	x	x	x			x			
Matenge, S.T., et al. [57]	2012	4 months	SA	Quantitative & qualitative	Purposive	>20	Males and females	12	x	x	x	x			x		x	
Bultosa, G., et al. [58]	2020	n/p	Bots	Quantitative	n/p	40–87	Males and females	39	x						x			x
Rankoana, S. [59]	2021	12 months	SA	Qualitative	Purposive	32–97	20 males, 49 females & 20 cattle headers	89	x	x					x			
Omotayo, A.O., et al. [60]	2020	n/p	SA	Quantitative	n/p	20–70	Males & females	180	x	x	x				x			
Semenya, S.J. and Mokgoebo M. [61]	2021	n/a	SA	Review	n/a	n/a	n/a	n/a		x	x					x		
Mbhatsani, H., et al. [62]	2011	7 months	SA	Quantitative	Convenience	9–14 years	Children	172		x					x			x

Table 4. *Cont.*

Authors	Year of Publication	Study Period	Geographic Focus	Research Design	Sampling	Age		Sample Size	Availability	Consumption Frequency	Utilization	Accessiblity	Harvest & Preservation	Preparation	Knowledge	Beliefs & Values	Perceptions & Attitudes	Frequency& Acceptance
Lewu, F.B. and Mavenga-hama, S. [63]	2011	2 months	SA	Quantitative & qualitative	n/p	>59	Households	99	x	x	x						x	
Munsaka, C. [4]	2018	n/p	Zim	Qualitative	Purposive	>18	11 males; 24 female & 21 youth	56	x	x	x			x			x	
Urso, A., et al. [64]	2017	3 years	Ang	Qualitative	Snowballing	n/p	26 females; 40 males	66	x	x	x			x	x			
Mawunu, M., et al. [65]	2022	2 months	Ang	Qualitative	n/p	18–53	35 females; 30 males	65	x	x	x		x	x	x			
Aparicioa, H., et al. [66]	2021	3 months	Moz	Qualitative	Random	40–86	14 females & 11 males	25	x		x			x	x			
Thandeka, N., et al. [67]	2011	n/p	SA	Quantitative & qualitative	Convenience	31–60	42 females & 22 males	64	x					x	x		x	
							TOTAL		26	28	21	9	6	13	20	4	13	6
							Percent of 33 studies		78	85	64	27	18	39	61	12	39	18

n/p: not presented; n/a: not applicable.

4. Data Analysis Section

Data were analysed qualitatively, making use of thematic analysis. Thematic analysis refers to various text readings and refining findings into key themes [68]. These can be derived through critical messages and coding, utilising grouping codes into descriptive themes and further interpreted to analytical themes [69].

4.1. Study Screening and Selection

Figure 3 provides a visual representation of the methodological and screening process. The systematic search of the literature yielded 11,795 studies (Google Scholar: (n = 5180), ScienceDirect: (n = 157), Africa-Wide Information: (n = 1405), CINAHL: (n = 1224), Medline: (n = 3160), and African Digital Research Repositories: (n = 669)), with 10,888 excluded as duplicates or not relevant to the current study aims on the basis of using specific filters in the various search engines. All the 3223 studies that remained after all filters were implemented went through the abstract screening, where 2098 studies were excluded, resulting in 1125 studies that proceeded to the title-screening phase. Of these, 1032 were excluded for various reasons, as shown in Figure 2. Thus, 93 studies passed the full-text screening, leaving 45 eligible studies to be reviewed.

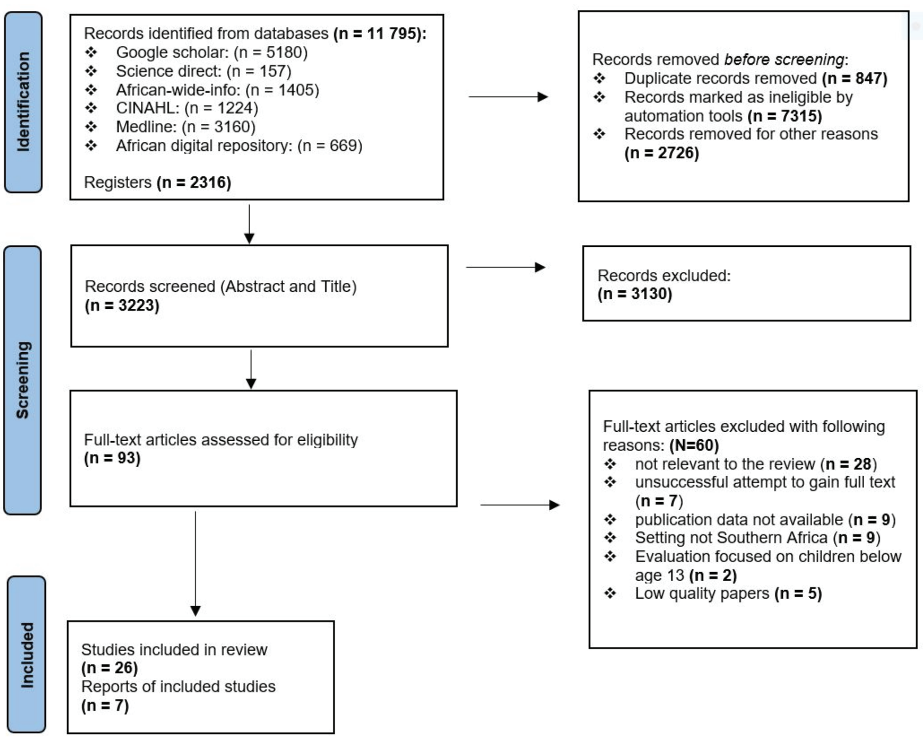

Figure 3. PRISMA flow diagram showing the process followed during the literature search and selection of included studies.

The 45 reviewed articles went through the GRADE-CERQual approach, where 12 were excluded, leaving 33 reviewed articles for analysis. Following a thorough evaluation of the entire texts of the 33 studies using the data inclusion/exclusion sheets, the second reviewer examined these studies and established 100% agreement on inclusion/exclusion.

4.2. Description and Characteristics of Included Studies

The review yielded 33 studies (3 reviews, 23 articles, and 7 theses). A summary of the descriptive characteristics of these datasets and studies is shown in Table 4. Of these datasets, 79% are from journals, and only 21% are from academic theses, which were not published in journals. Experience from 10 Southern African countries (Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Eswatini, Zambia, and Zimbabwe) was documented. The majority of the studies were published between 2011 and 2016. The age range of participants in this review varied greatly, ranging from 9 to 90 years. The 33 studies had 253,938 (range: 12–248,200) participants, including 1204 females, 593 males, and 252,141 non-specific genders. Most studies (79%) used primary data, and only seven (21%) presented secondary data. The three main sample selection strategies were convenience, snowball, and purposeful sampling. Most studies were conducted in South Africa (55%), followed by Botswana and Zimbabwe (12%), and Angola and Mozambique (6%). In contrast, Lesotho, Malawi, Namibia, Eswatini, and Zambia were least represented, with only 3% of articles included in the review. A variety of data methods and designs were represented from qualitative and quantitative (27%), qualitative (39%), quantitative (18%), and mixed-methods (6%) in the various studies.

4.3. Descriptive Themes Emerging from the Literature

The main findings from each study are summarised in Table 4. Not all variables applied to the studies were represented in each study. Table 4 shows how the other elements were distributed throughout the studies. This process entailed discovering patterns in the data, with themes emerging as categories to aid analysis. For each study, the identified factors were availability, consumption frequency, utilisation, preparation, harvesting and preservation, knowledge, perceptions, and beliefs. Of the 33 studies, only one identified all factors involved in using IFs. Most (85%, n = 28) studies reported the consumption of IFs, followed by availability (78%, n = 26 studies), utilisation (64%, n = 21 studies), knowledge (61%, n = 20 studies), preparation, perception, and attitudes (39%, n = 13), accessibility (27%, n = 9 studies), preservation, frequency, and acceptance (18%, n = 6 studies), with beliefs and values being the least represented variables (12%, n = 4 studies).

4.3.1. Availability and Accessibility of Indigenous Foods

One of the most common factors affecting the use of IFs is availability (71%), whereas accessibility (29%) was identified in several studies. It has been observed that IFs are accessible and available from various sources, [4–6,14,15,53,54] to name a few. Availability of IFPs has been reported to be found during three seasons (summer, autumn, and winter) [4,5,7,11,55–60]. Communities in Botswana [58] reported that during the rainy season, some green vegetables, such as morogo wa dinawa (cowpea leaves), were frequently accessible in summer.

According to a review by Welcome and van Wyk [24] and other studies [60,63–67,70,71], Southern Africa has a large diversity of IFPs. The review was conducted in five Southern African nations (Botswana, Lesotho, Namibia, South Africa, and Eswatini) and listed 23,000 different plant species found in these southern African nations. The same study found that 156 of these plant species' families belonged to IFPs species. They featured 137 edible species, Apocynaceae, which is reported to be at the top of the list. More surprisingly, the Fabaceae species, which includes 135 species, also appeared prominently in this review.

At least 35 native plants, spanning 29 genera and 23 botanical families, were identified by Mawunu et al. [72] in Angola. The top list of edible species included members of the Apocynaceae, Fabaceae, and Zingiberaceae families. These results are consistent with those of Göhre et al. [73], who carried out a similar survey across the entire Bakongo tribes in Uíge, Northern Angola, and listed 122 species spread across 28 botanical families, with Apocynaceae and Fabaceae being the two groups with the highest reported species numbers.

Fabaceae, Moraceae, and Annonaceae have the highest IFPs from 89 wild food plant species belonging to 47 families and 65 genera. In Zimbabwe, Mujuru et al. [74] demonstrated parallels with the studies described above. While Anacardiaceae, Moraceae, and Fabaceae families had excellent representation, Maroyi [45] counted 67 wild plant species in the Nhema communal area of Zimbabwe, and Fabaceae, Moraceae, and Annonaceae were reported to have the highest number of IFPs from 89 wild food plant species belonging to 47 families and 65 genera. In Zimbabwe, Mujuru et al. [74] demonstrated parallels with the studies described above.

Maroyi [45] found 21 edible IFPs in the Shurugwi district in Zimbabwe spread across 11 families and 15 genera. *Amaranthus* spp., *Corchorus* sp., and *Cleome* sp. Were the genera with the most edible species, while 108 edible IFPs were found by Bruschi et al. [49] in Mozambique, consistent with these findings. *Amaranthus* spp. Was reported to have the most significant number of edible species among IFPs [50]. Ochieng et al. [75] stated that IFPs such as *Amaranthus* spp., *Abelmoschus esculentus*, *Ipomoea batatas*, *Solanum nigrum*, and *Cleome gynandra* are frequently marketed in Zambia. *Amaranthus* spp., *Bidens pilosa*, and *Gynandropsis gynandra* were the three most widely accessible indigenous vegetables in Malawi, according to a survey by Kwapata and Maliro [76]. *Amaranthus* spp., *Bidens pilosa*, and *Cleome gynandra* topped the list of the seven most commonly referenced IFs in another USAID et al. [50] survey. The prevalence of the Apocynaceae is said to be unique to Africa [24]. On the other hand, Apocynaceae and Fabaceae are thought to have the highest species populations throughout the nine Southern African nations.

4.3.2. Consumption Frequency of Indigenous Foods

Even though the majority (85%) of the research studies covered IFPs consumption, just five research studies from various countries identified IFPs as being commonly consumed: cowpeas, *Cleome gyndra*, *Amaranthus* spp., pumpkin leaves (*Cucurbita pepo*, *C. moschata*, and *C. maxima*), and *Bidens pilosa* (e.g., 6,28,45,50,64,74). Similarly, these findings show that *Amaranthus* spp., *Cleome* sp., and sweet potatoes are reported to be the most common IFPs traded in Zambia [45], while *Bidens pilosa* is the most common IFP traded in Malawi [76].

These findings are supported by Dweba and Mearns [21] in South Africa, who identified 33 commonly consumed IFPs and reported *Amaranthus* spp., *Cleome gynandra*, *Citrullus lanatus*, and blackjack as the most popular IFPs. On the other hand, due to their regular commercial production and ease of accessibility, cowpeas and sweet potatoes are seen as the most traditional IFs in South Africa. A recent study in Angola by Mawunu et al. [65] reported IFPs being frequently consumed (weekly) [28]. Mbhenyane et al. [28] reported that IFs were consumed 2–3 times per week in Limpopo, which supported the current results. These vegetables were reported to be consumed more frequently in rural than peri-urban areas, mainly by the older generation compared with young people, and by unemployed people compared with employed people [48].

Many pregnant women were reported to consume IFs in Malawi and Zambia, as they perceived them to have a high nutritional value [50]. Additionally, these dishes were reportedly consumed by toddlers under the age of two as side dishes with maize porridge. At the same time, parents were reportedly feeding infants between the ages of six months and one-year IFs by chopping up vegetables, adding water to porridge, and grinding up traditional leaves to add to the porridge. Parents identified moringa and pumpkin leaves as crucial vegetables for young children to eat [50].

4.3.3. Utilisation Practices of Indigenous Foods

One of the most reported components influencing the promotion of IFPs is utilisation [4,7,11,44,48,49,51,55,57,63–66]. According to a study conducted in Zimbabwe, edible plant components identified as significant food sources included edible fruits, leaves, and young shoots that may be cooked into vegetables; edible roots, tubers, and corns; edible inner bark; edible kernel; and fruit juices that can be brewed into beer [44]. There is a clear distinction among the plant parts that are used (whole plants, underground storage organs, stems, etc.) and the categories of use (snacks, moisture sources, vegetables, meal, tea substitutes, coffee substitutes, alcoholic and non-alcoholic beverages, etc.) [77].

Studies in this systematic review revealed that some indigenous vegetables obtained from multi-purpose plant species are consumed as food and medicine to promote health [16,48,49,63,74]. These species' most frequently reported medical uses were digestive issues, respiratory illnesses, obstetric and puerperal issues, venereal disorders, and colds and flu [49]. One South African study found that 14 native plants were consumed and had both medical and nutritional properties [48]. *Bidens pilosa*, for instance, is consumed as umfino (the plant), cooked with maize meal, and may be eaten as a side vegetable, stir-fried, or boiled in a small amount of water, but it is also used medicinally. In traditional medicine, *Bidens pilosa* is frequently used as an antiviral to manage diabetes and treat gastroenteritis [52,71,78].

A Zimbabwean study by Munsaka [4] found that 10 IFPs, including fruits, tubers, and leafy vegetables, had medicinal properties. The same study reported that *Cleome* is eaten as food and used to treat the eyes. On the other hand, *Amaranth* leaves were said to be high in antioxidants, which protect one's cells against free radicals and play a role in heart disease, cancer, and other diseases [79]. These results support Lewu and Mavengaham's [63] finding that the three indigenous plants most commonly used for food and medicine are *Amaranthus* spp., *Chenopodium album*, and *Bidens pilosa*. In contrast, blackjack *(Bidens pilosa)* has been reported to be a potential IFP, which may serve as a food and medicine for lowering high blood pressure [4]. The same study reported that blackjack and *Amaranth* leaves have medicinal properties that help HIV patients recover and live longer, encouraging IFP consumption.

Additionally, various drinks made from IFPs are available, including traditional beer, fermented non-alcoholic beverages, and herbal teas [80,81]. Kobisi et al. [82] published a study on an IFP used to produce herbal teas in Lesotho. According to the same survey, sorghum is just as popular as malt in the country for making traditional beer, while in Angola, the *Raphia* spp. is utilised as a standard local drink (raphia wine) because of its cultural significance. According to Brushi et al. [49], consumption of homemade beverages prepared with traditional plants is common in Mozambique, particularly in rural areas, which likely explains the high alcohol consumption rate in that country. In Europe, Chen et al. [83] reported on IFPs used as hot beverages, which are thought to have some antioxidant, anti-inflammatory, antimicrobial, and anticancer properties.

In contrast, Bruschi et al. [50] reported that IFPs such as *Strychnos spinosa* and *Amblygonocarpus andongensis* are used in food and fishing in Mozambique. The latter's usage as fish poison and for making flour has been documented in South Africa. In Zimbabwe, Munsaka [4] reported that multiflora is used to make herbal tea and that local vegetable leaves are used to prepare sauces.

4.3.4. Preparation of Indigenous Foods

A few studies [4,5,14,44–48,51,65], which reported on IFs' preparation, claim that there are numerous ways to prepare and use IFPs. According to reports, cooking is the most popular method for preparing IFs to improve their digestibility and flavour [5]. In Malawi, preparation of IF was reported as either boiling the leaves or frying the vegetables. Women described the preparation of the indigenous vegetable process as gathering the plants from the garden, separating the leaves, cutting them into pieces, washing them in a colander basket and cooking with just a small amount of water [50]. This practice is distinctive in Southern Africa and other parts of Africa [83]. These results are consistent with those of Munsaka [4], who reported that vegetables are cooked in salty water for a short time in Zimbabwe and South Africa [48]. In many traditional African societies, most IFPs are consumed as a supplement (relish) to a starchy meal [48]. To cook wild sweet potato leaves and *Amaranth*, the leaves are rolled between the hands to remove the white sap, dried in the sun for 10–15 min, and then fried with tomato and onions [50]. Depending on the leaf's texture, the plants' cooking time ranges from 5 to 10 min. Due to their thicker texture, vegetable leaves, including cowpeas and cleome, require more time to cook [4].

Conversely, during the preparation phase, IFPs are combined with others. Most of the time, mixed plants are prepared as a single dish to reduce their bitterness and sliminess and increase their acceptability [51]. It is believed that combining IFPs in a meal increases the health benefits resulting from their synergistic complementarity in terms of nutritional and medicinal qualities. *Amaranthus dubius*, for instance, is frequently used individually, both in *imifino* and as *ulaxa* (ulaxa is a traditional term for numerous wild edible plants boiled in a small amount of liquid and served as a side complement to *imifino*, a collection of diverse wild dark green vegetable leaves) [48]. Some women reported eating indigenous vegetables as a relish with thick porridge made primarily of the staple grains, millet, sorghum, and maize [14,48].

In addition, IFPs such as *Monodora myristica, Piper guineense*, and *Xylopia aethiopica* can be used whole or crushed to make a spice for the creation of sauces or sprinkled on pork, chicken, or fish before they are butchered [14]. The primary ingredients are water, salt, peanut butter, and cow's milk or cow's milk cream, without a strong preference for either. Vegetables—including tomatoes, onions, or whatever is available—and other soups, can be added. While cooking oil may be used, peanut butter is preferable since it increases nutrient density and improves palatability [4].

To avoid starving during the famine, women in Zambia learned the abilities and methods for turning a variety of poisonous native food plants into edible food [49,64]. While *Dioscorea cochleariapiculata* and *dumetorum* tubers are harvested and consumed only during food scarcity in Zambia, these yams are recognised as meals in East Africa [49]. *Dioscorea cochleariapiculata* and *dumetorum*, when consumed uncooked in East Africa, are known to cause vomiting and even death [19]. However, the tubers of these plants can be consumed after proper preparation, such as "peeling the tuber, cutting it into thin slices, drying and washing for many hours in a river, constantly changing the area". Alternatively, boiling the ingredients with *mukuma* (a natural soda derived from the ash of the plant's *millettia stuhlmannii*, *afzelia quanzensis*, *Tabernaemontana ventricosa, or piliostigma thonningii*) can also help to remove the poisonous elements in this plant [49].

On the other hand, fruits, which are not poisonous, are typically consumed as soon as they are picked in the field [4]. These findings are consistent with another Zimbabwean study, which reported that *miombo* (fruit) were ingested unprepared and raw [74]. The *xima* plant is a common African food native to Mozambique and well-liked throughout the continent. It is a type of corn–flour porridge that is frequently served with sauce. This plant does not require the complex preparation techniques needed for other IFPs and is not harmful [49]. However, in other species, such as *Adansonia digitata*, the mealy pulp surrounding the seeds can be eaten raw or turned into juice by boiling or soaking it in water at room temperature; the mucilage or pulp can be ingested directly [14]. On the other hand, some seasonal fruits require boiling as part of the preparation process, such as *Canarium schweinfurtii* [49]. Of all the individuals surveyed in the various studies, rural women appear to favour IFs since they are quick and straightforward, making them popular [5].

4.3.5. Harvesting and Preservation of Indigenous Food Plants

Only 6 of the 33 studies discussed IFPs' harvesting and preservation [7,48,50–52]. According to these studies, women and children handled most IFP harvesting and preservation, as most men were out in the fields tending to cattle or cultivating the fields. There are many ways to harvest and collect IFPs locally, including obtaining only those abundant in that area. When gathering, it is essential to treat leaves and flowers carefully because their tissues make them considerably more susceptible to deterioration than roots [15]. According to Mawunu et al. [65], harvesting is one of the methods most frequently utilised to obtain IFPs. Dlamini [5] asserted that IFs are best harvested by hand while fresh and soft in the morning. Some indigenous green leafy vegetables, including *Amaranthus*, blackjack, nightshade, and bitter gourd, are typically harvested and consumed while young and succulent [14]. Other harvesting methods include tree felling, uprooting, defoliation, and peeling [70]. The last three methods, however, are not viable, as they may lead to the genetic erosion of locally cultivated edible plants [84].

Most people, especially those in rural areas, rely on locally grown food, so employing conventional food preservation techniques is necessary to guarantee that food is available in their homes all year round [55]. Some of these preservation techniques include sun-drying, minimal processing, canning, vacuum-packing, refrigeration, freezing, and irradiation [85].

Many studies reported sun-drying as a popular preservation method used by women because it is an affordable and practical way to preserve native food plants in bulk shortly after harvesting [5,48,50,51,55]. However, according to Dlamini [5], this preservation method can result in a significant loss of vital micronutrients, including vitamins A and C. Therefore, fresh leaves are first blanched or fried before being dried in the sun to preserve their nutrient content. This is congruent with findings from van der Hoeven et al. [51], who reported that all vegetables should be blanched in steam before drying to stop the action of enzymes and the loss of some nutrients.

Steam-blanching followed by dehydration [86] achieves ascorbic acid retention in vegetables. Matenda et al. [56] stated that *Cleome gynandra*, mbuya, *muchacha, munyemba,* and *mutsine* are blanched before sun-drying on either reed mats or sacks on elevated platforms. Drying surfaces are set up on platforms to shield vegetables from dust and domestic animals. The common belief is that vegetables dried from a stone are more delectable. This drying process is quicker on the rock than on the mat or sack, possibly better preserving the nutrients [50]. Other plants, such as beans, can be employed as preservatives for the plants being stored throughout storage [83].

According to the USAID report, Zambian IFP seeds of cultivated vegetables are available all year [50]. Women described preserving plants in their homes by drying them on mats in the sun and then putting them in grain bags. This is consistent with a Malawian community reporting that pumpkin and cowpea leaves were dried on a mat and then preserved in sacks within one's home. Wild sweet potato leaves are separated from the stems, briefly blanched, and then dried in the sun before being put away in a bag for consumption when indigenous vegetables are scarce [50].

Another traditional preservation technique involves using a storage ball called a *chikwati in Chewa/Tumbuku* in Zambia. Large leaves are typically used to create a storage ball, which is then twined up and hung from the rafters of a house, with stored items lasting up to a year. Using a clay pot is another method of preserving IFPs. For example, green leafy vegetables are stored in a clay pot, which is tied shut and covered with a plastic bag [50]. In addition to lowering post-harvest losses, IFPs preservation guarantees a steady food supply to fight hunger and disease, mainly in the rural population where medical facilities are scarce and not well-equipped [16]. This type of indigenous knowledge (IK) is typically passed down from elders, who were raised using the techniques, to the younger generation. If not passed down, this knowledge dies with that particular individual, as there is nothing written down to preserve it.

4.3.6. Knowledge of Indigenous Foods and Benefits

IFP knowledge has been the subject of much research conducted throughout Southern Africa, including in Zimbabwe [4,44,67,74] and Botswana [11]. Of the 33 studies reviewed, only 19 studies reported on IF knowledge. According to Kasimba [14], IK is learned chiefly through social interaction and is typically passed down from generation to generation through conversations. The use of IK to prepare or consume certain IF types can be seen in a society's religious and cultural beliefs, such as the notion that individuals enjoy particular foods because their ancestors or elders consumed them. Numerous food preservation and storage methods have been created and successfully used in specific traditional communities. For example, indigenous vegetables are cooked before consumption, while indigenous fruits are typically consumed raw in most African countries [65].

In many African communities, IK in food preparation and preservation is highly developed [14], making the process much easier. IFs are preserved for years without losing too much of their nutrient content. Maroyi [44] asserted that Zimbabwe's IFPs availability needs to be sufficiently recorded despite the country's wealth of IK, possibly because there need to be more academics conducting research in this area. For the comprehension, interpretation, and distribution of IK, it is essential to comprehend the role of gender and how it influences the intrinsic value of the local knowledge system. There is a separation of household duties in most rural communities (i.e., women are generally the chefs in the home), and this gender disparity and specialisation is thought to be the reason why women have more knowledge of IFP than do men [44]. These results are consistent with those of Munsaka [4], who found that women across different communities had joint expertise in cooking fresh and dried vegetables. For instance, the other rural communities reported that indigenous vegetables were primarily cooked and consumed soon after or immediately after gathering them [14], unless there was excess to store for consumption during the dry seasons.

However, a study by Maroyi [45] suggested that most community residents were aware of IFPs but needed help finding them because the landscape has changed, with most areas needing more fields for planting or vegetation in the surrounding area due to the modernisation/commercialisation of the nearby lands. In contrast, Matenge et al. [57] found that awareness of IFPs, their advantages, and their consumption was scarce among South African populations in the Limpopo Province, possibly for the same reason mentioned above. Nengovhela [47] suggested that the IFK level influenced consumers' views of IFPs. As a result, as consumers become more knowledgeable of IFPs and their advantages—because of the knowledge being passed down to younger generations and the willingness of the younger generation to use this knowledge to their benefit—their perceptions of these IFs may improve, which will raise the utilisation levels [47].

4.3.7. Perceptions and Beliefs towards Indigenous Foods

The USAID et al. [50] report asserted that Mawa villages in Zambia favour IFs. The latter was possible since these foods are believed to have health benefits, have a pleasant flavour, and are easily accessible. The people praised indigenous vegetables as being nutritious, high in vitamins, and effective at preventing illnesses. The same observation was noted in Malawians and the Mawa populations, who perceived IF usage similarly. Additionally, Mawa people mentioned that they commonly ate IFPs due to their accessibility, cost-effectiveness, pleasant flavour, and vitamin content [51]. However, this report contradicts van Hoeven et al. [51], who reported that taste was one of the reasons for reducing IF consumption in South Africa; however, IFPs found in Malawi and Zambia may be different from those found in South Africa, resulting in the other flavours.

A study by Nengovhela [47] suggested that communities in Limpopo view IFs favourably. These communities did not consider IFs to be food for the underprivileged, as did the findings by Cloete and Idsardi [6], who reported that IFs were considered poor people's food amongst communities of the North West Province of South Africa. In contrast, Limpopo communities recognised these foods as healthier and more reliable sources of nutrition and energy [47]. Another study by Kasimba [14] reported that communities in Botswana perceived IFs as more nutritious than exotic foods. The same study stated that these foods were characterised as natural foods that did not require using any chemicals or additives during production and processing other than salt, when necessary. These foods have a favourable impact on satiety, with an acquired taste in some of these communities. On the other hand, Mavengahama [15] agreed with the finding that IF is of superior quality, particularly in terms of freshness, nourishment, being natural, unprocessed, and produced locally, and having many health-related benefits.

Another study by Munsaka [4] suggested that participants in Zimbabwe had a positive attitude towards IFs, which may contribute to the high intake of these foods in that country. The same study reported that indigenous vegetables have natural, social, and cultural values and are crucial for meeting the daily dietary needs of most inhabitants in those communities. Most Zimbabweans share a common view that supports the assertion that cultural norms and people's beliefs about particular foods significantly influence their dietary choices when it comes to IFs [4]. The author also reported health and nutrition as the most significant reason for the consumption of IF by most participants from the studied area in Zimbabwe. Frequent response on the value and significance of IFs was that these foods formed part of their ancestors' diets, helping them have healthy lives and live longer [4].

On child-feeding beliefs and practices, mothers in Zambia agreed that they were responsible for feeding their children IFs, which meant giving them a healthy diet. These findings are consistent with findings in the USAID et al. [50] report. It was reported that pregnant women consumed IFs and fed indigenous vegetables to their infants starting at six months old, with the understanding and belief that the food was nutritious and healthy for the baby. In contrast, communities in Zimbabwe openly voiced their thoughts and convictions regarding their communities' child-feeding habits. The issues mentioned were unhealthy eating habits being modelled by others. Parents' perspectives on handling children who refuse to eat IFs differed significantly [14]. As a result, eating IFs has become a custom that most cultures share, which can be reinforced with positive attitudes and encouragement from the elders and the conveyance of the benefits of eating these foods.

5. Discussion

This review summarised and synthesised the findings from 33 studies examining the factors that influence IF consumption and its utilisation in Southern African countries. Many Southern African countries depend heavily on IFs in their diets, mainly in rural areas, which have been the focus of this study. Despite the importance of IFs in ensuring food and nutrition security, more research is needed on these foods in most Southern African countries. This is unexpected, given the significance of IFs in achieving SDG 1–3′s objectives to eradicate poverty and hunger and promote health and nutrition [87].

This review demonstrates that South Africa has led the way in promoting IF research. IFs in South Africa are being scaled up with financial assistance from several research organisations, including the Department of Science and Technology and the Agriculture Research Council [88,89]. The South African National Food and Nutrition Security Policy's strategic goal is to ensure that affordable, readily available, and nutritious food is available at the national and household levels. This goal includes using IFPs to support a variety of diets, including those containing *Amaranthus dubius*, *Cleome gynandra*, *Vigna subterraneae*, *Colocasia esculenta*, and *Vigna inguiculata* [88]. In this regard, other Southern African nations need policies for IF research and funding, as they possibly have the largest per capita consumption [90]. While there is so much research in South Africa and more government funding to support the uptake of IFs, there is still less consumption compared with other countries where there is no funding or support from the government.

The findings of this review suggest that Southern Africa has a wealth of IFPs. The availability of these IFPs in nearly all of the represented countries was reported in at least 24 (70%) publications. According to Welcome and van Wyk [24], the world's most prominent families are *Poaceae, Fabaceae*, and *Brassicaceae*, which somewhat correspond to the existing pattern in Southern Africa. While a total of 150 wild plant species have been recognised as emergency foods worldwide, including 87 species in Thailand and roughly 150 species in India, Malaysia, and Thailand [91], 211 species have also been reported in China [92]. These data demonstrate the widespread availability of IFPs. This analysis shows that IFPs are widely available in Southern Africa, encouraging consumer demand, especially among the youth.

These IFPs are not only accessible, but they are also consumed to provide both nutrition and health benefits in various communities. This is particularly important given that most rural areas in Southern African countries have little to no access to medical facilities or have to walk long distances to access medical facilities. Therefore, consuming a healthy diet of IFs keeps these individuals healthy, without the need to frequent medical facilities for medical assistance. Nearly all research discussed the frequency component of IF consumption (Table 2). Evidence from 19 studies revealed that availability and knowledge were critical determinants of IF intake. This was followed by the belief that IFs are more nutrient-dense than foreign foods. Other studies indicated that some IFPs contribute to various phytoconstituents, including antioxidant molecules and phytochemical composition [11,29]. These consist of protein and calorie content, minerals, vitamins, and other hormone precursors [48]. According to Ghosh-Jerath et al. [26], eating various IFs is linked to higher intakes of iron, calcium, carbohydrate, riboflavin, thiamin, vitamin A, beta-carotene, and folate, all of which are essential to maintaining a healthy body.

On the other hand, most Southern African countries value IFPs for their nutritional and medicinal properties [4,29,49]. These foods are used in numerous medications that treat illnesses and infections [4]. For example, *blackjack* is recommended as a food and medicine for reducing high blood pressure. The same study suggested that *Amaranth* and *blackjack* leaves are considered medicinal plants that assist HIV patients in their recovery and in living longer [4], making IFPs more important. This is important because it helps rural communities spend the little money they earn on other essential household responsibilities; as the saying goes, "let the food you eat be the medicine to all your ailments, rather than having to take medicines to treat those ailments". This further cements the importance of IFs in an individual's diet and calls for IFP knowledge to be transferred from one generation to another and IF consumption to be encouraged.

On the other hand, *Amaranth* leaves are reported to have antibacterial and antioxidant qualities in Zimbabwe, which help promote health by raising blood levels and preventing cancer and other chronic diseases [93]. Gowele et al. [94] claimed that *Solanum nigrum*, *Corchorus* sp., and *Amaranthus* spp. are all grown in Tanzania and are abundant in dietary fibre, vitamins, minerals, and other macro- and micronutrients. Oyetayo [95] from Nigeria described the widespread usage of local mushrooms as a medicine to cure gastrointestinal issues, headaches, and colds and fever, reinforcing the importance of IFPs in different regions.

Furthermore, Chang et al. [96] reported that *Bidens pilosa* is an extensively used indigenous vegetable in China for the treatment of several ailments, including influenza, gastroenteritis, and the management of diabetes. These global data suggest that IFs and dietary diversity benefit the defense against most ailments and disorders. Comprehensive data on IFs composition are critical in encouraging and incorporating these foods into daily diets. Mbhenyane [18] proposed that nutritional value composition data could be used to develop strategies for facilitating the intake, acculturation, and marketing of indigenous vegetables. Bvenura and Afolayan [46] suggested that adding more IF items to the IF database may facilitate the acceptance and consumption of IFs in communities' daily diets. This process can be achieved through awareness and promotion programmes across Southern Africa, creating a database that is freely accessible and working with government institutions to promote the uptake of IFs. It may also help to have the information of the published article broken down into lay terms and published in easily accessible newspapers and to have radio and TV programmes that can improve awareness and show people different ways of preparing and preserving such foods. This will ensure that a method which has been utilised in one region can be replicated easily in another area that would otherwise not have benefited from such a technique or preparation method.

Only a small number of research works addressed IFs' preservation. This explains why the IFP seed supply business in Southern African countries is underdeveloped. Food preservation involves storing food at off-peak times to provide a steady supply of nutritious foods [97]. IFPs, especially vegetables, are more readily available during wet seasons but become scarce during dry seasons [98], and their high moisture content makes them susceptible to spoilage after harvesting [99]. As a result, it is impossible to consume them all year long in their fresh state. Thus, they are usually dried and preserved for consumption during the dry period of the year. Due to the seasonal nature of most IFs and the lack of tools for processing or adding value to reduce food waste, indigenous people conserve their IFs (seeds, vegetables, and grains) [100]. According to Taruvinga and Nengovhela [47], indigenous people are highly knowledgeable about IF preservation methods. Although the majority of IFs are perishable, rural areas were able to extend their shelf life by using various preservation methods. Most IFPs are preserved for use in winter when supplies are low, which helps ensure household food security [101,102].

Regarding food security, Kamwendo and Kamwendo [84] stated that access to and availability of food remains a significant issue in most African countries. Stocking and storing food help ensure that households have access to it later and that it is safe to use. The type of preservation technique used [47] influences the nutritional value of the IFs. The long-term storage of IFs is significantly hampered by the lack of scientifically validated preservation techniques. Hence, conducting scientific testing on these techniques is essential to ensure that no nutrients are lost. This requires new and further development of existing IFP preservation strategies.

However, in-depth research and development are needed, even with modifying preservation technologies on exotic fruits and vegetables; for farmers to produce IFPs in large quantities and for households that choose to grow IFPs for their consumption and local sale, access to such information could have considerable influence. In addition, the availability, productivity, consumption, and quality of IFPs will all rise as more people become aware of the best preservation strategies to maintain the high nutrition components stored in the specific IFs. This study revealed a wide range of factors that encourage the uptake of IFs in Southern Africa. However, very little research is being conducted to preserve this knowledge in academic settings. For example, in Zambia, IFs were perceived to have good taste, ease of access, good availability, and health benefits [50]. In another study, Kasimba [11] noted that Botswana communities perceived IFs as healthier than exotic foods. IFs are thought to be nutritive, natural, and endowed with health advantages, according to Mavengahama [66].

On the other hand, Van Hoeven et al.'s [51] study contradicted the conclusions of USAID et al. [50] and identified drawbacks, citing taste as one of the reasons for the decline in IF consumption in South Africa; however, these findings have not been replicated in other studies. While some of these variables encourage the consumption of IFs, other factors are to blame for the decline of IFs' consumption, particularly in South Africa, given that there are concerted efforts by various organisations to encourage IF uptake in communities. The seasonal availability [60], lack of access to IFPs [84], the distance needed to collect IFPs [63], lack of knowledge of preparation, preservation, and nutritional content [47,102,103], and their nature of harvesting [15] also serve to discourage communities from exploring IFPs.

Even though IFPs are abundant in Southern Africa, many academics [14,16,29,30,79,81] have studied IFPs mainly for their nutritional and therapeutic benefits. Consumption of IFs is declining in most Southern African countries. This decline has been attributed to several factors, including the westernisation of African diets [57], the bitter and discouraging taste of wild vegetables [45], culture [14], and the perception that wild vegetables are low-income foods [48]. According to Ayua et al. [104], young people prefer exotic vegetables, as they claim them to be less bitter. For instance, Cloete and Idsardi [6] stated that in South Africa, the younger generation thought that IFs were a bitter food that only the poor would eat because they could not afford alternative options [51].

Additionally, a lack of interest in learning about IF or the absence of the older generation passing on information to the next generation about IFP identification, harvesting, preparation, and preservation has contributed to this decline [103]. Rural parents have even been reported to use various techniques to persuade their children to eat IFs [4]. Despite these negative perceptions of IFs, this review shows that IFs consumption is still ongoing, albeit not at the level that IFPs used to be consumed in the past. It is estimated that more than one billion people still rely on IFs globally [16,100].

In South Africa, the degree of urbanisation, the distance to fresh produce markets, and the time of year all have an impact on the consumption of IFPs [101], whereas in Kenya, it has been observed that ethnicity affects the decision to purchase and consume traditional leafy vegetables [102]. Little effort is being made to encourage IFP usage, given that more exotic plants are being cultivated, which has resulted in IFPs being neglected and nearing extinction in the areas where they used to be endangered.

The promotion of IFs is consistent with SDG 1–3, which deals with poverty, food security, and health concerns. The effectiveness of international, regional, and national policies will determine how well IF promotion is implemented and whether it succeeds. These policies should promote IFs to broaden dietary diversity and address other pressing issues, such as supporting rural communities' capacity building through developing relevant skills [102] and providing adequate and dependable infrastructure [105], as well as allocating sufficient funds for advertising campaigns that will assist in promoting IFPs that are less expensive, readily available, and do not taste bitter. Inclusion of various technical activities that incorporate IK of IFPs in a particular local community ensures that all communities have their IFP knowledge transferred from one generation to another [106]. This programme will increase the importance of rural communities to ongoing Southern African and national growth initiatives and encourage communities to take responsibility for promoting the use of IFs and marketing them to outside communities that could benefit from trading in these IFPs. Additionally, by utilising processing technologies that enhance the value of the completed products, farmers can boost their income from IFPs. IFs might become well-known through this popularisation for various functions, and improved packaging may improve their appeal, such as the aloe-vera-based products in Asia.

6. Conclusions

This review investigated the perspectives of factors influencing Southern African IF availability, consumption frequency, utilisation, preparation, harvesting, preservation, knowledge, perceptions, and beliefs. IFPs were reported in all of the studies in nine Southern African countries. Even though the assessment noted that IFs were consumed, it also stated that several Southern African countries were significantly cutting back on the intake of these foods, possibly because of modernisation or scarcity of IFPs in the areas where communities have been resettled. Patterns of consumption were noted across studies, with IF consumption generally more common in older generation groups. The various studies attributed the decline in consumption to urbanisation, decreased accessibility, lack of preparation and preservation knowledge, and nutritional content, to name a few.

This review also emphasises the significance of successful global, regional, and national policies in promoting IFs, with little to no supporting policies in most Southern African nations, save for South Africa. To reverse a decline in the utilisation of IFPs, these policies should also address concerns such as assisting rural populations in developing necessary capacity-building skills, providing suitable infrastructure, and devoting enough money to comprehensive research and marketing so that those involved in the growing of IFPs can earn a living through their jobs. Additionally, encouraging and incorporating these foods into everyday meals requires extensive information on the composition of IFs. This process can be achieved through awareness and promotion programmes across Southern African countries through workshops and programmes on the radio and TV stations, as well as having relevant governmental organisations involved in promoting the uptake of these foods in schools, hospitals, and many other facets of life.

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agriculture

Systematic Review

Europe's Large-Scale Land Acquisitions and Bibliometric Analysis

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Abstract: The agricultural sector in the European Union is largely characterized by a declining number of farms and an increasing size of surviving farms. The land is concentrating under the usage of fewer large agricultural producers. Meanwhile, a broad distribution of land ownership is the basis for the welfare of local economies and rural communities. Land distribution is one important component that guarantees our right to food, human rights, and sustainability in agriculture. The aim of this paper was to compile a systematic review of the existing literature on large-scale land acquisitions in Europe. The results are based on two different search methods. Firstly, documents and articles on large-scale land acquisitions were studied and, secondly, keyword research from the SCOPUS database and analysis using VOSviewer where performed. This study shows that large-scale land acquisitions are closely related to food security, human rights, global governance and international law, land tenure, biofuel production, and financialization through European Union common agricultural policy subsidies and foreign direct investments.

Keywords: land concentration; land grabbing; large-scale land acquisition; food security; EU agriculture; sustainable land use

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1. Introduction

Recently, sustainable agricultural production and land use in the agricultural sector have been the subject of discussion for several reasons. The COVID-19 pandemic and Russian invasion of Ukraine are the latest reasons to address this issue. The pandemic situation disrupted the global supply chains, closed the borders between countries (albeit for a short period), and restricted movement inside countries. It indicated the need for domestic agricultural production to use short supply chains (where production occurs close to the consumers). A study by Benedek et al. [1] showed that around 19% of small-scale farmers in Estonia, Hungary, Portugal, and Romania were actually able to boost sales during the first wave of the pandemic. Farm gate sales were one of the most important marketing channels both before and during the first wave [1]. However, our knowledge on how the COVID-19 pandemic affected land-use change is limited. Nolte et al. investigated the impact of the COVID-19 pandemic on the livelihoods of agricultural households and their land-use decisions [2]. The outcome of the study showed that smallholders' risk-coping capacities are weak and have been further weakened by the pandemic.

The COVID-19 pandemic provided the needed push for the European Green Deal. As a result, the EU is moving towards a more sustainable society and accelerating its transition to climate neutrality. The European Green Deal [3] strives for a climate-neutral economy by 2050, and its ambition is to apply more climate-friendly land use. The aim is to achieve emissions reductions of at least 55% by 2030 compared to 1990 levels. It has been recognized that the land-use sector has a critical role in reaching long-term climate mitigation objectives. The land use, land-use change, and forestry (LULUCF) sector can provide long-term climate benefits [4]. Nevertheless, there is a need to find a coherent strategy that will achieve both the Union's food security and climate change objectives.

The Russian invasion of Ukraine and the sanctions that were applied with the aim of crippling the Russian economy are already affecting the agricultural sector and our food supply. In this situation, a country's self-sufficiency in food is becoming increasingly important.

Europe, and especially its eastern region, is undergoing creeping agricultural land concentration. The concentration of agricultural land has an adverse effect on the availability of food supplies. It is distorting production and market processes.

The issue of land concentration in the EU and many parts of the world remains basic and is one of the most serious land issues in the district today [5,6]. Over the years, many review papers have been published in the large-scale land acquisition (LSLA) literature [7–18]. The aim of this paper is to compile a systematic analysis of the existing literature on land grabbing and concentration in Europe. It is important for mapping the cumulative scientific knowledge on the topic of LSLA and its relations to other subjects. This study included document and article analyses, keyword research from the SCOPUS database, and analysis via VOSviewer (Version 1.6.17, Nees Jan van Eck and Ludo Waltman, Centre for Science and Technology Studies Leiden University, Leiden, The Netherlands).

2. Materials and Methods

Different documents and scientific articles (30 materials in total) on the topic of LSLA were studied for Section 3.1. The aim of this section is to give a general review on Europe's large scale land acquisitions.

The SCOPUS database was used for Section 3.2. The aim of this section is to present a bibliometric analysis on land concentration and land grabbing. Firstly, some previously studied articles (used in Section 3.1) were used to determine popular keywords that could be used to search SCOPUS for articles on the topic. Keywords were chosen for this work assuming that the selected works were provided with keywords that successfully connect their research with their target audience.

The keywords identified were "agricultural land use", "land concentration", "land grabbing", "family farms", "large-scale farming", "smallholder farms", "smallholder agriculture", "farm size", "farm ownership", "smallholder", and "small family farming". Some of those keywords yielded results that were too broad and had to be excluded.

The first search from the database was performed with four keywords ("land concentration" OR "land grabbing" OR "large scale farming" OR "small family farming") and yielded 390 records. After screening those results, the search had to be narrowed down to only English written articles for which the content was restricted to within Europe, and to which we had free access through our institution or which were open access journals. This search yielded 112 results, of which 45 articles were not accessible (no free access, not digitized, etc.), and 15 were outside the current scope. Finally, there were 40 articles, published from 1982 to 2020, included in the study. A detailed description of the query made in the SCOPUS database is shown in Figure 1. The methodological approach for this study is presented in Figure 2.

The VOSviewer software was used to provide an overview of the terms used in the LSLA literature. The keywords from the last SCOPUS database search results (112 articles) were entered into VOSviewer, and the keywords represented at least three times were visualized.

KEY("land grabbing") OR KEY ("land concentration") OR KEY ("large-scale farming") OR KEY ("small family farming") AND NOT KEY ("Asia") AND NOT KEY ("Africa") AND NOT TITLE("Brazilian") AND NOT TITLE("Amazonian") AND NOT TITLE("Laos") AND NOT TITLE("India") AND NOT TITLE("China") AND NOT TITLE("Indonesia") AND NOT TITLE("Brazil") AND NOT TITLE("Thailand") AND NOT TITLE("America") AND NOT TITLE("Rwanda") AND NOT TITLE("Mapuche Huilliche") AND NOT TITLE("Ethiopia") AND NOT TITLE("Malawi") AND NOT TITLE("Uganda") AND NOT TITLE("Egypt") AND NOT TITLE("Sudan") AND NOT TITLE("Africa") AND NOT TITLE("Argentina") AND NOT TITLE("forest") AND NOT TITLE("medicine") AND NOT TITLE("Sierra Leone") AND NOT TITLE("Colombia") AND NOT TITLE("Sumba") AND NOT TITLE("Colombian") AND NOT TITLE("Iraq") AND NOT TITLE("Mozambique") AND NOT TITLE("Pakistan") AND NOT TITLE("Cameroon") AND NOT TITLE("Uruguay") AND NOT TITLE("Cambodia") AND NOT TITLE("Sri Lanka") AND NOT KEY("Kaiowa") AND NOT TITLE("ASEAN") AND NOT TITLE("Tanzania") AND NOT TITLE("Honduras") AND NOT TITLE("Ghana") AND NOT TITLE("Chongqing") AND NOT KEY("Brazil") AND NOT KEY("Laos") AND NOT KEY("Nigerian") AND NOT KEY("Mozambique") AND NOT TITLE("Zimbabwe") AND NOT TITLE("Ethiopian") AND NOT TITLE("Guatemala") AND NOT TITLE("Zambia") AND NOT TITLE("Mali") AND NOT TITLE("Peru") AND NOT TITLE("Guinea") AND NOT TITLE("Kenya") AND NOT TITLE("Ocean") AND NOT TITLE("Water") AND NOT KEY("Myanmar") AND NOT TITLE("Mexico") AND NOT TITLE("Bolivia") AND NOT TITLE("Algeria") AND NOT TITLE("Japan") AND NOT TITLE("Alabama") AND NOT TITLE("Bengal") AND NOT TITLE("Costa Rica") AND (LIMIT-TO (PUBSTAGE,"final")) AND (LIMIT-TO (LANGUAGE,"English"))

Figure 1. Search of the SCOPUS database.

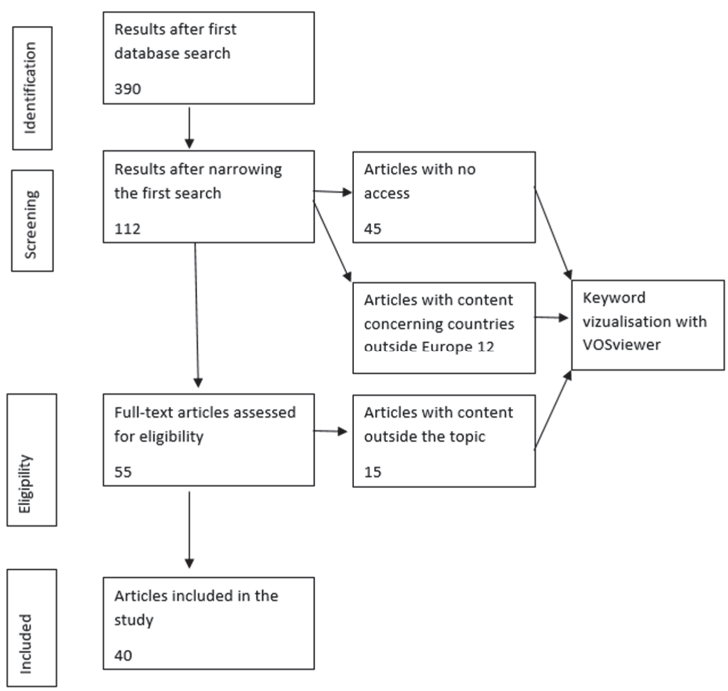

Figure 2. Methodological approach used for analyzing the literature.

3. Results

3.1. Europe's Large Scale Land-Acquisitions

The ever-growing world population and increasing consumption puts high pressure on the EU's agricultural land through competition for agricultural land use. For instance, agricultural land is used to grow products for biofuel production, and rapid urbanization also needs space [19].

Agriculture is a serious user of natural resources [20,21], although in diverse ways and to diverse extents depending on the operating system. This raises a question: are family farms the ones that will lead us to the future of sustainable agriculture and feed the population, or should we depend on large corporate agricultural businesses or mega-farms? Either way, there is a need to take actions towards greener agriculture. In the move towards sustainability, the European Green Deal and Sustainable Development Goals (SDGs) [22] set out necessary goals. Some of the objectives in the SDGs are directly linked with agriculture and its sustainability. Their aims include ending world hunger and ensuing sustainability in agriculture. In the 2019 United Nations Decade of Family Farming 2019–2028 [23] report, it is stated that family farming supports the SDGs by:

- Making food systems more sustainable;
- Creating income generation opportunities in rural areas;
- Implementing resilient and highly productive agricultural practices;
- Delivering inclusive rural services and contributing to territorial development;
- Promoting food systems that are more resilient to climate change;
- Preserving biodiversity;
- Strengthening sustainable integration between urban and rural areas.

From the beginning of the 2007–2008 financial crisis, land was acquired not only by investors keen in agriculture of food crops but also by financial institutions that awaited an increase in its value [24–27]. Suddenly, many influential economic actors started to invest in farmlands by buying them up or renting as much farmland as possible. International and domestic large-scale land deals became a growing global phenomenon. Today's structural arrangement in agriculture has seen resources transfer from smaller and less productive farms to larger ones. This increase, driven by a need for survival, will lead to larger farms, sometimes creating larger parcels, and this upscaling can lead to a decrease in landscape diversity and ecological value [28].

Structural change in the agricultural sector in the EU is also largely characterized by a dropping number of farms and a growing size of surviving farms [4,29–31]. In consequence, the critical choice of farms can be summarized as "grow or go". Therefore, the EU faces land concentration, but there are no reliable data about its scope [32–34]. Different studies showed that, in recent years, the number of agricultural producers has dropped in the EU, while the size of farms has increased [31,32,35]. These qualitative case studies on the effect of land concentration, pushed by further investments in rural societies, can rather be found in post-socialist EU countries [32]. For example, in 2001, there were 55,748 agricultural producers in Estonia; this number decreased each subsequent year to 18,755 in 2013 and 16,696 in 2016, while, concurrently, the area of utilized agricultural land remained almost stable [31,32,35]. This decrease took place largely at the expense of small producers [35].

In Romania, small-scale farms have been vanishing quickly, and between 2002 and 2010, 150,000 small-scale farms disappeared, while large-scale farming increased by 3% [6]. In 2020, the average monocultural land parcel situated in Slovakia reached a size of 12 hectares [13]. In 2010, the number of farms in Hungary was 351,000, which dropped to 235,000 by 2020 [14]. Meanwhile, these numbers do not show how much land the agricultural producers own and how much they rent.

LSLA transforms land use and food systems in their targeted regions worldwide [15]. It is found that LSLA threatens socio-economic loss, including income generation and food access [16]. The European farming model is built on the recognition of the multifunctionality and diversity of European agricultural systems [17]. It is estimated that, by 2040, an additional 6.4 million farms may disappear in Europe [17]. Toma, Redman, Czekaj et. al. found that the programming of the EU's Common Agricultural Policy at national and regional level does not respond to small farms' needs [18]. At the FAO regional conference for Europe 2022 it was suggested that member states strengthen their resilience by investing in smallholders and family farms, and updating agrifood systems to be better prepared, adaptable and autonomous [36].

Different studies are searching for the answer to the question of which farming model (large-scale agriculture or small farms) is most suitable for the environment and will ensure food security in the future. Ren et al. [37] found that farm size has a large influence on agricultural sustainability from the aspects of economy, environment, and society. Some studies have found that environmental harm resulting from large-scale industrial farming practices includes the loss of soil fertility, pollution of water sources, loss of biodiversity, and draining of wetlands, and large-scale landowners in the agricultural labor market depress labor income in the primary sector [33,38,39]. Wuepper, Wimmer, and Sauer [40] found, on the contrary, that small-scale farming does not lead to more sustainable farming practices. The result of this study was that small-scale farms are less likely to conserve structural elements, leave a higher share of their soils bare during winter, and use more of their fields for monoculture.

Therefore, land policy is severely important in shaping who farms, how farming is done, and the future of rural communities. For example, there are congruous land policy tools with direct intervention in the land market in Estonia. Restrictions on the acquisition of immovables used as profit-yielding land were enacted through the Restrictions on Acquisition of Immovables Act under Chapter 2. There are limitations for legal persons of the Contracting States and persons of third countries. In Poland, there are strict rules maintained for potential buyers, in order to scare the mass buy-out of land after the regulations restricting land purchases by foreigners were eased [41]. Restrictions on agricultural land acquisitions are necessary to avoid large tracts of land ending up in the ownership of a few large companies.

Nevertheless, even if there are restrictions against companies acquiring large tracts of land, the links between companies can be very complicated, and through complex relationships between different companies, agricultural land can still end up in foreign companies' portfolios. It also makes it challenging to track down how much land different companies (foreign or domestic ones) really use (own or rent).

The problem of the complexities of evaluating land use concentration regarding closely related companies was addressed by Rea [42]. The study's outcome showed the complexity of the relationships between companies in Estonia, and the result was that it is hardly possible to estimate the land use concentration based on simple and easy inquiry. Schemes based on extracts included simple systems containing one company and more complicated ones [42]. Finally, the thesis pointed out that it is essential to develop a methodology that would allow us to determine the scope of land use concentration concerning connections between companies. Visser, Mamonova, and Spoor [43] also described these complex relations between companies. A broad distribution of land ownership is the basis for the welfare of local economies and rural communities [13]. An increase in the area of agricultural land farmed by large agricultural producers raises concerns that agricultural development may not be favoring small-scale farming and has an important environmental footprint [44]. Farming should provide livelihoods for farmers, while retaining natural ecosystems and services [45].

3.2. Bibliometric Analysis

According to the 40 articles that were included in this study, the number of publications written about LSLA has increased over the years (Figure 3). Between 1991 and 2011, there was one article written on the topic, but between 2019 and 2020, there were 16 publications on LSLA.

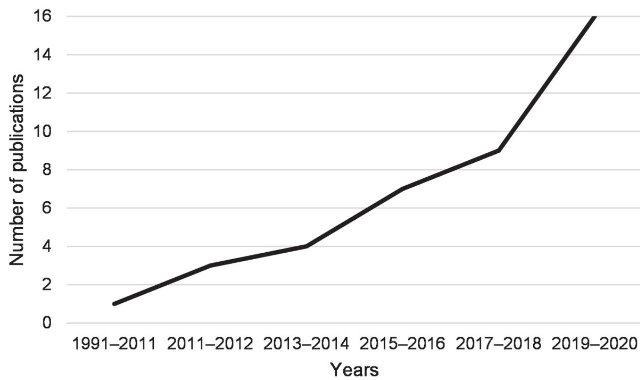

Figure 3. Number of publications written about LSLA between 1991 and 2020.

VOSviewer visualized 20 keywords, of which the earliest, most-used keywords emerged before 2013 and between 2013 and 2014 (Figure 4). The most-used keywords at that time were "land concentration", "land tenure", "global governance", and "governance". From 2013, the number of publications written on the topic started to increase more quickly (Figure 3). Between 2014 and 2015, the keywords "land", "biofuels", and "food sovereignty" started to emerge as the most-used keywords.

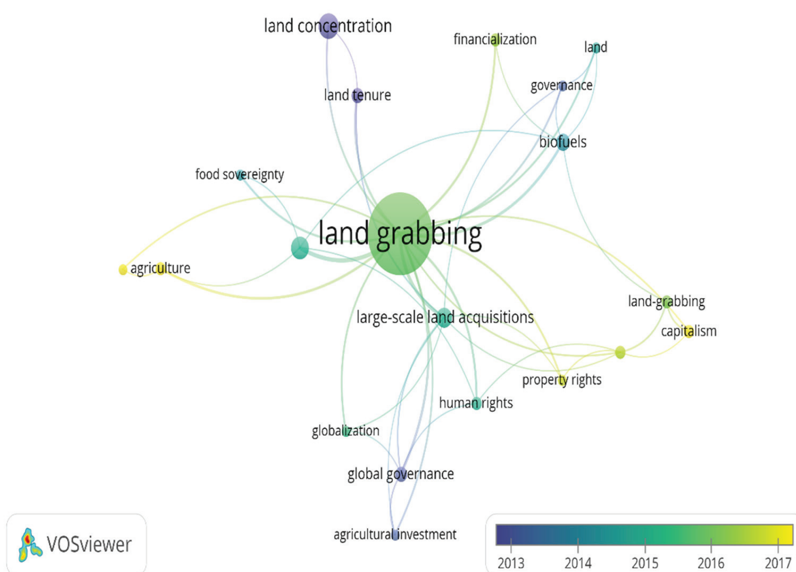

Figure 4. Keyword overlay visualization through VOSviewer.

Between 2015 and 2016, the keywords "food security", "large-scale land acquisitions" "human rights", and "globalization" were the most used in the publications. Between 2016 and 2017, the keywords "land grabbing", "financialization", "international law", and "land-grabbing" started to emerge strongly in publications. After 2017, the keywords "property rights", "capitalism", "agriculture", and "land fragmentation" started to emerge as the most-used keywords.

The majority (85 + 4) of the literature studies included the keywords "land grabbing" or "land-grabbing", which are linked with the other 19 keywords visualized in Figure 4.

The term “land grabbing” started to emerge strongly in the literature after 2016. Before that, the term “land concentration” was primarily used in these studies.

4. Discussion

There is no commonly accepted definition for the concept of “land grabbing”; nevertheless, since 2000, it has become a crucial concern for the academic community, civil society, governments, corporations, and financial institutions [46–49]. Land grabbing is frequently associated with the disempowerment and loss of local farmers, involving violence in some cases [11,50–54]. Nonetheless, land grabbing is not illegal or immoral in all cases [46,53].

In the EU, land grabbing takes place mainly in the Eastern and Central countries, but there are no reliable data about its scope. The Land Matrix Global Observatory includes only transactions that involve over 200 ha and are made in severe economic situations [32]. The EU’s directives, including the common agricultural policy (CAP), fuel land grabbing and concentration [46,55]. Currently, 80% of direct payments are concentrated only in the hands of 20% of the EU’s farmers [56]. This means that the principles on which the EU has been established require appropriate changes within the CAP. The CAP has a series of precise objectives, both economic and social, which basically pursue the protection of producer and consumer interests [57]. The post-2020 CAP reform has promised to deliver a fairer CAP and to change the abovementioned distribution [56].

As the CAP is closely related to land grabbing and land concentration in Europe, it is interesting that it did not come up as a keyword in Figure 4. After undertaking a new analysis (to find out if there was at least one CAP keyword) with VOSviewer and entering all keywords that had even one occurrence, the keyword CAP came up (it occurred once). There was only one article containing the keyword CAP, from 112 articles and 419 keywords.

The term “land concentration” was used as a keyword in 12 articles (Table 1), and it has been used in the LSLA literature since 1984. This keyword is linked with the terms “land tenure” and “land grabbing” (Figure 2). Land concentration is a process in which large agricultural corporations increasingly buy up or lease land from other agricultural producers [31]. The concentration of agricultural land makes it really challenging for the younger generations to buy or lease agricultural land, and the aging of the population employed in agriculture threatens the viability of rural communities [46]. Land should be regarded not as a commodity, but rather as a crucial resource for food security and safety. Therefore, land is fundamental to existence for the generations of today and tomorrow.

Various factors drive land concentration. As a result of the present form of the EU subsidy scheme CAP, where a subsidy is paid for each hectare of land, small-scale farms become weaker, and large-scale farms grow stronger [5,55]. Large agricultural enterprises are increasingly flooding our markets with low-cost food and agricultural commodities, and through this, small farms become less capable of competing in the market. This means that growing numbers of farms are likely to go out of business and have to sell their lands. Large and rapidly expanding farms are more likely to go bankrupt because their high debt-to-asset ratios make them more sensitive to market volatility [5]. This, in turn, may result in huge tracts of land coming on the market at a time when other farmers will find it difficult to buy additional land [5]. To avoid this, a relationship between large agricultural enterprises and small-scale farms must be enabled so that both farming types can stay in fair market competition [58]. This means that LSLA can be, to some extent, good for the local population [59].

“Food security” was used as a keyword in 10 studies and “food sovereignty” was used in three studies. These keywords are directly linked with the keyword “land grabbing”. The Food and Agriculture Organization of the United Nations (FAO) defines food security as “a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” [60]. Movement toward global food security is strongly related to agriculture, as most of the poor depend on agriculture and related activities for a significant part of their livelihoods. Food security is compromised by “land grabbing" and "land concentration". Local food security and food sovereignty, especially in developing countries, can be undermined by the export of agricultural products [61]. Moreover, the outbreak of COVID-19 and the restrictions that followed it have shown us that it is imperative that countries have their own food supply [62,63]. This means that relying only on food imports from other countries can threaten a country's food security. It has also been noted that several mechanisms accompanying LSLA may contribute to the emergence of zoonotic diseases [64].

Table 1. Keyword occurrences in the examined studies.

Keyword	Occurrences
Land grabbing	85
Land concentration	12
Food security	10
Large-scale land acquisitions	8
Biofuels	6
Global governance	5
Land tenure	5
International law	4
Human rights	4
Agriculture	4
Capitalism	4
Financialization	4
Land-grabbing	4
Agricultural investment	3
Governance	3
Globalization	3
Land	3
Property rights	3
Food sovereignty	3
Land fragmentation	3

"Large-scale land acquisitions" occurred as a keyword in eight studies (Table 1) and is linked with eight keywords ("land grabbing", "land tenure", "governance", "globalization", "agricultural investment", "global governance", "property rights", and "international law") (Figure 4). In general, terms like "land grabbing", "land concentration", and "large-scale land acquisition" are used to mark the takeover of large land areas; nevertheless, these terms are not synonymous. LSLAs have been promoted as a mechanism to support rural development through the increased input of financial capital, job creation, agricultural technology transfers, and gains in agricultural productivity [65]. However, these developments may come at the expense of reducing water access for local farmers and their future ability to irrigate [65,66].

LSLAs have been widely reported during the last two decades across Africa, Asia, Latin America, and even Eastern Europe. The Land Matrix reported that, since 2019, EU-based companies have been engaged in 909 land deals globally, involving a total of 29 million hectares of land [34]. The results of research by Burja et al. [46] showed that land concentration and land grabbing pose a serious threat to the sustainable development of agricultural holdings and rural areas due to their inimical social effects.

"Biofuels" was used as a keyword in six studies, and it is linked with six other keywords ("land", "governance", "financialization", "land-grabbing", "land grabbing", and "food security"). Biofuel production may harm food security [67]. Its production influences the food supply by increasing greenhouse gas emissions and food prices [67]. As the EU biofuel directive requires that 10% of all transport fuel should come from biofuel by 2050, its production has tripled in the last decade [61]. This directive does not help relieve hunger and may increase both the rate of land grabbing and food prices [61,67].

"Global governance" was used as a keyword in five studies, and it is linked with five other keywords ("land grabbing", "agricultural investment", "large-scale land acquisitions", "human rights", and "globalization"). Global governance as an academic notion arose in the 1990s in response to new global-scale problems (HIV, climate change, international migration, etc.). As land grabbing and land concentration is a global-scale phenomenon that is taking place in all regions and parts of the world, and has become a matter of public concern, it has provided the political sense of urgency to move forward on global land governance [68,69]. There has been criticism of the lack of a binding and consistent regulatory regime for LSLA [47].

Growing concentration has shaped governmental agricultural policies, including the different modalities of the CAP subsidy scheme, which has favored long time large-scale holdings, marginalized small-scale farms, and blocked the entry of possible future farmers [5]. The voluntary nature of different regulatory instruments is seen as being weak for protecting against human rights violations caused by LSLA and poor for facilitating sustainable development [47].

"Land tenure" was used as a keyword in five studies, and it is linked with the keywords "land concentration", "land grabbing", and "large-scale land acquisitions". There is no international definition of land within the context of tenure [70]. The meaning of the word may be defined within the national context. This keyword mostly arose in studies where FAO's voluntary guidelines on the responsible governance of tenure of land, fisheries, and forests in the context of national food security (VGGT) were discussed. For instance, Margulis et al. [68] wrote that the VGGT are the most concrete element of emergent global governance related to LSLA. Their overarching goals are to achieve food security for all and support the progressive realization of the right to adequate food in the context of national food security [70].

"International law", "human rights", "agriculture", "capitalism", "financialization", and "land-grabbing" were used as keywords in four studies. All these keywords are linked with "land grabbing" or "land-grabbing". In particular, "human rights" as a keyword is linked with "international law", "land grabbing", "food security", and "global governance". Throughout the world, human rights are pivotal in human development [71]. Secure tenure is an internationally recognized human right, and this right includes the human right to livelihood and land [72]. In the past few decades, several countries have adopted forceful land reforms to deal with poverty, equity, restitution for past expropriation, investment, and innovation in agriculture or sustainability [73]. For example, Scotland's unusually concentrated pattern of land ownership is a matter of longstanding concern. In Scotland, 432 families (0.008% of the population) own 50% of the private rural land, and if only a small fraction of society owns the land, inequality will rise [74]. Scotland has made some progress on land reform, and the Scottish government, in consultation with a wide range of stakeholders and experts, is in the progress of specifying the maximum amount of land that any individual is permitted to hold. Nevertheless, this kind of land reform is complex and has already left behind exhausted communities and enriched landowners [74]. This means that it might be better for society to control land concentration before it reaches an extent (as has happened in Scotland) where there is a need for complex land reform.

"International law" as a keyword is linked with "capitalism", "land grabbing", "land-grabbing", "human rights", "property rights", and "large-scale land acquisitions". "Agriculture" as a keyword is linked with "land fragmentation", "land grabbing", and "food security". "Capitalism" is linked with "land grabbing", "land-grabbing", and "international law". "Financialization" is linked with "biofuels" and "land grabbing". "Land-grabbing" is linked with "biofuels", "capitalism", and "international law". "Agricultural investment", "governance", "globalization", "land", "property rights", "food sovereignty", and "land fragmentation" were used as keywords in three studies, and keywords that had linkages with them are aforementioned.

5. Conclusions

As the COVID-19 pandemic closed the world, and Russia invaded Ukraine at the beginning of 2022, domestic agricultural production to ensure short supply chains began to look more and more essential. Closed borders between countries, disrupted global food supply chains, and restricted movement inside countries showed that it is essential to keep food production as close to the consumers as possible from the viewpoint of food security.

As land concentration remains basic and is one of the most serious land issues today, the aim of this paper was to compile a systematic literature analysis literature on land grabbing and concentration. To fulfil this task, different documents and articles were first studied (Section 3.1), and, in Section 3.2, literature from the SCOPUS database was analyzed. In Section 3.1, the phenomenon of Europe's LSLA was described. It was found that the agricultural sector needs to change to reach the goals set out in the European Green Deal and SDGs. The trend in today's EU agricultural sector is characterized by a declining number of agricultural producers and an increasing size of farms. An increase in the area of agricultural land farmed by large agricultural producers raises concerns that agricultural development may not be favoring small-scale farming. Increase in the number of agricultural producers is coming at the expense of small farms. Although different studies have sought to determine which farming model is most suitable for the environment and will ensure future food security, there is no single answer to this question.

For Section 3.2, VOSviewer was used to visualize 20 keywords. Results showed that the majority (85 + 4) of the examined studies from the literature included the keywords "land grabbing" or "land-grabbing", which were linked with the other 19 keywords. The term "land grabbing" started to emerge strongly in the literature after 2016, but before that, the term "land concentration" was primarily used in these studies. The study also showed that the number of publications written on LSLA has increased over the years.

The land is a fundamental element for our existence, and, because of that, it is difficult to overstate its strategic importance to our wellbeing and prosperity. The ownership of land can make it available for community and business development, or keep it in the hands of a small number of large agricultural users. Investments in small agricultural producers remains one of the most direct ways to address food security and rural poverty. This study shows that LSLAs are closely related to food security, human rights, global governance and international law, land tenure, biofuel production, and financialization through EU CAP subsidies and foreign direct investments. This means that land distribution is one important component that guarantees our right to food, human rights, and sustainability in agriculture and other related areas. Equitable agricultural land distribution should ensure, in addition to food supply, a range of ecosystem services at prices that sustain a living income for producers of food.

As the topic of LSLA is broad, and different countries in various ways are involved, this topic needs successive studies. One way for developing the study further is by investigating the LSLA phenomenon in different countries and highlighting good practices in the discussed topic.

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Losing the Plot: The Impact of Urban Agriculture on Household Food Expenditure and Dietary Diversity in Sub-Saharan African Countries

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Abstract: Urban agriculture (UA) is proposed as a solution to the social and economic challenges presented by cities by providing urban households with food and income using environmentally friendly food production techniques. To date, most analysis of UA has been based on single-city studies. This paper aims to contribute to the literature by using a cross-country approach and by analysing household level data from nine sub-Saharan countries—Burkina Faso (2014), Ethiopia (2013), Ghana (2009), Malawi (2013), Niger 2014, Nigeria (2012), Tanzania (2010) and Uganda (2013). This paper sets out to answer three questions; the first investigates which are the main characteristics of households engaged in urban agriculture; the second looks at the role played by UA in diversifying household diets and reducing household food expenditure; the third examines the heterogeneity in the impact of UA across the food expenditure distribution. Using an inverse-probability weighted regression adjustment method, the results show that households engaged in agriculture reduced expenditure on food and modified their food expenditure profile by spending more on protein rich food -nuts, legumes, fruits, dairy products, meat and poultry. The study also finds substantial variation on the impact of UA across the food expenditure distribution.

Keywords: urban agriculture; household level data; sub-Saharan countries; food expenditure; dietary diversity

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1. Introduction

By 2050, the world population will reach 9.6 billion, and the majority are likely to live in urban areas of less developed regions [1,2]. The urbanisation trend is already evident in sub-Saharan Africa, where the urban population is projected to double between 2010 and 2030 [3]. An expansion of urban populations inevitably puts pressure on rural agricultural production and distribution to provide food to city dwellers [4]. Despite many technological and mechanical improvements in food production—as well as the use of genetically modified crops—distribution bottlenecks and malnutrition remain prevalent and food poverty continues to be problematic in many cities around the world [5]. This situation is going to worsen. It is estimated that 40% of urban inhabitants across the world live on less than US $1 a day, while 70% live on US $2 a day [6]; urban households in the poorer strata of the population spend up to 80% of their income on food, making them extremely vulnerable to food price volatility. The importance of agricultural activities practised in an urban setting—in terms of food access, dietary diversity, health related outcomes and additional income—is clear [7,8].

Urban agriculture (UA) is defined as the growing of crops and the raising of (small) livestock in areas within the urban boundaries of cities and towns with the purpose of either personal consumption or selling the crops in urban markets. UA is practised in several locations, e.g., home gardens, vacant lots, roadsides, green areas and balconies, but also in privately or institutionally owned land [9]. Urban farmers mostly plant vegetables along with fruit, root or leguminous crops, depending on local demand, as well as poultry and small ruminants [10]. Although official numbers on the size of the overall UA phenomenon do not exist, a conservative estimate suggests that between 15 and 20% of the world's food is currently being produced in cities [11].

A positive narrative has been built around UA, as it is regarded as a solution to the social, economic and environmental challenges cities face [12,13]. Urban farmers engage with UA to meet their daily food requirements; in this regard, UA improves households' access to food in times of shortage, instability or uncertainty, and provides them with an additional source of income, strengthening households' resilience in times of crises. The balance between UA intended for individuals' own consumption and for income generation varies and may depend on several variables, including the gender of the farmer, wealth of the households, area of residence and size of the allotment [14].

Despite the potential benefits that UA can generate (not only in terms of food provision and income, but also in terms of empowerment for women), UA does face several constraints: lack of available and extensive green areas, an absence of clearly defined property rights, a shortage or unavailability of low-cost feed for livestock, and environmental and health concerns regarding waste and soil/water used in the plots [15]. Access to free land is problematic and—alongside the lack of property rights—represents a challenge for long-term farming strategies. In addition, UA still lacks a proper legislative frame capable of reducing negative environmental externalities [16]. Along the same lines, there are several diseases and pathogenic agents that can be passed to, and cause harm to, humans through vegetables, livestock and animal products [17].

Overall, the current scientific literature on UA is vast, but has shortcomings. Most studies are single-city studies [18], and there is need for a larger examination, which can be provided by a cross-country analysis of nine sub-Saharan countries.

In this paper, we set out to answer three questions; the first investigates the typology of households engaged in UA; the second looks at the role played by UA in diversifying household diets and in reducing overall food expenditure for the households; the third examines the heterogeneity in the impact of UA across the food expenditure distribution.

The estimation strategy comes with its own challenges. Household with given traits, as an example, households already employed in agricultural activities, are more likely to practice UA and this could lead to a selection bias in the estimation measuring its impact. To address this, the Propensity Score Matching (PSM) approach can be used, however, the estimate of PSM can itself produce biased results in the presence of misspecification [19]. For this purpose, an inverse-probability weighted regression adjustment (IPWRA) method is used, as it can model both the outcomes and the treatment to control for the endogeneity in the non-random participation in UA by the households [20].

Results indicate that households engaged in agriculture reduced food expenditure by 3 percent and modified their diet by eating more types of protein rich food, such as nuts, legumes, fruits, dairy products, meat and poultry. Although the analysis carried out here highlights that the contribution of UA in increasing food diversity—both in terms of food count and food categories—is on average very modest, it is acknowledged that UA could still play a role in household food security by significantly reducing the food expenditure. The effect UA has on households' expenditure and diet vary; the country-related quantile analysis suggests the existence of substantial variation, with bigger decreases in percentage points of food expenditure at the higher end of the expenditure distribution.

The paper is organised as follows; the next section will briefly look at part of the existing literature on UA. Section 3 will describe the data used and offer descriptive statistics. Section 4 presents the methodology used and Section 5 provides the results. The concluding remarks are in Section 6.

2. What We Know about Urban Agriculture

The complete literature on UA is vast; in this section we look at the most notable contributions that examine UA participation, its drivers and the main challenges faced.

2.1. Who Practices Urban Agriculture?

It would be unrealistic to expect an urban environment to ever become entirely self-sufficient when it comes to the provision of food; this is prevented by the (lack of) space, as green areas in the urban context are limited and virtually all cereal crops grow more efficiently in rural (larger) fields. Given this, UA already makes a significant contribution to enhance food security in many major cities. The UNDP estimates suggest that the 800 million urban farmers around the world are responsible for about 15% of the global food production [21]. In sub-Saharan Africa, UA agriculture activities are mainly conducted by women. This is overwhelmingly the case in East and Southern Africa, but less so in West Africa, where both women and men are involved in UA activities [22,23]. Two factors explain the higher proportion of women engaged in UA: women overall have lower levels of formal education, which makes it more difficult for them to find formal employment vis-à-vis men, and the localised nature of UA fits well with women's domestic duties. Practicing UA is compatible with the role they traditionally have within households, i.e., being wives and mothers [24,25]. However, women often face difficulties accessing land, water, labour, capital and technologies, and may be prevented by laws and informal attitudes from owning assets or making decisions about how to use assets [26,27].

UA can be a household business too, where all the family members are involved. Women tend to be more involved in the planting, weeding and hoeing activities [24], and men more responsible for preparing the land beforehand [28]. This stems from the cultural tradition showing that men are more suitable for activities involving harder physical labour. This applies to a lesser extent in urban plots which are smaller and more continuously farmed, making labour less arduous [29].

While keeping livestock is still considered to be a male domain, there is a consensus that women are the ones selling UA products of either vegetable or animal origin [30].

2.2. The Drivers behind Urban Agriculture

UA may help households in two main ways; it improves their diet through the inclusion of more freshly grown produce, and it improves their financial well-being through additional income gained by selling excess produce. Urban farmers engage in agricultural activities to enjoy fresh foods that have higher nutritious qualities—mainly fruits, vegetables and eggs—which otherwise would not necessarily be available for purchase [31,32]. UA improves households' financial security and resilience in times of uncertainty via the possibility of selling those fresh products in local markets.

In terms of food security—defined as "access by all people at all times to enough food for an active healthy life" [33]—UA represent an alternative to food produced in rural areas. The urbanisation process—which, among other effects, reduces the pool of workers in the agricultural sector—the increasingly harsh climate condition, longer supply chains and transportation represent only a few of the factors making rural agriculture less reliable [34,35]. The production of vegetables and fruits within urban and peri-urban boundaries provides food for millions of urban dwellers as well as livelihoods for urban farmers.

A study using household-level data from 15 developed/transition economies highlights that a high share of households earn income from UA [36]. The overall positive effectiveness of many UA projects has been assessed by Masset et al., (2011) [18]. Their review of 23 existing agricultural programmes points out that UA activities increase the consumption of food rich in protein and micronutrients, although the impact on growth-stunting and children health-related indicators is limited [37].

Poulsen et al., (2015) reviewed 33 studies on UA in sub-Saharan Africa and compiled urban farmers' perception about UA. Evidence of the positive contribution of UA comes from, among other countries, Kenya, where 40% of surveyed urban farmers "think they would starve if they were stopped from farming" [38]. In Cameroon, urban farmers considered UA to be the most important source of calories for their households [25], and in Zambia, UA is considered a key tool for meeting shortfalls in household food requirements [39].

2.3. Barriers to Urban Agriculture

Land availability within the urban perimeters is a crucial issue. Insecure land tenure can trigger conflicts, and municipalities acknowledging the benefits of UA struggle with outdated regulations as they try to facilitate its expansion [40,41].

Land access is not the only barrier to UA. Farming on contaminated soil, irrigating crops with untreated wastewater and the use of chemicals represent some of the environmental and health issues that must be considered when discussing UA [42]. There are several kinds of potential food hazards, including physical, chemical or microbial. Potential hazards for food contamination relate to fruits and vegetables grown near major roads, railways and industrial sites. Chemical food hazards—i.e., water and soil pollution caused by organic pollutants—endanger the product quality (Nabulo et al., 2010). Microbial contamination may occur throughout the production chain and may be a consequence of contaminated common pool resources [43]. As an example, the presence of pathogens in the soil, application of contaminated manure, irrigation with untreated water or the cleaning of a product by using polluted water. The absence of legislation and protection regarding UA poses a threat to crop yields and overall quality. Even so, banning the use of wastewater for irrigation may not be the solution as there is little access to other water sources. Health implications for producers need to be considered along with concerns about the final product.

Any discussion on barriers to UA should also mention livestock practices; contagious diseases, including zoonoses, have negative impacts on animal production and constitute a severe public health risk. The spread of such diseases is facilitated in areas where there are markets selling live animals. Livestock manure used for local crops or left as waste poses risks for the transmission of diseases to animals as well as to humans. Anecdotal evidence regarding possible sources of COVID-19 may well influence government decision-making regarding UA and animal markets.

At the same time, UA does have the potential to contribute to a healthier environment by recycling and reusing some of a city’s organic wastes. Connecting produced waste with the need for fertiliser solves two problems: decreasing soil fertility and pollution of organic waste into the environment [44]. Compost cannot fully replace other fertilisers as some nutrients—e.g., nitrogen—are low, but the net effect of compost on nutrient poor soils is still positive.

3. Data and Descriptive Statistics

The analysis that follows is based on household level data representative at the urban level, drawn from surveys in sub-Saharan African countries and made available from the World Bank via the Living Standards Measurement Study (LSMS). The data from the following surveys were used (corresponding survey years in parentheses): Burkina Faso (2014), Ethiopia (2013), Ghana (2009), Malawi (2013), Niger 2014, Nigeria (2012), Tanzania (2010) and Uganda (2013) (Table 1). Although the questionnaires used for data collection vary from country to country, data have been standardised for comparison purpose (see Tasciotti and Wagner (2018) on the quality of household level data). While the surveys are recent (collected within the last decade), two of them—Ghana and Tanzania—were launched more than 10 years ago. In the presence of rapid urban transformation, the conclusion we may be drawing for some of the countries may be out of date but will still indicate the contribution UA has had in terms of food security. The number of observations—i.e., urban households—ranges between 800 for Uganda and 4000 in Burkina Faso, with most of the countries having data on approximately 1000 urban households.

Table 1. List of countries, year of the surveys and number of observations.

Country	Year of the Survey	Number of Observations
Burkina Faso	2014	4260
Ethiopia	2013	1939
Ghana	2009	2010
Malawi	2013	1046
Mali	2014	1405
Niger	2014	1298
Nigeria	2012	1488
Tanzania	2010	1295
Uganda	2013	816
Total		15,557

Source: Authors' calculation from LSMS data. Notes: the number of observations (column three) relates to only urban households.

To understand the magnitude of the UA phenomenon we look at the rate of participation in urban agricultural activities in each of the nine countries and in each of the five wealth quintiles. The results are summarised in the histogram presented in Figure 1. Participation rates do vary across countries and across quintiles and generalisation are not easy to make; however, there are some regularities. On average, about 20% of the urban households practice some form of UA. More households in the lower wealth quintiles engage in UA, between 19 and 32%; this regularity does not happen in Ethiopia, where households in the third quintile are the ones engaging in the most UA (25%). The statistics show a lower engagement compared to the one presented by Zezza and Tasciotti (2010) [36] in which between 60 and 70% of the households in the poorest quintile were engaged in UA. The participation statistics show how UA—while it could not be considered negligible—does not appear to be the income generating activity mostly practised in urban areas; instead, it is a side activity mostly practiced by households in the lower income quintiles.

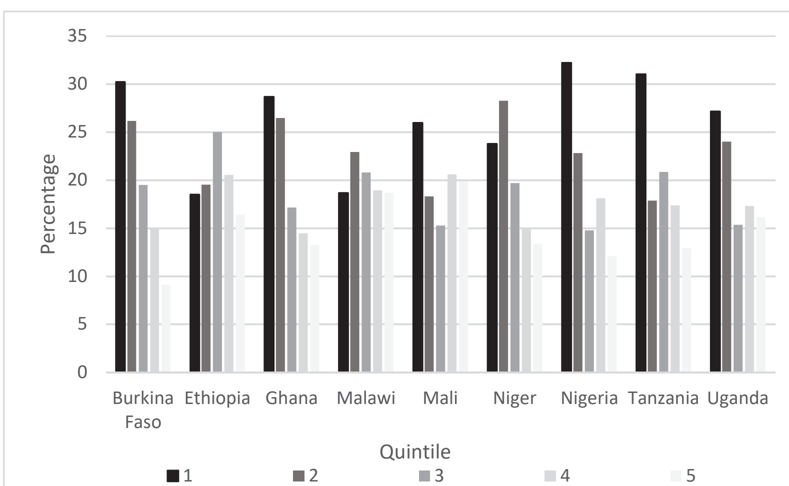

Figure 1. Share of households engaged in urban agriculture, by country and quintiles of wealth. Source: Authors' calculation from LSMS data.

The statistics on the household food expenditure—albeit nonconclusive—show a lower yearly food expenditure profile for those engaging in UA (Table 2). The computation of the food expenditure does not consider in-kind food, e.g., foods being produced by the household via UA or received for free. The difference can be minimal—30 USD in Ghana—or higher, as in the case of Uganda (about 600 USD); the same trend is observed for the per-capita food expenditure. The lower expenditure profile does not necessarily translate to a less diversified diet, as the rest of the table indicates. We employ two indicators related to dietary diversification: the food count and the food group. The first one is a simple count of the different food items the household report having consumed during the survey reference period, while the second one is based on 12 food groups (the 12 food groups considered here are: cereals, starch and tubers, nuts and legumes, vegetables, fruits, milk products, oil and fats, meat and poultry, fish, sugar and syrups, beverages and miscellaneous). The statistics do not show any major difference between the two categories of households (the differences are rarely statistically significant). Results in Table 2 point out that practicing UA is associated with lower food expenditure, and that this does not prevent the household from having a diversified diet.

Table 2. Food expenditure (household and per-capita), food count and food group for UA/non-UA households, by country.

Countries	Yearly Household Food Expenditure (in USD)		Yearly per-Capita Food Expenditure (in USD)		Food Count		Food Group	
	Not Engaged in UA	Engaged in UA	Not Engaged in UA	Engaged in UA	Not Engaged in UA	Engaged in UA	Not Engaged in UA	Engaged in UA
Burkina Faso	1847	1428	515	212	16	17	6.60	6.50
Ethiopia	848	939	259	226	10	10	6.03	6.01
Ghana	1172	1140	502	361	24	23	8.50	8.77
Malawi	1412	1368	391	284	23	23	8.73	8.57
Mali	2999	2890	531	363	22	23	8.07	7.69
Niger	2520	2472	471	328	25	24	7.24	7.38
Nigeria	2919	2844	690	520	16	16	7.26	7.23
Tanzania	1998	1663	558	350	15	16	7.98	8.21
Uganda	2534	1929	1091	560	17	19	8.15	7.91

Source: Authors' calculation from LSMS data. Notes: The expenditure values have been converted from local currency to USD 2020. The variable 'food count' counts the number of foods consumed by the household; this variable ranges between 0 and the maximum number of foods surveyed (which varies from country to country). The variable 'food group' ranges between 0 and 12 for all the countries.

Table 3 below presents the summary statistics of the variables used in the analysis. The household who are engaged in UA have a lower food expenditure ($1578.39) compared to those who are not engaged in UA ($1904.22). Both the groups have similar food group, food count, and number of food products consumed. Those households not engaging in UA activities tend to have higher scores for the food group and food count categories, although the difference is very marginal. The differences between UA and non-UA households in terms of food count in the 12 categories used here are very negligible. The households practicing UA have a lower amount of assets. (We created an asset index using Principal Component Analysis. The index utilises information on assets such as refrigerator, stove, bed, mobile, TV, video player, sofa, bicycle, motorcycle and car.) The head of the households practicing UA are older (49 years compared to 43.5 years for non-UA households), more likely to be male (82% compared to 74% for non-UA households) and married (81% compared to 69% for non-UA households). The head of UA households has, on average, completed 4.6 years of education; this is significantly lower the head of non-UA households, who have completed 7.69 years of education on average. The households practicing UA are more likely to be employed in agricultural activities and have a higher number of children, adults and senior adults.

Table 3. Summary statistics.

Variable	Households Engaged in UA			Households Not Engaged in UA		
	Obs	Mean	Std. Dev.	Obs	Mean	Std. Dev.
Food Expenditure	3580	1578.39	1335.82	10,680	1904.22	1718.72
Food Group	3853	7.31	1.88	11,704	7.37	2.43
Food Count	3853	17.81	7.2	11,704	18.3	8.66
Cereals	3796	3.11	1.56	11,066	3.34	1.54
Starch & Tubers	2070	2.17	1.3	7323	1.98	1.21

Table 3. *Cont.*

Variable	Households Engaged in UA			Households Not Engaged in UA		
	Obs	Mean	Std. Dev.	Obs	Mean	Std. Dev.
Nuts & Legumes	2713	1.71	1.01	7665	1.69	.87
Vegetables	3754	3.99	1.79	10,730	4	2.15
Fruits	1524	1.84	1.14	6088	1.83	1.15
Milk Prod	1313	1.25	0.59	5559	1.27	0.58
Oil & Fats	3538	1.45	0.65	10,664	1.54	0.7
Meat & Poultry	2095	1.41	0.68	7388	1.37	0.65
Fish	2792	1.09	0.56	8346	1.07	0.72
Sugar & Syrup	3024	1.2	0.46	9252	1.29	0.51
Beverages	2854	1.59	0.96	8296	1.68	1
Miscellaneous	3409	2.42	1.38	8783	2.7	1.73
Head’s Age	3849	49.02	15.06	11,551	43.56	14.93
Female Head	3852	0.18	0.38	11,703	0.26	0.44
Head Married	3845	0.81	0.39	11,627	0.69	0.46
Head’s Education	3791	4.6	5.24	11,386	7.69	5.84
No of Children	3853	2.81	2.38	11,704	1.8	1.91
No of Adults	3853	3.44	2.35	11,704	2.83	2.03
No of Senior Adults	3853	0.29	0.56	11,704	0.15	0.4
Assets Index	3853	0.23	1.79	11,704	1.53	2.15
Employed in Agri	3853	0.53	0.5	11,704	0.34	0.47

Source: Authors’ calculation from LSMS data.

4. Methodology

The objective of this study is to analyse the impact of UA on food consumption patterns. This can be calculated by using average treatment on the treated (ATET), which is the difference between the mean outcomes of households engaged in UA and the mean outcome for the same group if they had not been engaged in UA. ATET can be written as:

$$\text{ATET} = E[Y(1) - Y(0) \mid I = 1] = E[Y(1) \mid I = 1] - E[Y(0) \mid I = 1] \tag{1}$$

where Y(1) and Y(0) represent the variable of interest for households engaged in UA and not engaged in UA, respectively. ‘I’ represents the treatment indicator that takes the value 1 if the household is engaged in UA and 0 otherwise. $E[Y(1) \mid I = 1]$ is the expected outcome for the household engaged in UA, conditional on practicing UA and $E[Y(0) \mid I = 1]$ is the expected outcome for those households are not engaged in UA, conditional on practicing UA. However, it’s not possible to observe the outcome for $E[Y(0) \mid I = 1]$. It would not be statistically correct to replace it with the outcome of the household not engaged in agriculture ($E[Y(0) \mid I = 0]$)—since factors that influence the participation in agriculture may also affect decisions on food consumption, leading to bias ATET estimates (Takahashi & Barrett, 2013). To address this issue, we can apply the propensity score matching technique which attempts to approximate a randomised experiment by statistically creating a synthetic sample based on observed covariates xi which are independent of participating in UA.

The ATET psm can be written as:

$$\text{ATETpsm} = E[Y(1) \mid I = 1, p(x)] - E[Y(0) \mid I = 0, p(x)] \tag{2}$$

where ATET psm is propensity score weighted mean difference in outcomes, x is the vector of covariates which are not independent of I, and p(x) is the propensity score.

However, misspecification in the propensity score matching method can lead to bias [19]. To address the misspecification bias, we employ IPWRA methods. The advantage of this method over others—including the PSM one—is that it estimates both the treatment and the outcome model [20]. The resulting estimator may produce consistent and robust results even when one of the models is mis-specified [45], a trait predominately known as double robust [46]. For technical details on IPWRA, see Wooldridge (2010) [19].

Following Wooldridge (2010) [19], the IPWRA estimations can be conducted in two steps. In the first step, we estimate the propensity scores $p(x;\hat{\gamma}\ )$ based on a set of observable variables. In the second step, a series of regressions are conducted to estimate $(\alpha_0\ ,\ \beta_0)$ and $(\alpha_1\ ,\ \beta_1)$ using inverse probability weighted least squares as indicated in (2) and (3) as seen in Manda et al., (2018) [47]:

$$\frac{\min\limits_{\alpha_0,\ \beta_0}\ \sum_{i=1}^{N}(\ y_i-\alpha_0-\beta_0 x_i)}{1-p(x,\hat{\gamma}\ )}\ if\ I\mathrm{i}=0 \tag{3}$$

$$\min_{\alpha_1,\ \beta_1}\ \sum_{i=1}^{N}(\ y_i-\alpha_1-\beta_1 x_i)/\ p(x,\hat{\gamma}\ )\ if\ I\mathrm{i}=0 \tag{4}$$

By utilizing inverse-probability weights from the difference between equation above, the IPWRA estimates the ATET as follows in (4):

$$\mathrm{ATET}_{\mathrm{IPWRA}}=\frac{1}{N}\sum_{i=1}^{N}[(\hat{a}_1-\hat{a}_0)+(\hat{\beta}_1-\hat{\beta}_0)x_i] \tag{5}$$

where $(\hat{a}_{1,}\ \hat{\beta}_1)$ are estimated inverse probability weighted parameters for households that practice UA while $(\hat{a}_{0,}\ \hat{\beta}_0)$ are the parameters for members who did not practice UA, xi represents a vector of exogenous variables that affect the dependent variables used for the analysis (food expenditure, food group, food count and number of food products in the 12 food categories, and N indicates the total number of households who practice UA (since some of outcomes are categorical variables (food group, food count and the 12 categories of food), we used the IPWRA estimation procedure with Poisson regression as an outcome model to perform the analyses).

Additionally, we employ an unconditional quantile treatment effect (QTE) using the residualised quantile regression approach by Borgen, Haupt, and Wiborg (2021) [48]. Unconditional quantile treatment effect (UQTE) is a measure of the average treatment effect on a specific quantile of the outcome distribution that is not conditioned on any covariates. Unlike the conditional quantile treatment effect (CQTE) which estimates the treatment effect at a specific quantile while taking into account the values of one or more covariates, UQTEs estimate the treatment effect for the entire population. (UQTEs are less sensitive to the choice of covariates used in the estimation than CQTEs. Since UQTEs do not depend on any specific set of covariates, they can provide a more robust estimate of the treatment effect. These effects are of particular interest in policy evaluations as they are simple to interpret and can be easily conveyed and summarised [49].)

5. Results

The paper uses a probit model to investigate the profile of the households most likely to engage in UA. The dependent variable in this model is a binary variable which takes the value 1 if the household practices UA, and 0 otherwise, and the probit regression is completed by including all the observations—i.e., all the urban households—in the nine countries. Table 4 presents the probit estimation and marginal effect (second and third column respectively), indicating how each variable affects the likelihood of being engaged in UA activities. Results indicate that the age of the head of the household, whether the head of the household is currently married, whether the head of the household is already employed in agricultural activities, and the number of children, adults and older members (65 years old or more) of the household all increase the likelihood of the household practicing UA. This effect is particularly strong for households where the head of the household is already married (7.4 percent, significant at 1 percent) and employed in agricultural activities (9 percent, significant at 1 percent). Contrary to what some of the literature suggests, the variable 'female head of the household' does not increase the likelihood of participating in UA activities. This result is related to the fact that UA is often considered an activity involving all the household members, with the men being more responsible for the harder work and the women being more involved in the planting and weeding activities [28].

Table 4. Participation in urban agriculture using probit model.

Variables	(1) Urban Agriculture	(2) Marginal Effects
Head's Age	0.011 ***	0.002 **
	(0.001)	(0.000)
Female Head	−0.265 ***	−0.066 ***
	(0.038)	(0.009)
Head Married	0.296 ***	0.074 ***
	(0.037)	(0.009)
Head's Education	−0.025 ***	−0.006 ***
	(0.003)	(0.000)
No of Children	0.109 ***	0.027 ***
	(0.007)	(0.001)
No of Adults	0.040 ***	0.009 ***
	(0.007)	(0.001)
No of Senior Adults	0.009	0.002
	(0.034)	(0.008)
Ethiopia	0.819 ***	0.205 ***
	(0.069)	(0.017)
Uganda	1.091 ***	0.273 ***
	(0.075)	(0.018)
Malawi	1.477 ***	0.370 ***
	(0.073)	(0.017)
Nigeria	0.867 ***	0.217 ***
	(0.071)	(0.017)
Tanzania	1.242 ***	0.311 ***
	(0.070)	(0.017)
Ghana	1.193 ***	0.298 ***
	(0.068)	(0.016)
Burkina Faso	1.123 ***	0.281 ***
	(0.060)	(0.014)
Mali	−0.015	−0.003
	(0.078)	(0.019)
Niger (reference group)	-	-
Assets Index	−0.175 ***	−0.043 ***
	(0.008)	(0.001)
HH occupation (1 employed in agriculture.; 0 otherwise.)	0.358 ***	0.089 ***
	(0.027)	(0.006)
Constant	−2.526 ***	
	(0.088)	
Observations	15,063	15,063

Source: Authors' calculation from LSMS data. Notes: Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$.

The results in Table 4 shows that education level of the head of the household and the household's assets negatively affect the likelihood of the household practicing UA, while household size—more children and more adults—does positively and significantly affect UA uptake.

To address the issue of non-random engagement of household in UA—i.e., households self-selecting themselves into UA activities—we employ the IPWRA method to balance the covariates. The ATET estimates are presented in Table 5 model (1). We find that households that practice UA reduced their expenditure on food by 3%, freeing up some additional cash for other household non-food needs. This result is in line with the existing evidence (see [9] for a systematic review of the food security related impacts of UA). The 3% saving represents an average across the population that participates in UA; later, we will analyse how those savings differ across the food expenditure deciles.

Table 5. Impact of urban Agriculture using IPWRA estimates.

Variables	(1) Food expenditure	(2) Food group	(3) Food Count	(4) Cereals	(5) Starch & tubers
Urban Agriculture	−0.03 ***	0.206 ***	0.660 ***	0.016	0.143 ***
	(0.013)	(0.035)	(0.124)	(0.032)	(0.021)
Observations	13,380	15,063	15,063	14,471	9135
Variables	(6) Nuts & legumes	(7) Vegetables	(8) Fruits	(9) Milk products	(10) Oil & fats
Urban Agriculture	0.090 ***	−0.076 ***	0.066 **	0.042 **	−0.057 ***
	(0.020)	(0.031)	(0.032)	(0.019)	(0.014)
Observations	10,061	14,112	7373	6629	13,834
Variables	(11) Meat & Poultry	(12) Fish	(13) Sugar & Syrup	(14) Beverages	(15) Miscellaneous
Urban Agriculture	0.10 ***	−0.041 ***	0.006	0.068	0.059 ***
	(0.018)	(0.012)	(0.008)	(0.022)	(0.017)
Observations	9183	10,922	11,965	10,895	11,846

Source: Authors' calculation from LSMS data. Note: Models (2) to (15) are estimated using Poisson regression as an outcome model. Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$.

To further investigate the contribution of UA in terms of households' diet, we look at the impact of UA on several indicators related to the household's consumption: the yearly food expenditure, the food group and food count indicators, and the 12 categories of food. The results (Table 5) suggest that households practicing UA do consume more categories of food items in general as the coefficients associated to both food group and food count are positive and significant at the 1% level. The increase in the number and categories of food consumed happen via a re-shuffle of the diet; households engaging in UA reduce the number of vegetables, fish, oil and fats consumed but increase those of fruits, meat and poultry, milk products, starch & tubers, nuts & legumes. This change in the diet—which is minimal but significant—implies that households engaged in UA eat more types of protein rich food—nuts, legumes, fruits, meat and poultry—while cutting down on oils and fats. Regarding the decrease in the number of vegetables consumed, urban farmers are more likely to grow vegetables in their plots, hence they tend to consume only those specific vegetables. Fish is usually a costly luxury product—unless the household lives near the coastline—so households may be consuming fewer types of fish while consuming more types of meat, which are cheaper and easily available. We found no impact of UA on food items such as cereals, sugar products and beverages. The lack of a significant impact of UA on those three categories of food can be interpreted as a falsification test; food in those three categories is not directly produced by the urban farmers [50].

We report the results from PSM methods in Table A2. The ATET estimate from this method shows households engaged in UA reduce their food expenditure by 8 percent. This suggests that the effect of UA would be overestimated without the adjustment of IPWRA method. (To check the robustness of our results, we excluded the data from Ghana (2009), Nigeria (2012) and Tanzania (2010) to make our data consistent with the time span. We ran the same model to find that the coefficients are very similar to our main results.)

The results presented here are in line with findings presented in other studies, which reported a positive association between engagement in UA and indicators related to nutrition. Unlike in this paper, most of the studies on UA only "report a simple association between variables, unadjusted for potential confounding factors, thus making it difficult to draw firm conclusions from the data presented" [51]. Even if the analysis presented here does not consider how UA affects food consumption/calorie intake, this study does indicate a positive role played by UA in terms of increasing food security via an increase in the food count/food group categories and of reducing the overall household food expenditure.

A very similar association is suggested in several studies (for a review of the results on the nexus between UA and food consumption, please refer to [49]). [50] Masashua et al., (2009) [52] shows an increase in the consumption of protein, vitamin and mineral-rich foods and food groups for urban farmers in Dar es Salaam. Likewise, a study conducted in the Philippines found an association between UA and both a decrease in carbohydrate intake and an increase of fruit and vegetables consumption [53].

The number of studies looking at the effect of UA based on indicators related to dietary diversity is rather limited, but their results suggest a positive association between the engagement in UA and the food count/food diversity scores. In another cross-country and cross-sectional study, Zezza and Tasciotti (2010) [36] found evidence that engagement in urban farming is positively correlated with an increase in the food group (food count) indicator in 10 out of 15 (11 out of 15) countries analysed in their study. The size of the change in those two dietary-related indicators varies between countries, with an average increase of 24% in the number of food groups consumed; in this study, we estimate an increase of 20%.

It's important to highlight that results here and in other studies point out that UA's direct contribution to food consumption and dietary diversity may be quite small, suggesting that UA is not a magic bullet in terms of food insecurity, but that it does represent a tool urban households have to increase their food resilience [54].

We now move to estimate quantile treatment effects of UA on food consumption expenditure of the households. We find substantial heterogeneity on the impact of UA across the food expenditure distribution (see Figure 2 and Table 6). The coefficient of UA is positive for the households in the first decile of the food expenditure distribution. After that, the coefficients become negative throughout the rest of the distribution, hinting at a reduction of the overall food expenditure via UA. The returns to UA in terms of food expenditure savings are the largest at the 60th percentile, where households engaged in UA enjoy a saving of 12.6%, declining thereafter to 5.4 percent at 90th percentile. Thus, the effects of UA are more negative (meaning they reduce the amount of food expenditure) as we move along the food expenditure distribution; this suggests that UA is more beneficial for households displaying a higher food expenditure profile. Figure 2 partially explains the contribution of UA in terms of reducing food expenditure as it is a pooled representation; when we observe the UA contribution in terms of food expenditure at the country level (Figure A1 in the Appendix), we don't see a homogenous pattern. Ethiopia, Nigeria, Burkina Faso, Tanzania and Ghana show similar trends in the lower quantiles—the coefficients decrease as we move along the food expenditure distribution. The coefficients associated with the households in the upper quantiles increase in Ethiopia, Malawi, Nigeria, Ghana, Burkina Faso and Niger, which is similar to the pooled results. The country level results show that households engaged in UA reduced food expenditure on average by 8.7 percent in Tanzania, 9.9 percent in Burkina Faso, and 17.9 in Mali (Table A1 in the Appendix). No significant impact is found in Ethiopia, Malawi, Nigeria and Niger (See Table A1 for country level impact of UA on food expenditure, food counts and groups).

Table 6. Quantile Treatment Effect.

	Q.1	Q.2	Q.3	Q.4	Q.5	Q.6	Q.7	Q.8	Q.9
UA	0.057 *	−0.022	−0.085 ***	−0.118 ***	−0.113 ***	−0.126 ***	−0.119 ***	−0.092 ***	−0.054 *
	(0.032)	(0.025)	(0.022)	(0.021)	(0.021)	(0.021)	(0.022)	(0.024)	(0.028)
Constant	6.155 ***	6.556 ***	6.829 ***	7.056 ***	7.256 ***	7.440 ***	7.640 ***	7.865 ***	8.167 ***
	(0.014)	(0.011)	(0.010)	(0.009)	(0.008)	(0.008)	(0.008)	(0.008)	(0.010)
Observations	13,880	13,880	13,880	13,880	13,880	13,880	13,880	13,880	13,880

Source: Authors' calculation from LSMS data. Note: Q stands for 'quintile'. Robust standard errors in parentheses. *** $p < 0.01$, * $p < 0.1$.

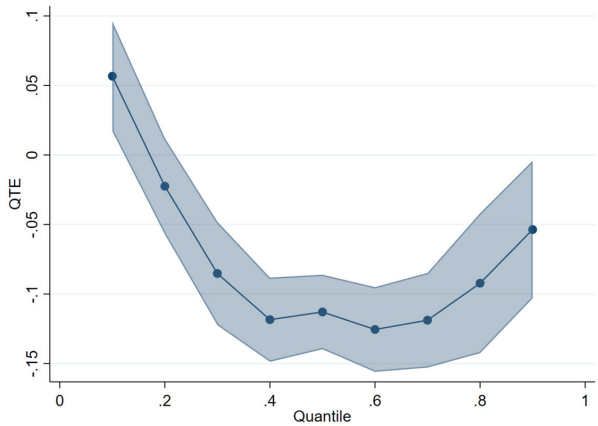

Figure 2. Quantile treatment effect of UA on food expenditure. Note: QTE on the y-axis indicate the quantile treatment effect of participating in UA on the food expenditure. Source: Authors' calculation from LSMS data.

Taken together, we find an overall negative relationship between UA and household food expenditure; however, this relation presents a significant level of heterogeneity with higher and negative impacts mostly for the middle and top end of the distribution.

6. Conclusions

The UA phenomenon has received significant attention in the literature over the past 15 years; multiple studies present evidence that highlights the importance of UA in terms of dietary diversity scores, food consumption and caloric intake. The contribution of UA in terms of food resilience is particularly important in times of food crises, such as the surge in the price of staple foods during the COVID-19 pandemic and ongoing war between Russia and Ukraine, both of which affected the food supply chain and made the provision of food in urban areas more challenging.

This paper sets out to answer three questions; the first investigates the typology of households engaged in UA; the second looks at the role played by UA in diversifying household's diet and in reducing household food expenditure; the third examines the heterogeneity in the impact of UA across the food expenditure distribution. Although the analysis carried out here highlights that UA does contribute to increasing food diversity—both in terms of food count and food categories—and to reducing food expenditures, it is important to acknowledge that its impacts are very modest on average. The analysis here presented uses household level data representative at the urban level for nine sub-Saharan countries—Burkina Faso (2014), Ethiopia (2013), Ghana (2009), Malawi (2013), Niger 2014, Nigeria (2012), Tanzania (2010) and Uganda (2013).

The results show that the profile of those engaging in UA activities does not show much regularity; unlike what anecdotal literature suggests, female heads of the households do not necessarily engage in UA; on the contrary, male headed households and households which are bigger in size tend to practice UA more often.

UA is associated with improved performance of two indicators of dietary diversity: food groups and food counts. After controlling for the wealth status and for a set of household characteristics, the results of the IPWRA estimation indicate that practicing UA is associated with a decrease in food expenditures of 3%.

It is important to stress that the econometric results, albeit statistically robust to models' specification, indicate a moderate impact of UA on several indicators of dietary diversity. This should be considered when assessing the overall contribution of UA in terms of food security in urban areas. On one hand, this paper represents a contribution to the relatively large and positive literature on the effect of UA on food diversity and composition; on the other, it emphasises that country ad-hoc case studies are needed to better measure the magnitude of those dietary changes and to explore the existence of causal links to UA diets. To our knowledge, and apart from a few countries and across countries studies, most of the research on UA has been limited to single cities, which fail to provide a nationally representative picture of the contribution of UA. At the same time, we would like to see more support from local governments in terms of investing in and training of UA farmers, but we recognise that food produced using UA is not sufficient to feed the urban population.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Impact of urban agriculture using IPWRA estimates, country level.

Aggregate	Burkina Faso	Ethiopia	Ghana	Malawi	Mali	Niger	Nigeria	Tanzania	Uganda
Food Expenditure	−0.099 ***	0.038	0.105 **	0.030	−0.179 **	0.004	0.006	−0.087 **	N/A
	(0.021)	(0.044)	(0.054)	(0.033)	(0.076)	(0.041)	(0.037)	(0.035)	
Food Group	0.305 ***	0.195 *	0.496 ***	0.023	−0.183	0.462 ***	−0.117	0.214 *	−0.288 *
	(0.055)	(0.110)	(0.141)	(0.083)	(0.171)	(0.175)	(0.146)	(0.128)	(0.161)
Food Count	0.320 *	0.677 ***	2.304 ***	1.047 **	−0.750	1.352	0.320	0.225	−1.063 **
	(0.180)	(0.224)	(0.547)	(0.493)	(0.649)	(0.833)	(0.396)	(0.333)	(0.524)
Cereals	−0.046	0.264 ***	−0.009	0.156	0.326 **	0.515 **	0.180*	−0.321 ***	−0.270 **
	(0.050)	(0.074)	(0.101)	(0.107)	(0.153)	(0.202)	(0.101)	(0.083)	(0.105)
Starch & Tubers	0.074 **	0.109 ***	0.380 ***	0.019	0.073	0.194 *	0.307 ***	0.087	−0.025
	(0.037)	(0.032)	(0.089)	(0.071)	(0.130)	(0.108)	(0.088)	(0.091)	(0.105)
Nuts & Legumes	0.087	0.282 ***	0.087	0.323 ***	0.062	0.258 **	−0.056	−0.128 ***	0.117
	(0.070)	(0.076)	(0.070)	(0.099)	(0.090)	(0.116)	(0.046)	(0.046)	(0.078)
Vegetables	−0.285 ***	N/A	0.244 **	0.250 **	−0.875 ***	−0.240	0.098	0.074 **	−0.206
	(0.054)	N/A	(0.110)	(0.105)	(0.208)	(0.191)	(0.094)	(0.032)	(0.149)
Fruits	N/A	−0.240	0.183 **	0.084	N/A	0.111	−0.003	0.096	−0.188
		(0.191)	(0.090)	(0.087)		(0.183)	(0.065)	(0.077)	(0.129)
Milk Prod	0.019	0.093 **	0.056	−0.061	0.084	0.080	−0.047	0.084 **	−0.018 *
	(0.019)	(0.038)	(0.039)	(0.089)	(0.094)	(0.095)	(0.038)	(0.040)	(0.010)
Oil & Fats	−0.109 ***	−0.023	0.076	−0.064**	−0.165 **	−0.087	0.037	0.009	−0.064 **
	(0.030)	(0.021)	(0.048)	(0.032)	(0.083)	(0.059)	(0.039)	(0.012)	(0.032)
Meat & Poultry	0.190 ***	0.077 *	−0.038	0.063	0.081	0.056	−0.176 **	0.151 ***	0.057
	(0.031)	(0.041)	(0.069)	(0.069)	(0.076)	(0.069)	(0.070)	(0.045)	(0.061)
Fish	−0.075 ***	−0.007	0.002	N/A	−0.026	0.032	0.097 **	0.012	−0.048
	(0.021)	(0.009)	(0.024)		(0.071)	(0.070)	(0.048)	(0.029)	(0.050)
Sugar & Syrup	0.007	−0.008	−0.030	0.029	0.051	−0.005	−0.007	−0.028	N/A
	(0.005)	(0.020)	(0.034)	(0.048)	(0.045)	(0.047)	(0.014)	(0.031)	
Beverages	0.077*	N/A	0.050	0.138	0.044	0.130	−0.030	0.035	−0.116
	(0.040)		(0.050)	(0.096)	(0.093)	(0.135)	(0.115)	(0.039)	(0.073)
Miscellaneous	0.114 ***	0.130	0.047	−0.021	−0.177	−0.197	N/A	−0.081 ***	−0.004
	(0.029)	(0.135)	(0.062)	(0.040)	(0.107)	(0.166)		(0.024)	(0.007)

Source: Authors' calculation from LSMS data. Note: Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A2. Propensity score matching estimates.

Variables	(1) Food expenditure	(2) Food group	(3) Food Count	(4) Cereals	(5) Starch & tubers
Urban Agriculture	−0.079 ***	0.061	0.335 *	−0.089 **	0.083 *
	(0.023)	(0.053)	(0.184)	(0.042)	(0.043)
Observations	13,880	15,063	15,063	14,471	9135

Variables	(6) Nuts & legumes	(7) Vegetables	(8) Fruits	(9) Milk products	(10) Oil & fats
Urban Agriculture	0.055	−0.115 **	−0.019	0.036	−0.034 *
	(0.034)	(0.049)	(0.049)	(0.024)	(0.018)
Observations	10,061	14,112	7373	6629	13,834

Variables	(11) Meat & Poultry	(12) Fish	(13) Sugar & Syrup	(14) Beverages	(15) Miscellaneous
Urban Agriculture	0.093 ***	−0.026	−0.018	0.041	0.099 ***
	(0.023)	(0.018)	(0.013)	(0.029)	(0.033)
Observations	9183	10,922	11,965	10,895	11,846

Source: Authors' calculation from LSMS data. Note: Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

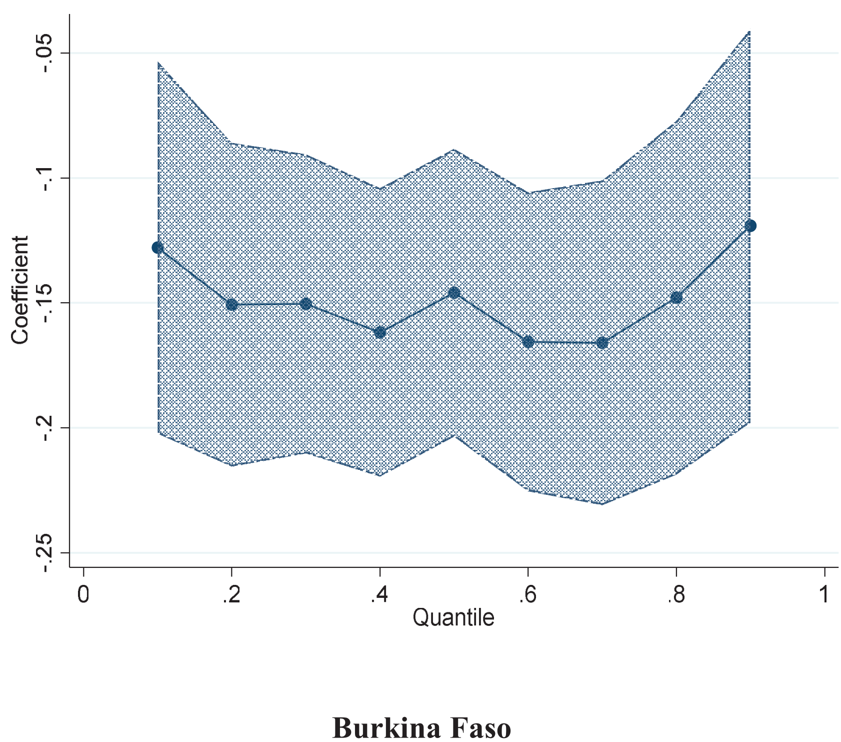
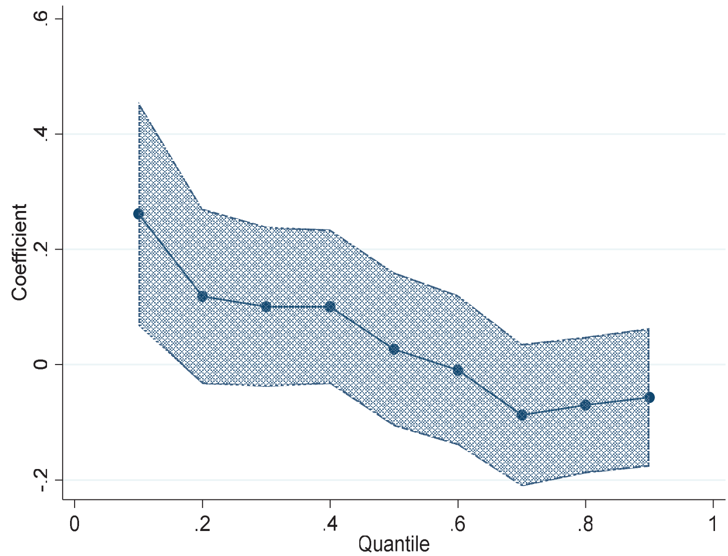
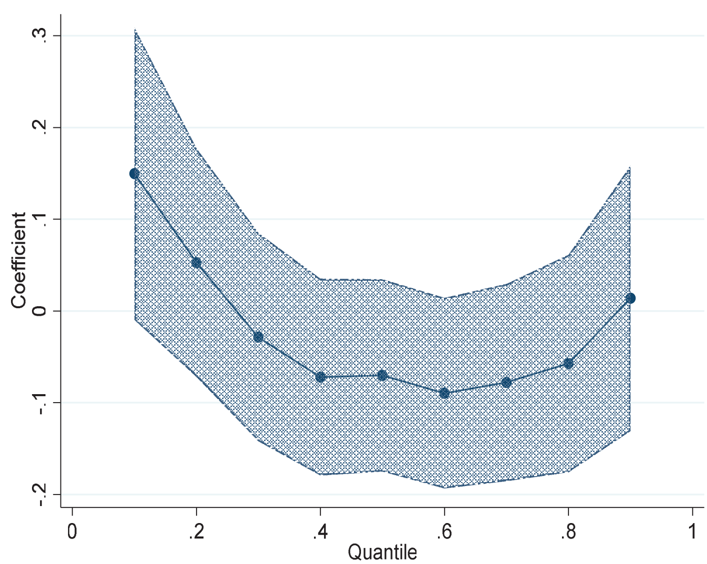


Figure A1. *Cont.*

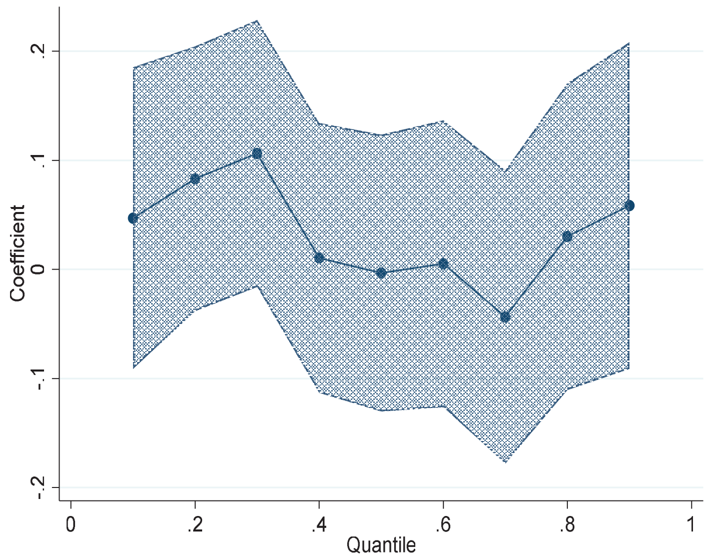


Ethiopia

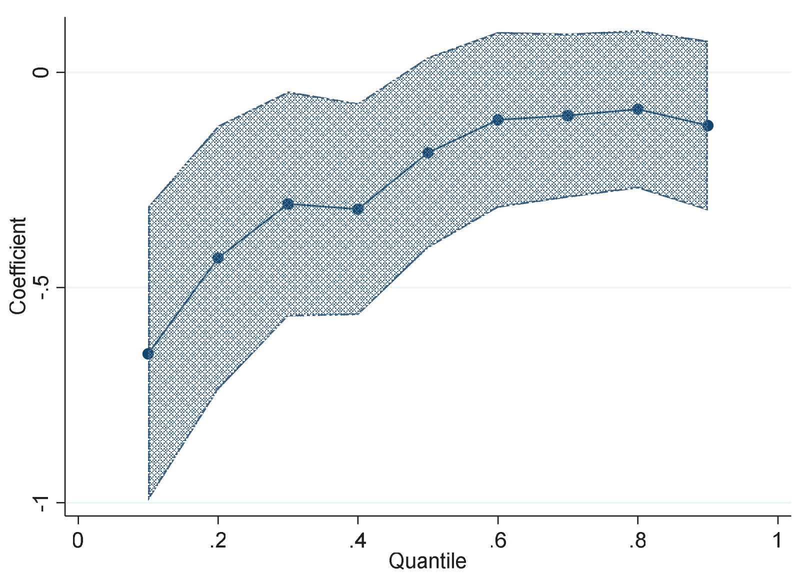


Ghana

Figure A1. *Cont*.

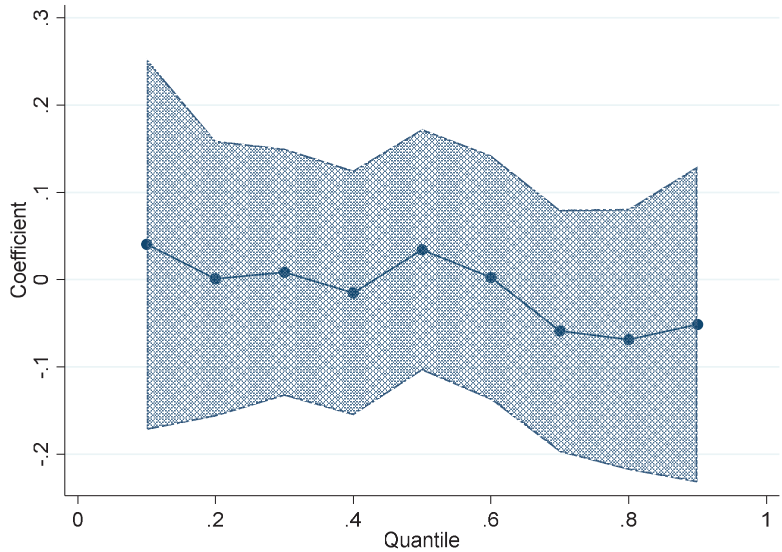


Malawi

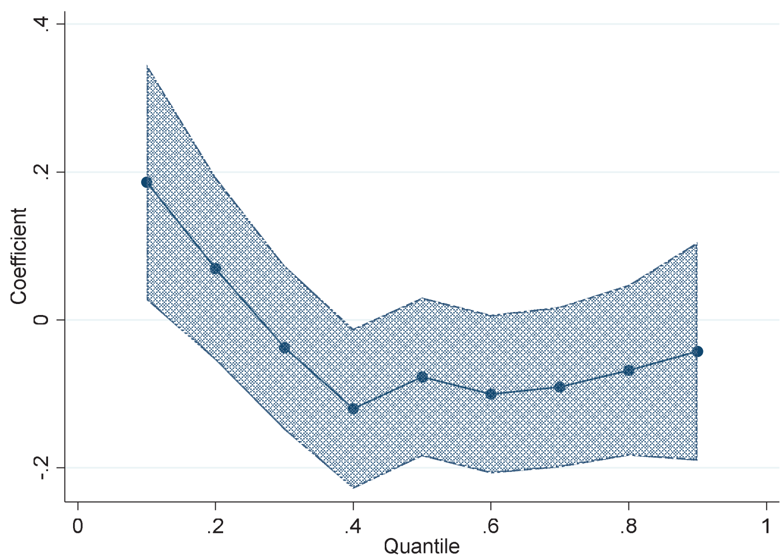


Mali

Figure A1. *Cont*.



Niger



Nigeria

Figure A1. *Cont*.

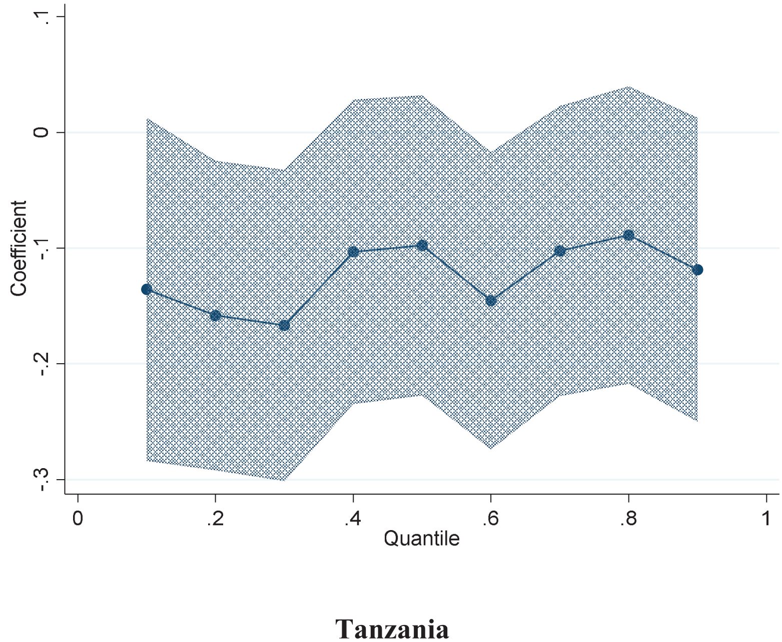


Figure A1. Quantile treatment effect of urban agriculture, country level.

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Article

Visioning a Food System for an Equitable Transition towards Sustainable Diets—A South African Perspective

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Abstract: The global goal to end hunger requires the interpretation of problems and change across multiple domains to create the scope for collaboration, learning, and impactful research. We facilitated a workshop aimed at understanding how stakeholders problematize sustainable diet transition (SDT) among a previously marginalized social group. Using the systems thinking approach, three sub-systems, namely access to dietary diversity, sustainable beneficiation of natural capital, and 'food choice for well-being', highlighted the main forces governing the current context, and future interventions of the project. Moreover, when viewed as co-evolving processes within the multi-level perspective, our identified microlevel leverage points—multi-faceted literacy, youth empowerment, deliberative policymaking, and promotion of sustainable diet aspirations—can be linked and developed through existing national macro-level strategies. Thus, co-designing to problematize transformational SDT, centered on an interdisciplinary outlook and informational governance, could streamline research implementation outcomes to re-structure socio-technical sectors and reconnect people to nature-based solutions. Such legitimate aspirations could be relevant in countries bearing complex socio-political legacies and bridge the local–global goals coherently. This work provides a collaborative framework required to develop impact-driven activities needed to inform evidence-based policies on sustainable diets.

Keywords: agri-food system; systemic analysis; marginalized communities; sustainable diet; stakeholder engagement; interactive facilitation; multi-level perspective; deliberative policymaking

1. Introduction

The complexity of local and global problems challenges the agricultural, health, and socioeconomic sectors [1–3]. Moreover, the environment and biodiversity are increasingly under threat from climate change and competing development needs [4]. The food system, for instance, both threatens environmental sustainability and nurtures human health [5]. These, as well as competing societal needs, are addressed within the framework of the United Nations Sustainable Development Goals (SDGs) [6–8]. A major challenge today, and in the future, is to sustain the beneficial contributions of nature [5,9], whether from natural or managed systems [10], including food systems [11–13], to improve wellbeing for all. However, not all countries can transition towards equitable development pathways for all because of slower macroeconomic growth that reduces the pace of structural change in some countries [14].

As with its other Sub-Saharan counterparts, South Africa faces multiple biophysical, political, and socioeconomic pressures that interact to compound livelihood vulnerability, and hence limit adaptive capacity [7] Moreover, the apartheid legacy and delayed transformation suggest that new development strategies and outcomes of institutional arrangements are warranted in tackling socio-economic disparities, such as chronic poverty, household food insecurity [14,15], and other protracted socio-ecological problems [16]. Well-intended policies can lead to unintended consequences when there are incongruous policies and implementation strategies, such as skewed prioritization of economic gains over poverty alleviation, local economic development, and/or nature-based food security [17,18]. Growing evidence and, increasingly, decision-making, focus on developing the societal capacity to guide transitions that align with social and environmental alternatives. Despite having the potential to promote environmental sustainability while supporting human health and wellbeing [11,19], current trends indicate that inequalities will persist [20].

A broad range of conceptual frameworks has been applied to promote transitions towards food sustainability. Herein, we draw insights from the multi-level perspective (MLP) on socio-technical transitions [21,22], to better understand how to realize the transition towards sustainable diets amongst vulnerable, previously disadvantaged communities in South Africa. The strength of transition research is its ability to address systemic changes through long-term, multi-dimensional, and fundamental transformation processes, towards a more sustainable society [23], noting that its relevance and applicability within the agri-food sector requires an integrative approach [24,25]. The multi-dimensional concept of sustainability can cause some ambiguity as to the different normative values of food, and the tension between commodity vs. commons, which can be assisted by a more unified worldview amongst diverse stakeholders [26]. Hence, the specific objectives of this paper were to (i) examine the intricate relationships that emerged when stakeholders collectively interpreted and envisioned conceivable ways to shape a "sustainable and healthy food system" as the future desired state, against the state of the current food system; (ii) evaluate, through a scoping review, the concept of transition concerning agri-food systems; (iii) use a logical framework to demonstrate how the interventions proposed for leveraging a sustainable diet transition call for a consideration of the wider context within which the transition takes place; and (iv) identify contextual pathways to inform future policies guiding sustainable diet transitioning that take into account the influence of multiple systemic interactions and the type of actors that need to be involved.

2. Methods

The present work uses a mixed-method approach (Appendix A) to co-design emergent research–practice collaboration for the SHEFS program, a Wellcome Trust (UK)-funded Our Planet Our Health project, in South Africa. We applied systems thinking principles using causal loop diagramming to develop insights, make distinctions, i.e., which knowledge disciplines or institutional settings to consider, identify interrelationships and subsystems, and establish the most pertinent perspectives. Through interactive facilitation and mapping, we helped stakeholders to acknowledge and observe the complexity of interventions linked to transdisciplinary sustainability research collaboration. To unpack the complex issues linked to sustainable and healthy food systems, we aligned the interventions proposed by the workshop participants, viewed as leverage points, with the SDGs within a logical framework. Finally, we embedded these leverage points within a multiple-level perspective framework, encompassing a niche–regime–landscape continuum [27], aimed at informing the types of evidence-based policies that could potentially be devised to inform sustainable diet transitioning. The niche–regime–landscape multiple-level perspective is a prominent framework to analyze socio-technical transitions towards sustainability, which stems from evolutionary economics and the social construction of technology [27]. Central to this is that economic processes evolve and that economic behavior is determined both by individuals and society as a whole [28]. In the present context, sustainable socio-technical transition, therefore, refers to new kinds of agri-food systems shifts, and the types of actors required to support participatory consensus outcomes that encourage desired change.

Thus, the paper uses an exploratory approach to examine the co-design process applied at the beginning of the SHEFS project. The emergent issues raised during the interactive facilitation, consisting of the stakeholder meeting and de-briefing analysis, were used to guide further interdisciplinary evidence building throughout the project. To enhance the robustness of this paper's outcome, insights [29] from scientific realism are used [30]. Thus, on the one hand, the bibliometric method is applied to corroborate with the systemic relationships identified in the causal loop analysis, i.e., from the stakeholder engagement process. On the other hand, the systematic review is used to support the argument for creating a sustainable diet innovation system (SDIS) based on the premise that sustainable diet transitioning (SDT) can be viewed from the socio-technical perspective. The papers reviewed in the scoping review aid in building the framework in the current paper. Viewed together, the causal loop analysis, bibliometric analysis, scoping review, and multiple-level perspective of the transition systems theory serve as a means of triangulation to conceptualize the emerging and co-evolving issues that need to be considered to inform policies on SDT.

Ethical approval was granted by UKZN, and all participants provided informed consent for their participation.

2.1. Systemic Analysis of Sustainable Diet Drivers

We captured the outcomes of the first Sustainable and Healthy Food Systems (SHEFS) Program key stakeholder workshop to define the current and desired state of the agriculture, environment, and social system in South Africa. The facilitated workshop brought together stakeholders (n = 39) from key government competencies, across the three levels of government policymakers and practitioners (municipality, provincial, and national), as well as academics and post-graduate students from crop science, food security, nutrition, health sciences, development studies, environmental science, and biodiversity conservation. For the systems-approach-based interactive facilitation exercise, the targeted sample size, n, was 50. However, some of the participants could not attend the workshop. The shortcomings, if any, were counteracted during the peer debriefing session on the following day.

To facilitate the process, participants were asked to consider, firstly, SHEFS's (https://shefsglobal.lshtm.ac.uk/ accessed on 3 March 2022) overarching aim: "to provide policymakers with novel, interdisciplinary evidence to define future food systems policies that deliver nutritious and healthy foods in an environmentally sustainable and socially equitable manner" as a guiding star, which is a preferred future state of the system. Secondly, a "near star" question was asked: "What is the effectiveness of the current food-crop-environment-health system for addressing human livelihoods and welfare, considering knowledge, understanding, legislation, policies, implementation, and sustainability?" For this exercise, the workshop participants spent 3 h in groups, each including representatives of all stakeholder types, to brainstorm and map (i) the state of knowledge, and (ii) the possible desirable states.

We then wanted to capture a systemic overview from each group, through causal diagrams, about how the stakeholders' mental models related to the SHEFS program's overall objectives. Following a briefing on the conventions of drawing interrelationship digraphs (concept terms connected by a bi-directional line) [31] and causal loop diagrams [32], the participants in each group were then asked to respond to the questions by drawing their group's collective interpretation of the system (without idea exchange amongst groups). All diagrams generated were refined by engaging with the participants through interactive facilitation during the workshop to ensure that the ideas were accurately captured and representative, and, thereafter, updated by the author team to produce conventional causal loop diagrams (CLDs). CLDs are used to conceptually model dynamic systems, which can be social and/or ecological, by mapping how variables, i.e., factors, issues, and processes, influence one another, [33]. Common variables that appeared in the different group diagrams were identified, and the nature of their causal relationships was highlighted to create interlinkages among the sub-systems, uncover any underlying feedback structures, and identify leverage intervention points in the system [34,35].

The following day, we conducted post-workshop expert deliberations, including the principal SHEFS investigator and nutrition expert (AD), the principal investigators in the environment (RS) and crop (AM) fields, the project coordinator for South Africa (RS), one researcher in diet and health (PS), and two researchers representing the health sciences co-investigator. Collectively, we acted as key informants to identify science–action interventions, from the previous day's outcomes, with high leverage impacts for biodiversity (Nature) and end-user beneficiaries (People). During a five-hour focus group discussion, we interrogated the linkages and nature of the different sub-systems identified the previous day to develop a strategic framing. The causal loop diagrams were reviewed by the experts with the workshop facilitator (NS) and complemented by (i) groundwork that was already being undertaken by the researchers, as well as (ii) additional potential research gaps capable of delivering sustainable diet leverages that had not been identified the previous day but emerged from the interrogation of the linkages and causal loops. Causal loop analysis was performed and, where relevant, system archetypes [36] were applied to present a systems view of the interplay between the different forces identified. Color coding based on subsystems, identified archetypes, and/or inter-linkages was then used to enhance the representation of the diagrams. Relevant literature was used to substantiate, align, and unpack the interpretations of the stakeholder views concerning the guiding star and near star questions.

2.2. Review of Bibliometric Studies on the Sustainable Transition of Food Systems

2.2.1. Review of Multi-Level Perspective in Food Agri-Systems

The emergence of persistent environmental degradation worldwide has raised the question of how to induce a societal transformation towards more sustainable production, consumption, and biodiversity protection [37]. New technologies or governance approaches, economic deregulation, and changes in consumer behavior have been introduced to relieve urgent problems [38,39]. However, generally, transformational processes are slow or even failing, technology diffusion is inefficient, governance concepts are implemented in theory only, deregulation causes high uncertainties, and consumers do not act as anticipated [37]. A broad range of frameworks has been used to explore the transition towards sustainability [24], such as the multi-level perspective (MLP) on socio-technical transitions [40], transition management [41] (TM), strategic niche management [42] (SNM), technological innovation system [43] (TIS), and the social practice approach [25] (SPA). MLP argues that transitions, i.e., large-scale socio-technical change, occur through interactions between processes at three levels. First, niche innovations build up impetus through knowledge production processes, such as research and/or performance improvements, and support from powerful civil society groups. Herein, the concept of 'experimentation' occupies a central position within the academic component that investigates transformations towards sustainable socio-technical systems. This focus on experimentation is a key agent of change that sets the sustainability transitions field apart from the wider literature of social change and policy theory [23,44]. 'Socio-technical experimentation' can be contrasted with the notion of experimentation used in the natural sciences. It implies a more engaged and social constructivist position, whereby society is itself a laboratory and a variety of real-world actors commit to the messy experimental processes tied up with the introduction of alternative technologies and practices, to purposively re-shape social and material realities [44,45]. Second, the concept of the socio-technical regime has been formulated to account for the delay and path-dependency experienced in articulating and understanding transformative change [46]. Regimes, therefore, result from the co-evolution of institutions and technologies over time, which become positioned in practices and routines. Sociologists of technology refer to regimes as consisting of a variety of actors, that is, scientists, policymakers, consumers, and special-interest groups that contribute to the patterning of technological development [47]. The sociotechnical regime concept, therefore, accommodates a broad community of social groups, and their alignment of activities and their interactions result in the stabilization of socio-technical trajectories in many ways: Regulations and standards, the adaptation of lifestyles to technical systems, investments in machines, infrastructures, and competencies [48–50]. Third, the socio-technical landscape, which could be macro-economics, deep cultural patterns, or macro-political developments, constitutes an exogenous environment beyond the direct influence of niche and regime features [24]. Changes at the landscape level usually take place over decades, and such changes can exert pressure on the regime through a selective process of societal change—sectoral policies, education system, and market-driven technological novelty—and create windows of opportunity for regime change, subsequently providing leverage for niche innovations to emerge and create a new regime [51]. A transition therefore occurs when a regime is transformed as it responds to systemic changes. The MLP framework is useful in understanding contexts that have co-evolutionary properties as it aids in justifying the importance of an adaptive policy approach when addressing complex problems burdened with intrinsic dynamics [50].

We conducted a search in the Web of Science Core Collection (SCI-EXPANDED, SSCI, A&HC1, ESCI), dated 3 August 2021, for publications on sustainable food transitions, more specifically those that applied the multi-level perspective. The output was narrowed down to include articles that deal with the "food systems" topic. Hence, the search term used was:

TOPIC: (socio-technical transition AND multi-level perspective) AND TOPIC: (food systems).

The search identified 15 articles ($n = 15$), and given the small sample size, all were retained for scrutiny. In the analysis of the output, the following attributes were derived: The context of the transition research, the transition process, any specific methodologies/approaches, and the action domain that emerged.

2.2.2. Developing Multi-Level Insights for Sustainable Diet Transition from the Stakeholder Systemic Analysis

Having explored MLP transitions in the literature, we then used the output from the stakeholder workshop within the MLP to showcase how evidence-based sustainable diet policies can be rendered more effective in addressing barriers and opportunities, thereby realizing sustainability transition in the near future. We identified examples of interventions that were co-designed by stakeholders and assessed by the expert deliberations as leverage points within the socio-technical and socio-ecological context. We then categorized those as proposed policy measures against the niche–regime–landscape (micro-level, meso-level, meta-level, respectively) continuum and described the network of actors responsible.

3. Results

3.1. Impact of Extrinsic Systemic Issues on Small-Holder Farming (SHF) in South Africa-A Nation-State Level Perspective

Participants were questioned whether the end of apartheid had improved the situation for the South African smallholder farming sector, which is essentially comprised of the previously disadvantaged population. It was agreed that this sector remains seriously limited and poorly structured, being embedded in a reinforcing vicious cycle (R1) (Figure 1) that undermines capacity-building for sustained and diverse local food production. Not only is the smallholder farming sector disadvantaged from a productivity standpoint, but the institutional dynamics related to the socio-economic conditions render it nearly impossible for emerging farmers to thrive [52,53]. Loop B1 (Figure 1) describes how the economic transformation policy agenda aims to reduce the current limitations of the historically underprivileged smallholder food producers through an emphasis on sectoral development planning as is elaborated in the National Development Plan [54]. Under apartheid rule, the relative economic outcome beneficiated the privileged societal group (Loop R2) to the detriment of the historically underprivileged group (Loop R3) (Figure 1). With the advent of democracy in 1994, the objective of the transformative agenda was to redress privileged beneficiation by opening the economy and progressively offsetting the unequal economic outcomes. In the new South African Constitution, 'every citizen is equally protected by law' and all are obligated to 'heal the divisions of the past' while 'recognizing injustices of the past' [55]. Yet, inequality is still pervasive [56]. More than two decades after the dispensation, and despite the various initiatives of the economic transformation processes, the governance and reality of the smallholder farming sector at large still grapples with systemic limitations, as represented in the balancing loop B2 (Figure 1).

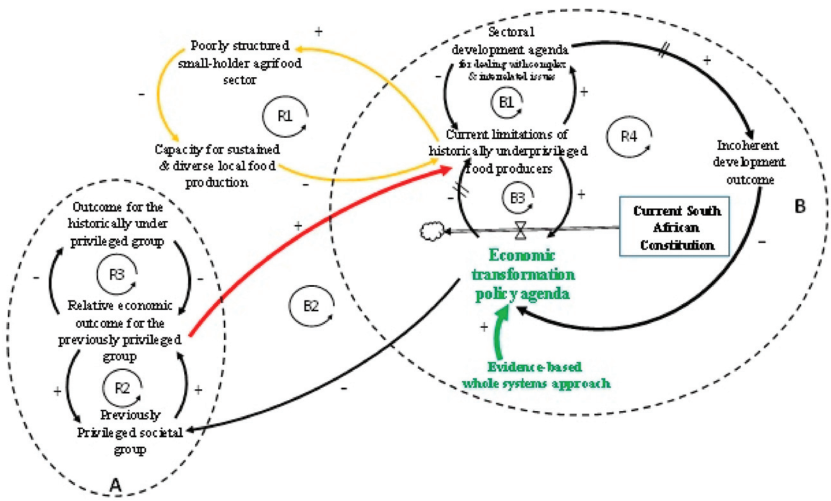

Figure 1. Interlinkages and causation pathways impacting current limitations faced by historically underprivileged food producers. (**A**) A 'Success to the successful' archetype that explains South Africa's previous segregated socio-economic situation. (**B**): A 'Shifting the burden archetype', whereby an over-emphasis on sectoral development with the insufficient implementation of whole-systems evidence-based approaches results in incoherent development outcomes that eventually undermine the achievement of the economic transformation. Red arrow: An anomaly that persists for more than two decades among the previously marginalized despite the end of apartheid rule. Ideally, the current limitations of the historically underprivileged should have decreased, given the inclusive and/or affirmative opportunities offered through the new Constitution. This means that development solutions that are being brought about are not tackling the root causes of problems, resulting in inadequate outcomes, e.g., the small-holder agri-food sector remains poorly structured with insufficient capacity for a thriving local production (Loop R1 with yellow arrows: The vicious reinforcing consequence that perpetuate limitation in the smallholder food sector). Arrows with a double dash: Intrinsic systemic delays characteristics of complex systems; hourglass symbol: Dynamic nature of the variable represented as a rate of change, herein indicating that the economic transformation ought to be an on-going adaptive process, driven by the democratic Constitution that acts as a guiding principle for a new normal in South African politics to influence governance and steer other multi-dimensional change.

3.2. Efficacy of Structural Adjustment for Socio-Economic Upliftment

3.2.1. Transitioning of Smallholder Farmers

As part of unpacking loop B2 (Figure 1), and especially the associated causal factors, participants referred to the unintended consequences of agricultural policy. This was based on the premise that creating opportunities for the previously disadvantaged to own farmland would help subsistence farmers' attempts at commercialization, and create a middle group termed the 'emerging farmer' sector. Policies enabling the shift from smallholder farming (SHF) to small-scale commercial farming (SCF) have had two types of spill-over effects

(Figure 2). The first one creates a causal pathway with desirable effects whereby the farmers who have enough leverage to invest can improve their socioeconomic status. This would alleviate their poverty level by improving their flow of household revenue (Loop R5). Subsequently, they can improve their living standard, and, in effect, ensure access to fresh and convenient foods. The variable 'consumer's revenue' here refers to the previously disadvantaged population that are also food consumers in the SHF system.

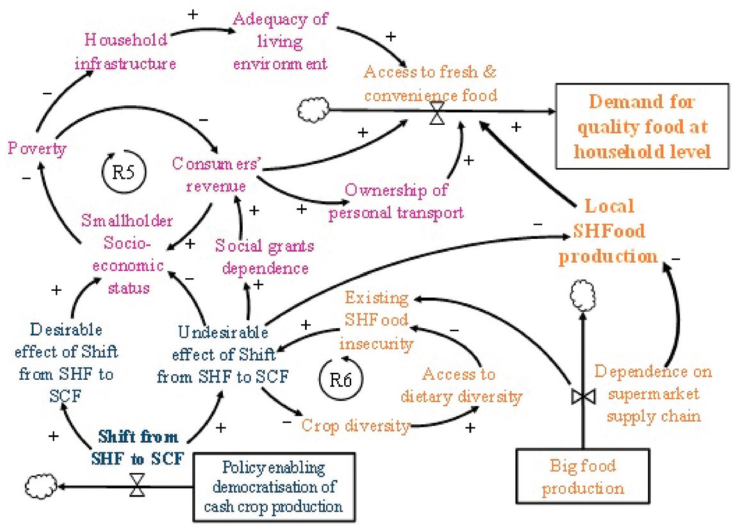

Figure 2. Impact of the shift from small-holder farming (SHF) to small-scale commercial farming (SCF) on small-holder socio-economic status. Reinforcing loop R5: The spill-over effects resulted in desirable and undesirable effects on the socio-economic status of the smallholder farmers, which either relieve or exacerbate poverty level depending on how successful they emerge as small-scale commercial farmers. Reinforcing loop R6: Unsuccessful cash crop ventures diminish access to dietary diversity and worsen food insecurity, such that eating habits are linked to key issues around affordability and convenience. Orange variables: Smallholder/previously under-privileged access to food and dietary diversity. Blue variables: Effect of policy enabling the democratization of cash crop production. Purple variables: Socio-economic realities of the smallholder sector.

The second effect is when the farmers, despite aspiring to farm successfully, still find their socio-economic and household food security status undermined. This occurs due to a combination of factors [57,58] such as a poor business framework and insufficient input support, know-how, and infrastructure, hence contributing to an undesirable effect on the shift from SHF to SCF. The example of cash crop production, such as sugarcane in the KwaZulu Natal Province, was used to illustrate the unintended consequence in the reinforcing vicious loop, R6. In striving to produce sugarcane as a monocrop, on-farm crop diversity is reduced because food crops are neglected. Dietary diversity within such households, which depends on subsistence farming, is undermined, leading to household food and nutrition insecurity. These consumers must increasingly rely on the 'Big Food Industry'. Such a type of food sourcing from supermarket outlets creates a dependence on supermarket supply chains, which is unaffordable and inaccessible to poor communities, further exacerbating existing household food insecurity.

3.2.2. Impact of Socio-Economic Conditions on Access to a Healthy and Sustainable Diet

When the socio-economic status of smallholder and underprivileged communities result in sub-optimal revenue, poverty remains rampant and pervasive. The ubiquitous prevalence of poverty creates dependence on social grants to support household revenue for consumption. This dependence is counter to other policy decisions, such as improving smallholder socio-economic status through economically sustainable means. The 'adequacy of the living environment', itself dependent on revenue generation, is a critical factor that prescribes the type of food consumed (Figure 2). The poor and previously underprivileged communities occur in the peri-urban region as sub-organized settlements or as informal segments in the metropolitan cities. It is only when adequate revenue is allocated towards household infrastructure and facilities, such as access to electricity and the ability to store perishable and/or convenience food in a refrigerator, and the ownership of car or access to another form of transport, that access to food can be definite at the household level.

Moreover, participants referred to the fact that the ways the previously under-privileged people consume food culturally, and the historically conditioned meanings ascribed to food and eating, must be considered to understand how to shift current food consumption towards a sustainable transition. The emerging patterns [59] consist of a preference for cheap grain staples, sugar, soft drinks, and chicken, frequently sourced through informal channels. This implies that, apart from price and convenience, the symbolic and aspirational domain of food aesthetics and the social functions of visible consumption become key forces shaping food choices. Currently, individual preferences and attitudes are stronger determinants of food choice, rather than sustainable food choice for well-being acting as determinants of food choice (Figure 3). This is a consequence of the increasing individualization of society, an outcome of western lifestyle fast-food aspirations. When it comes to food choice and consumption, on the one hand, the individualization of lifestyle and lavish food preferences represent the fulfillment of historically unfulfilled desires dating from apartheid rule. The resulting attitude renders 'past foods', mainly maize porridge and vegetables, as an undesirable reminiscence of the 'difficult past', and healthy food is perceived as unappealing or too expensive. On the other hand, the sprawl of informal settlements and abject poverty leads to poor food choices due to financial constraints and the inability to afford healthy food [Poverty → Food choice for well-being (Figure 3)]. Both situations are not aligned with food choices that promote well-being.

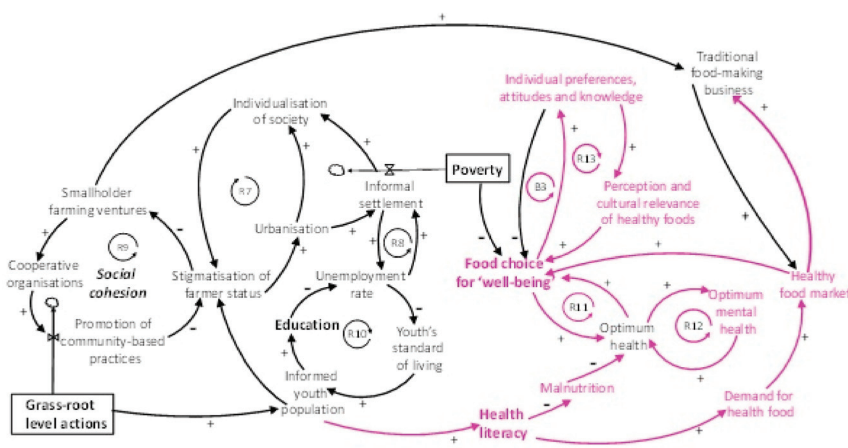

Figure 3. Socioeconomic factors that impact small-holder farming ventures and 'Food choice for wellbeing'. Blue variables: Spill-over effect of de-agrarization through stigmatization leading to the proliferation of informal settlement and unemployment. Pink variables: Influence of 'health literacy' in leveraging food aspirations and 'food choice for well-being'. Stimulating smallholder farming ventures and driving the demand for a healthy food market ought to stimulate traditional food-making businesses, which could then influence positive feedback upon food aspirations and choice. 'Traditional food making business' emerged as a currency to stimulate both smallholder farming ventures and to create a drive for the healthy food market and eventually 'Food choice for well-being'.

The individualization of lifestyle is the outcome of a spill-over effect resulting from a vicious reinforcing loop involving stigmatization of farmer status and urbanization, as seen in R7 (Figure 3). Participants discussed how, despite the political will for a more inclusive agricultural economy, smallholder farming has been on the decline in recent years because of a combination of macroeconomic constraints. In particular, the stigmatization of farming activities has discouraged youth participation in agriculture [60,60]. Post-apartheid de-incentivization of agriculture was deemed as the major systemic barrier that deterred communities from sustaining small-holder farming. Coming from a difficult past characterized by restrictions on movement, education, wealth accumulation, among other things, the palpable post-apartheid response has seen an increase in movement, leading to a rural exodus because of the perceived opportunities and prosperity that the urban regions could potentially provide.

3.3. Interventions to Leverage Sustainable Diet Transition

3.3.1. Socio-Economic Factors, Social Aspirations, and Individual Food Choice Behavior

Participants posited that high-leverage interventions would necessarily have to include improving the health literacy of consumers to tackle problems of malnutrition, and to create the demand for healthy food. Therefore, instead of "Individual preferences, attitudes and knowledge" influencing whether consumers opt for "Food choice for well-being", participants proposed that the sustainable diet transition should be stimulated in such a way that "Food choice for well-being" becomes the determinant for food preferences and attitudes. Participants emphasized that strategies to shift from meat-centered dishes to a variety of healthy dishes might not be viewed by consumers as authentic and convenient food. This is because meat alternatives might not be viewed as aligned with the post-apartheid freedom of choice lifestyle, which is intrinsically linked to self-determination realities [61]. As such, individual choice is a complex dietary behavior and is influenced by various physiological, social, and cultural factors [62,63]. Therefore, taste profiles should be taken into account when proposing healthy and sustainable menus and meals [63,64]. In Figure 3, this is represented as the balancing loop, B3. As a result of the "Food choice for well-being" → "Individual preferences, attitudes and knowledge" relationship, a desirable and aspired-to loop is created as R13.

Table 1 explains the causation pathway from the proposed interventions to the expected outcomes. The UN SDGs are used to provide the overarching context and relevance of the transformative trajectory.

Table 1. Transformative pathways to influence food-related social aspirations towards sustainable and healthy food pathways.

Interventions	Causal Pathway	Expected Outcomes	Relevance as Functionally Interrelated SDG Targets
Socio-economic factors, social aspirations, and individual food choice behavior			
Mobilize cross-sectoral resources to promote sustainable diet choices through health literacy	Health literacy → R11: Pathway to influence food choice that promotes health and well-being	Health literacy to reduce malnutrition and improve health, including mental health	*T2.2* End all forms of malnutrition
			T3.4 Reduce mortality from non-communicable diseases and promote mental health
			T4.6 Universal literacy and numeracy
	R12: A reinforcing loop that highlights the holistic nature of health as comprising of both physiological health and mental health	Diet and lifestyle based on "Food choice for well-being"	*T12.8* Promote universal understanding of sustainable lifestyle
			T8.3 Promote policies to support job creation and growing enterprises

Table 1. *Cont.*

Interventions	Causal Pathway	Expected Outcomes	Relevance as Functionally Interrelated SDG Targets
Support growing traditional and healthy food-making	Spill-over effects of boosting small-scale farm ventures to promote healthy traditional food-making	Driving consumer demand to create a market for healthy local food and support agri-food entrepreneurship	*T1.1* Eradicate extreme poverty food
Foster pro-poor food choices for high-quality sustainable diets	R13: A desirable and aspired reinforcing loop which only occurs if 'food choice for well-being' can influence 'Individual preferences & attitudes'	'Food choice for well-being' habit positively impact 'Individual preferences and attitudes', which can then lever 'Perception & cultural relevance of healthy foods'	*T 2.1* Universal access to safe and nutritious *T 10.2* Promote universal socio-economic and political inclusion *T12.8* Promote universal understanding of sustainable lifestyle
	B3: An important goal-seeking loop to improve preferences & attitudes which cannot be achieved without the 'health literacy' causal pathway and outcome of loop R11, to then, link 'Food choice for well-being→ Individual preferences & attitudes'. B3 is however compounded by poverty level.	Successful behavior change provided food choice determinants such as poverty level and therefore access to food, are tackled. A pro-poor sustainable lifestyle would counteract individual preferences and attitudes which do not align with healthy diet pathways	

1. Loops and variables unpacked are from the causal loop diagram in Figure 3. Causal pathways are relationships that are anticipated to generate expected outcomes; impacts of interventions could occur through different pathways but eventually share the same overarching sets of UNSDG outcomes. The relevant United Sustainable Development Goals (UNSDGs) targets are from GOAL 2: Zero Hunger; GOAL 3: Good health and well-being; GOAL 4: Quality Education; GOAL 10: Reduced Inequality; GOAL 12: Responsible Consumption and Production.

3.3.2. Reinforcing the Democratization of Knowledge to Unleash Sustainable Diet Transitions

Based on the types of interventions endorsed by the participants, the theme of education emerged as a common enabling concept in addressing the limitations of the smallholder sector concerning sustainable diet transitions and environmental conservation. Functional education could leverage the implementation of sustainable income-generating community-based interventions to promote food security and sustainable beneficiation of natural capital from agriculture and related novel entrepreneurial activities. Participants referred to the Strategic Plan for South African Agriculture [59], dated as far back as 2001, which has already aimed to increase the incomes of the poorest groups in society through opportunities for small-/medium-scale farmers. In effect, the National Department of Agriculture [65] pays particular attention to small-scale agriculture with three strategic aims: (i) Making the sector more efficient and internationally competitive, (ii) supporting production and stimulating an increase in the number of new small-scale and medium-scale farmers, and (iii) conserving agricultural natural resources. However, these aims are yet to gain adequate leverage, [66] and, hence, are still relevant as expected outcomes of multi-lateral evidence-based interventions in achieving sustainable and healthy food systems. Environmental literacy and agri-food literacy were deemed as important drivers to leverage new types of ecosystem services through inclusive social innovation (Figure 4). The example of reduced crop diversity as an outcome of sector-based thinking in policy planning was mentioned again by participants. In this instance, the lens of coherence in land-use planning was used to explain how a change in land-use patterns (Linkage between 'Change in land use pattern for monocropping' → 'Crop diversity', Figure 4), caused by avocado, sugarcane, and agroforestry, when unchecked, can jeopardize crop and food plate diversity. Therefore, ongoing evidence synthesis on environmental change (Loop B5) in local sustainability experiments would be important in understanding how to alleviate cross-cutting issues and unintended consequences arising from sectoral policy decisions.

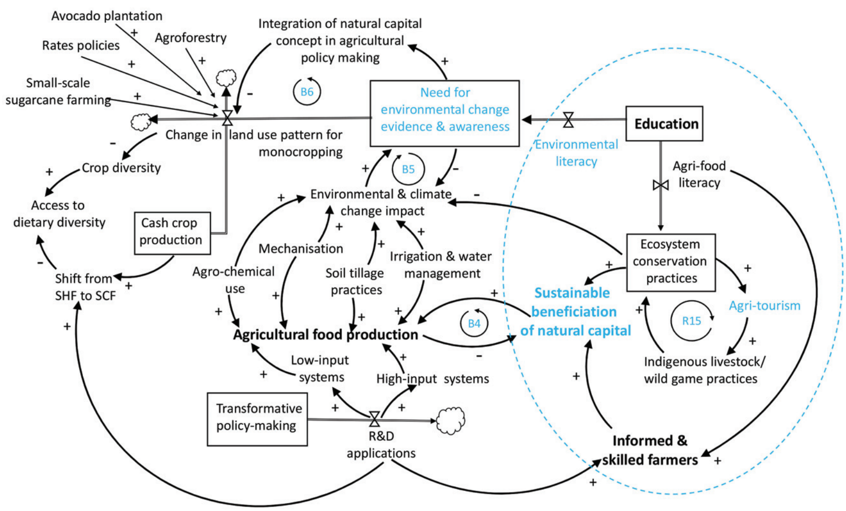

Figure 4. The emergence of functional education as a key nexus to improve environmental awareness and promote agri-food literacy. Agricultural food production in South Africa is essentially a dual system consisting of the low-input subsistence system and the high-input commercial systems that are stimulated through ongoing R&D policies. Agricultural operations (mechanization, irrigation and water management, soil tillage practices) and input (agrichemical use) applied to boost food production worsen climate change and environmental impacts and have a dampening effect on the sustainable beneficiation of natural capital (Balancing Loop B4). Emphasis on multi-faceted literacy ought to incentivize social entrepreneurial innovation and sustainable beneficiation of natural capital from agricultural activities (Loop R15: Virtuous reinforcing loop where the variables mutually reinforce agritourism, indigenous practices, and promote ecosystem conservation practices; all stimulated through functional agri-literacy). Loop B5: Evidence-building and awareness can reduce the impact of agricultural activities. Loop B6: On-going evidence-building and creation of awareness regarding environmental change ought to influence multi-sectoral policymaking, for instance by framing natural capital as transformational.

Ideally, the democratization of knowledge ought to strengthen bottom-up actions, e.g., in the form of cooperative organizations and civic actions, to deliver greater awareness of policy incentives to community members (Figure 5). Moreover, the inclusion of curriculum and governance components that enable the formalization of the Indigenous Knowledge System (IKS) ought to complement mainstream education, to enhance the ongoing development of the much-aspired knowledge-based economy (Loop R16). Participants emphasized that to provide a consolidated frame of action to such an endeavor would require the inclusion of a vibrant policy process that is designed to be adaptive in accommodating IKS (Loop 17). An improved organization of democracy and civic interest could create sufficient grounds to render the education system more contextually functional, improve employment relevance for youth, and, consequently, their standard of living. The ability to make an informed choice would further motivate the pursuit of appropriate information and enhance the subjective appropriation of their life course based on sustainable well-being tenets [67], amongst others. Such a course of action would enable youth to transition into responsible citizenship. Young individuals will have garnered a better understanding of individual responsibility concerning the different dimensions of sustainable well-being, for instance in terms of diet and health choices [68], and the shaping of environmental civic engagement within communities [69]. Table 2 displays the transformative pathways capable of leveraging sustainable and equitable food security from a knowledge economy perspective. It shows, amongst others, the comparative advantage of including IKS in policies. This could become an opportunity to adjust the general concept of the innovation system to local contexts and practices and include bottom-up socio-ecological approaches to create a stimulus for biodiversity and conservation-friendly entrepreneurial and social innovation. The expected outcomes would have direct relevance to several UN SDGs as shown in Table 2.

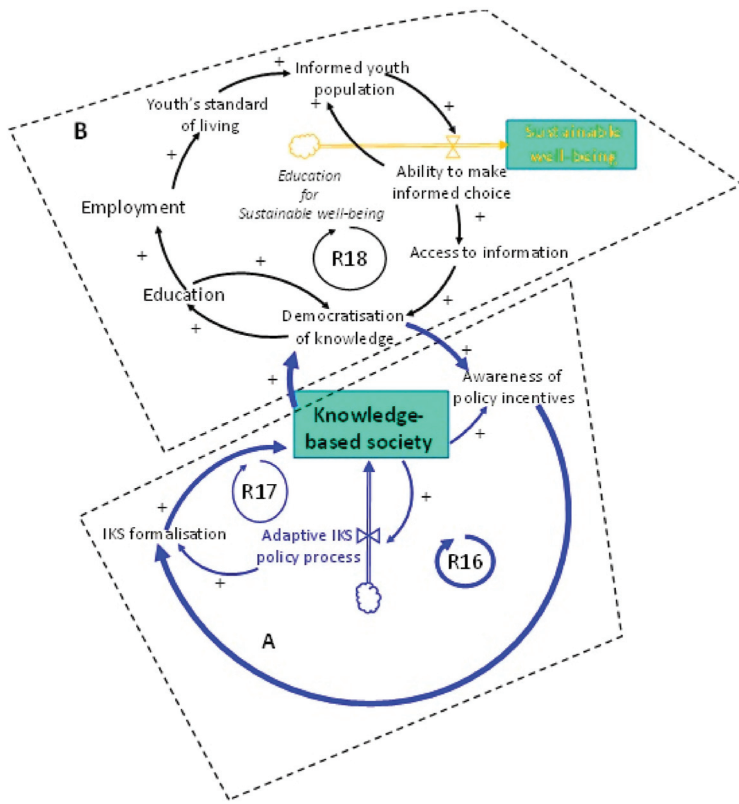

Figure 5. Interventions capable of driving sustainable well-being from the education perspective. (**A**) Reinforcing loop, R16, on the consolidation of knowledge-based society by inclusion of Indigenous Knowledge System (IKS) formalization, mediated by the democratization of knowledge and awareness of policy incentives. Loop R17: An adaptive IKS policy process reinforces the inclusion of indigenous cultural capital and knowledge; (**B**) tackling unintended effects of social exclusion of youth by using education as a mechanism to enable and drive responsible individual choice for sustainable well-being.

Table 2. Transformative pathways to leverage sustainable and equitable food security from a knowledge economy perspective. [2].

Interventions	Causal Pathway	Expected Outcomes	Relevance as Functionally Interrelated SDG Targets
Implementation of sustainable income-generating community-based interventions to promote food security and alleviate poverty for the marginalized within a knowledge economy perspective	Environmental & Agri-food Literacy with Loop R15: Reinforcing virtuous loop where agri-food and environmental literacy could leverage the development of joint entrepreneurial ventures to boost indigenous livestock & wild game practices	Use capabilities of functional education to create a stimulus for biodiversity and conservation-friendly entrepreneurial and social innovation Uplift, promote, and preserve indigenous conservation practices and know-howSustainable use of ecosystem services as innovation instruments to reduce social inequality	*T4.6* Universal literacy and numeracy
			T8.6 Promote youth employment, education, and training
			T8.9 Promote beneficial and sustainable tourism
			T9.3 Increase access to financial services and markets
			T13.3 Build knowledge and capacity to meet climate change
			T15. An Increase financial resources to conserve and sustainably use ecosystems and biodiversity
Education as vehicles for sustainable development actions	R18: 'Education for sustainable well-being' to elevate the youth's standard of living and knowledge base	An educated youth would cultivate the capacity of discernment for: satisfaction with sustainable lifestyle and built environ-mentemployability & entrepreneurial opportunities awareness adequate access to information to be informed on food choice and guide individual aspirations	*T4.7* Education for sustainable development and global citizenship
			T8.3 Promote policies to support job creation and growing enterprises
			T8.6 Promote youth employment, education, and training
			T9.C Universal access to information and communications technology
			T10.3 Ensure equal opportunities and end discrimination
			T12.8 Promote universal understanding of sustainable lifestyle

Table 2. *Cont.*

Interventions	Causal Pathway	Expected Outcomes	Relevance as Functionally Interrelated SDG Targets
Promotion of informational governance	R9: Reinforcing virtuous loop aimed at strengthening collective actions through cooperative and social organizations to promote LED	Strengthening of social cohesion through grass-root level actionsCapacitate dignity and identity construction to advocate a novel idea around the status of rural and/or peri-urban farming	*T8.2* Diversify, innovate and upgrade for economic productivity
			T10.2 Promote universal social, economic, and political inclusion
			T16.7 Ensure responsive, inclusive, participatory, and representative decision-making at all levels
	R16: IKS based policies to improve implementation coherence in a knowledge-based economyR17: Raising awareness of the advantages of policy incentives ought to boost the formalization of IKS through an adaptive process	Creation of IKS-based comparative advantages and contextual rationale for positive societal change in the previously marginalized communities	*T10.2* Promote universal socio-economic and political inclusion
			T11.3 Protect the world's cultural and natural heritage
			T16.6 Develop effective, accountable, and transparent institutions at all levels
			T16.7 Ensure responsive, inclusive, participatory, and representative decision-making at all levels

[2] Loops and variables unpacked are from the causal loop diagrams in Figures 3–5. The interventions and their impact indicated through causal relationship(s) are described. The outcomes created for a successful transition towards sustainable diet transition are shown with the relevant United Sustainable Development Goals Targets (https://www.globalgoals.org/resources accessed 3 March 2022). Main goals are-GOAL 1: No Poverty; GOAL 2: Zero Hunger; GOAL 4: Quality Education; GOAL 8: Decent Work and Economic Growth; GOAL 9: Industry, Innovation, and Infrastructure; GOAL 10: Reduced Inequality; GOAL 13: Climate Action; Goal 15: Life on Land; GOAL 16: Peace and Justice Strong Institutions. Causal pathways are thought to generate expected outcomes; impacts of interventions have different pathways but can have the same overarching sets of outcomes as per the SDG Targets; LED: Local Economic Development.

3.4. Mobilising Systems and Coalition of Actors for Sustainable Diet Transition

3.4.1. Review of Food Systems Sustainability Transition

The use of transition systems research in agri-food systems [70,71] becomes prominent when the problem is complex, ambiguous, and requires the concerted action of many different types of actors to make transformation processes effective. The dialectic relationship between stability (i.e., established rules, governance, habits) and desired and feasible change in understanding how the transition occurs is central. There are multiple interpretations of what is to be sustained and what is to be developed when considering any socio-technical system. This is because there are multiple goals and pathways for development, but, in practice, only a subset will be fully pursued. Knowledge is also socially constructed, and politics of power influence explain why some systems or certain sustainability goals tend to be prioritized. In the MLP framing, the concept of "local sustainability experiments" is used to describe what would be the sectors and actors co-existing and operating at the niche level to create novelty. When the unit of analysis lies in sociotechnical systems, the analysis involves a wide range of actors, and no agent has full accountability or ownership of sociotechnical systems. The novelties can be a combination of scientific research or civil society actions that generate evidence for change.

In agri-food systems, the multiple-level perspective is useful to empower communities to generate grass-root and social innovations [72]. As such, it is a long-term process, spanning decades, characterized by uncertainty and open-endedness. In effect, sustainability journeys are intrinsically dynamic as there are multiple transition pathways, which implies multiple values, and disagreement, since the sustainability notion is highly contested [73]. To catalyze desirable changes in such a context, public policy [74,75] plays a central role in shaping the sustainability transition. As a means to support evidence-based understanding of transition transformation whereby the different dimensions of socio-technical systems transitions are considered, various research constructs are used as methods and/or approaches [76] such as systems thinking [77], system diagnosis [78], retroduction [76], scenario analysis [79], and critical realism, and are applied to design the interdisciplinary space that requires action.

3.4.2. Empowering Vulnerable Communities to Achieve Sustainable Diet Pathways

Table 3 illustrates how the leverage points can be developed to generate evidence capable of stimulating the policymaking process. Based on the multi-level perspective of the socio-technical transitions, the proposed leverages are expressed as policy measures that could be developed, and the categories of actors that could influence the cross-scale transformation process identified. Thus, using the reference of the overarching objective of the SHEFS program, society is viewed as a set of overlapping socio-technical systems consisting of networks of actors such as consumers, environmental action partnerships, small-scale food producers/farmers, socio-cultural/non-governmental organizations, value chain financing specialist, and youth/women groups, who act upon institutions, cultural practices, and knowledge. Much emphasis is placed on developing substantiative equality, given the socio-political legacy of South Africa. At niche levels, this can be achieved through local experiments on agri-food systems, not only as a science but to unleash capabilities, empowerment, inclusivity, and embrace the socio-ecological viewpoint. For instance, at the time of conducting the current workshop, the Neglected and Underutilized Species (NUS) component of the project had started to generate evidence through scoping reviews and multi-criteria suitability analysis, which subsequently informed a policy brief [80–83].

Because agents/stakeholders with different behavioral characteristics play a role in the distinct stages of transitions, notably pre-development, take-off, acceleration, and stabilization (establishing the change over time) [84], they influence the transition process through their goals, knowledge, information, power, interactions, relations, and interests. Thus, for instance, regime-level policy measures that need to be designed to advance rural agritourism as a development tool must consider new transformational challenges. For agri-tourism to exist, it not only requires mastering ecosystem conservation and indigenous wildlife practices, but entails a seamless harmonization with rural entrepreneurship processes to become transformational transitions [85,86]. Criterion 8 of the IUCN standard emphasizes the need to learn from the implementation of nature-based solutions (NbS) to ‘trigger transformative change’ [87]. However, for this to be realized, NbS must be framed as transformational. The framing of an issue is a key point of focus in transformations, as it influences how people understand the topic itself, shaping how problems and solutions are defined and addressed [88,89]. To catalyze change, the drive for successful transition can be addressed by beginning with developing policies with positive reinforcing loops between the niche (micro-level triggers) and the window of opportunities provided at the landscape (macro) levels.

Table 3. Multi-dimensional and multi-scalar interactions among the sustainable diet transition sectors, technology, markets, policy, and culture, capturing the complexity of systematic changes towards sustainability.

Level	Policy Measure	Example of Interventions That Can Leverage the Notion of Sustainable Diet Within Socio-Technical and Socio-Ecological Systems	Stakeholders as Coalition of Actors					
			Consumers	Environmental Action Partnerships	Producers/ Farmers	Socio-Cultural NGOs	Value Chain Financing Specialist	Youth/Women Groups
Niche Micro-level: Stimulation of local experiments refers to An inclusive, practice-based, and challenge-led socio-technical initiative designed to promote system innovation through social learning under conditions of uncertainty and ambiguity	Policies supporting niches	Elaborating effective schemes for embarking in: NUS crop production value chain Promotion of crop and dietary diversity	✓		✓		✓	✓
	Support for the creation of niche networks between various stakeholders	Establishing communication channels between stakeholders: Fostering access to credit/value chain establishment at small-scale levels	✓	✓	✓		✓	
		Mainstreaming awareness of biodiversity loss and the cascading impacts across socio-ecological systems	✓	✓	✓			
	Monitoring food choice determinants	Understanding the shift from traditional to modernity through lived experience Social media analysis of food choice	✓		✓	✓		✓
		Public co-funding of bottom-up initiatives: small-scale traditional (Gogo, meaning Grandmother) food canteens	✓	✓	✓	✓	✓	
	Normalizing environmental impacts of land use shifts	Systematic mapping of sugarcane and forestry land use			✓			
	Supervision of sustainable beneficiation of natural capital	Improve cross-sectoral evidence on natural capital sustainability		✓	✓			✓
Regime Mesolevel: The Food Environment that needs to be changed, but consists of dominant actors, institutions, practices, and presumed shared objectives	Support for the expansion of a targeted sector	Rural agri-tourism	✓	✓	✓	✓	✓	
		Education	✓	✓	✓	✓		✓
	Policies limiting the power of regimes	Transparency of lobbying processes	✓	✓	✓	✓		✓
		IKS inclusion						
	Promotion of technical or resource diversity	Public R&D investments and subsidizing private R&D in agroecological intensification		✓	✓			
	Regulating unhealthy consumption activities	Taxes or tradable permits, command-and-control of products such as sugar tax, fast food	✓		✓			
Landscape Meta level Economic, ecological, socio-political, conditions, e.g., the South African Constitution that provides the context to drive niche experiments and actions	Promotion of civic debate	Public participation in policy development (round tables).	✓	✓	✓	✓		✓
	Information provision	Informative campaigns for consumer behavior	✓					✓
	Creation of informed debate	Supporting public participation in setting the policy agenda	✓	✓	✓	✓		✓
	Developing policy integration (technology, environment, consumers)	Making one ministry responsible for coordinating all initiatives and policies concerning long term sustainability transition	✓	✓	✓			

[3] NUS: Neglected and Underutilized Species. IKS: Indigenous Knowledge Systems.

4. Discussion

4.1. Understanding the Mechanism Used to Co-Design Change Towards Sustainable Diets

The study uses an interactive facilitation process among stakeholders to envision and co-design a future state of the food system by prioritizing the research focus for the SHEFS consortium that ought to be both sustainable and healthy for the smallholder system and previously disadvantaged group in South Africa. To this end, policymaking would require interdisciplinary evidence capable of leveraging the outcomes of future implementation efforts. Sustainable food consumption occurs in the nexus between the national context and private individual lifestyle [67]. Similarly, the synergy required between the perception of health and sustainability differs across contexts [74]. Therefore, taking these multiple domain relationships into account, we have shown that, due to the inherently complex nature of socio-technical and socio-ecological systems within which sustainable diets must be embedded, most intervention strategies are likely to take effect by way of multiple mechanisms, although it remains an empirical and/or contextual issue whether one mechanism is primary, and others are ancillary. In effect, it is also likely that the same mechanism might be involved in the operation of multiple implementation strategies as shown in the causal loop diagrams (CLDs). To gain clarity on the emergent outcomes of the CLDs [67], these were unpacked in a logical framework comprising the following elements: Intervention → Causal pathway → Expected outcomes → Relevance to global goals. The logical analysis acknowledges that these transformative processes ought to occur through multi-dimensional mechanisms—comprising institutional rules, economic requirements, multi-level political negotiations as well as social and cultural rules and expectations—from the local to the global scale. Herein, following Lewis et al. [90], we consider "mechanisms" as the processes or events through which an implementation strategy functions to achieve desired outcomes. Careful considerations were taken to ensure that each strategic intervention is well-specified and judiciously linked to its corresponding mechanisms in a coherent manner. This is because underspecified strategies can potentially leave the interdisciplinary research space vulnerable to inappropriately synthesizing data across studies [91,92]. Herrfahrdt-Pähle et al. [93] used the example of successful water governance in post-apartheid South Africa to emphasize that different phases of transformation require different features and capacities. It is to ensure such coherence that the interventions proposed by the stakeholders in the present study were derived through causality and system loops, and thereafter embedded in the niche–regime–landscape transition framework.

4.2. Emergent Entry-Points for Transformative Evidence Building

Five inter-linked areas have emerged from the stakeholder engagement process, which can be used to define priority entry points to build evidence-based policies that align with sustainable and healthy food systems. The first one refers to breaking away from the legacy of apartheid by advocating transformative governance that acknowledges the pervasive disconnect between, on the one hand, the microlevel socio-political reality of the previously disadvantaged, parochial evidence synthesis and practice and, on the other hand, the positive expectations of the macro-level landscape—Bill of Rights in the South African Constitution [94,95]—but which is crippled with counterintuitive effects due to emphasis on the sectoral development agenda that results in decades-long pervasive delays to alleviate the smallholder sector. Successful political transformation, that is the shift to democratic South Africa, has not realistically ensured a new normal in terms of social and economic transformation, especially for historically underprivileged smallholder food producers, as the country remains the most unequal society [96]. Second, there was consensus that the critical challenges to be acknowledged in realizing intervention efforts requires multi-dimensional evidence-based policy solutions, similar to a Context–Mechanism–Outcome configuration [30], that exhibit dynamics of three functional properties of a knowledge economy about wider transformative processes: Identifying positive feedback patterns through education to accumulate multi-functional capabilities, nurturing evidence synthesis for improved practice by way of informational and adaptive policymaking, and empowerment of youth through grass-root actions to capacitate social cohesion, dignity, and identity construction. Third, the development and governance of the smallholder food sector ought to foster environmentally sustainable and resilient food systems that can mitigate the impact of unintended consequences of policies that promote commercialization/intensification of food production to the detriment of subsistence farming, household food security, food crop diversity, and dietary diversity. Although huge transformative efforts have been achieved to break the "Success to the successful" apartheid system archetype, the transitioning achieved in the last decades is crippled by the "Shifting the burden" archetype due to systemic delays across sectors. Socio-political shocks can be windows of opportunity, but the process needs to be navigated. Fourth, the ensuing dietary diversity could be partly aligned with the needs of providing healthy diets. In addition, to further essential nutrition actions, supportive educational measures promoted by health literacy ought to guide social ambitions towards food choice for well-being by promoting sustainable and healthy behavioral shifts when aspiring to transition from a traditional to a modern lifestyle. Fifth, proper recognition of the importance of environmental literacy should be actioned by mainstreaming awareness of biodiversity loss and its negatively reinforcing impacts across socio-ecological systems. At the same time, environmental literacy could improve cross-sectoral evidence on natural capital sustainability, and support the expansion of entirely novel sectors such as agri-tourism at the smallholder level.

Key features need to be mobilized for transformation for a sustainable diet innovative system. At the cognitive level, this would require change at the individual level as well as in broader social units and communities of practice, e.g., through transdisciplinary participation and collaborative governance. Structurally, the combination of different types of knowledge, and preserving and making knowledge available, ought to evolve as conditions for identifying sound policy instruments to improve the ability to deal with transformative change. Swensson et al. [97] reviewed the role of the regulatory framework in the facilitation of public food procurement for the implementation of socio-economic objectives through public procurement. Although such policy instruments have been adopted in various countries within this specific context, comprehensive analysis is still lacking in the food policy context. In this paper, we have a number of measures in the meso-level policy regime.

The process used for interactive facilitation, and subsequently embedding the emergent outcomes in the MLP of the transition systems framework, has contributed to a broader reflection on deliberatively strategizing, shaping, and modulating sustainable diet pathways towards desirable individual and societal outcomes, in full awareness of the scale, influence, and urgency of the effort required. The co-designing process used to problematize sustainable diet transition, as reported in the current work, set the pace in developing actionable research for the project and its Theory of Change.

5. Conclusions

The emergent outcomes of the current work demonstrate the complex nature of sustainable diet transitioning by highlighting the multiple interdependencies across sectors and cross-scale dynamics. Intervention strategies to inform policies, therefore, cannot be designed as stand-alone approaches. Rather, emphasis should be placed on co-evolutionary sets of measures to inform decision-making for the real world. This work examines key issues raised by stakeholders' considerations by combining causal mechanisms leading to sustainable diets and embedding the proposed strategies in a multi-level perspective of the transition theory. The mapping of these issues builds knowledge from, and for, practice, by linking different perspectives, including dietary diversity, sustainable beneficiation of natural capital, and food choice for well-being, via the "Intervention → Causal pathway → Expected outcomes → Relevance to global goals" mechanism. A similar approach could be applied in other contexts to problematize sustainable diet transitioning. We have set out five major emergent outcomes of the co-designing process with stakeholders. Despite the very wide knowledge base, disciplines, and methodological differences involved in framing sustainable diets in South Africa, we show how the different levels of the sustainable diet innovation systems (landscape, regime, and niche) could interact to pave the way for initiating such transformations and which key features (cognitive, structural, and agency-related) are mobilized for transformation.

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Informed Consent Statement: Written informed consent was obtained from all subjects in the study as per the ethical clearance guidelines of the University of KwaZulu Natal, South Africa. Informed consent was obtained from all subjects involved in the study.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Action learning: Conceptualization of the interrelationships of the sustainable and healthy food systems in South Africa

Revans's [98] action learning concept was applied to capture the learning outcome of the workshop. The concept specifies that unless problems are open to a purely technical solution, there is more learning to be grasped before action is taken by those involved with an issue. It constitutes (i) System alpha, which centers on the investigation of the problem, examining the external context, structural values, and available resources; (ii) System beta focuses on problem resolution, through decision cycles of negotiation and reflection and, (iii) System gamma concerns the participant's cognitive framework, their assumptions, and prior understanding, and is concerned with learning as experienced by each stakeholder type. The three systems, alpha, beta, and gamma are not linear or sequential, nor are they entirely discrete. All types of stakeholders possess "Programmed Knowledge", which can only help individuals or organizations up to a point. However, dealing with change requires greater insight and this is gained by posing "Questions". Therefore, "Learning" then becomes a function of acquiring programmed knowledge and combining it with questioning insight, expressed by Reg Revan's Learning Equation: L (Learning) = P (Programmed Knowledge) + Q (Questioning Insight)

The principal interest in developing effective learning to achieve adaptation and deal with change was to focus on Q, Questioning Insight. It is the ability to exploit the questioning insight that would give rise to the interrelated multiple perspectives in co-designing the SHEFS program objectives. Action learning recognizes that, in the absence of insight, the use to which an abundance of programmed knowledge may be put is limited. Problems and opportunities are treated by leaders (in funded research, these refer to program managers/principal investigators) who must be aware of their value systems, differing between individuals (i.e., stakeholders), and the influences of their past personal experiences [98].

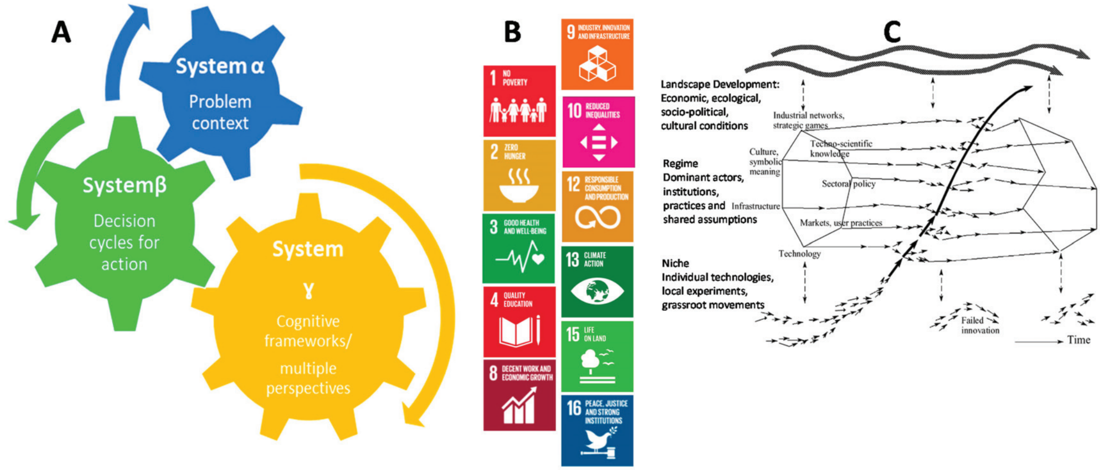

Figure A1. Describes the workshop process and causal loop diagram. (**A**) Systems alpha: Context-specificity consideration. Systems beta: Which components and/or lenses to consider to optimally intervene and focus on the investigation of the problem. System gamma: Focus on the learning, i.e., how to intervene collectively based on the dimensions identified. The three systems are best understood as a whole, with interlocking yet overlapping parts [99]. (**B**) Unpacking the systemic interactions of the problem context through a logical framework that identifies relevance with the SDGs. (**C**) Developing leverage points, identified from processes in A, to generate evidence capable of stimulating the policymaking process through alignment within a multiple-level perspective (niche–regime–landscape) of the transition theory. Part C of the diagram is adapted from Geels [51].

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Food Systems in Informal Urban Settlements—Exploring Differences in Livelihood Welfare Factors across Kibera, Nairobi

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Abstract: The number and sizes of informal settlements are expected to increase drastically in the future, and dramatically so in Sub-Saharan Africa, where migration from rural to urban areas is increasing, and poverty and food insecurity threaten livelihoods. Data sources explaining livelihood factors in informal settlements are scarce, and often highly disputed. In this study, Kibera is investigated, one of the largest informal settlements in Africa. The main aim is to analyze differences in livelihood factors across the villages in Kibera, and to explain some of the existing discrepancies in food security levels among its population. In particular, livelihood factors such as tribe, welfare and trust can explain some of the variation in food security across 12 of the 13 villages located in Kibera. The analyses inform of significant differences across the villages when it comes to, among others, income, food insecurity, ownership of land in rural areas, tribal background and trust levels in strangers and community leads. To reach the millions of people living in informal settlements now, and increasingly so in the future, it is advised that research and implementation go hand in hand, with enhanced understanding of the complexities within rural–urban food systems to ensure solutions that are affordable and accessible to low-income groups. On this pathway to fight poverty and hunger in the future, today's policies and programs must take such complexities into account to positively contribute to strengthening the resiliency and sustainability of rural–urban food systems by ensuring an increase in welfare levels with zero climate impact.

Keywords: resilient food systems; livelihood welfare factors; indicator mapping; household survey; informal settlement; food security; Kibera; Kenya

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1. Introduction

The African continent is urbanizing faster than other continents, with the expectation that more than half of the Sub-Saharan Africa's (SSA) population will live in urban areas by 2030 [1–3]. Of the total urban residents living in Sub-Saharan Africa, it has been estimated that more than 70% live in informal settlements or slums [3,4]. In Kenya, about 60–80% of the population live in informal settlements [2,5,6]. In the capital city Nairobi, about half of the people live in at least 100 slums and squatter settlements [6], including the major slums called Kibera, Mathare, Korogocho, Kangemi, Kawangware, Mukuru and Kiambio [ibid.]. Because of the informal character of these settlements, information is not selected regularly and facts are frequently disputed.

This is also the case in Kibera, one of the largest informal settlements in Africa. A lack of systematic data collection has made it complicated to officially confirm the complexities of livelihood, which has led to many misconceptions and misinformation about the size of the location, its exact population, poverty status, land and property ownership, etc. Often rough estimates are based on assumptions of the shares of the total population in Nairobi, or research conducted in one of the 13 villages of Kibera is assumed to be representative of Kibera as a whole. For instance, the true population size in Kibera is highly disputed [7]. According to the literature, different authors have given varying estimates of the population in Kibera [7–9]. The total population of residents in Kibera in 2019 according to the national census was only 185,777 [10]. Notably, this estimate is questioned [11]. Other sources report differently, including estimates of between 235,000 and 270,000 [12] and for some NGOs, they report up to 1,5 million [13]. In some of the literature, the assumed high population of Kibera has given it the reputation of being the largest slum in the region and the second largest in Africa after Cape Town, South Africa [14,15]. In contrast, others believe that the actual population estimates in Kibera most probably are too high [16]. Not knowing the exact number of people living in Kibera, it also becomes unclear how livelihood welfare factors, such as income, food security, access to energy, etc., vary across the 13 villages of Kibera.

Against this background, in this article the main aim is to analyze the differences in livelihood factors across the villages in Kibera, and to explain some of the existing discrepancies in food security levels among its population. The specific research questions are:

(1) Who are the people living in Kibera, and how are tribes distributed across the villages?
(2) How do selected welfare factors vary across Kibera, such as income, land and source of electricity?
(3) How do trust levels differ for various actors across the villages of Kibera?
(4) To which extent do levels of food insecurity vary across the Kibera villages?

In this study, a food system approach was applied to account for the complexities of the explanatory variables of food insecurity in Kibera. In this approach, targeting a minimum of 30 households in each village with variable representativeness across gender, age and tribe, a total of 386 households distributed across the villages in Kibera were interviewed to contribute to the analyses, and their locations were identified. The livelihood factors are further presented visually to illustrate the variations across the Kibera informal settlement visually, supported by tests of significance between each single village and the average values for Kibera. The enhanced understanding of the variabilities of livelihood welfare factors fills some of the information gaps, and provides increased opportunities for more targeted future support, development and investments, which again can enhance the resiliency of the food systems and livelihood.

The article is structured as follows. A food system approach is introduced in Section 2. Subsequently, the methodological approach and materials are provided in Section 3, followed by Section 4 presenting the main results of the household survey. Based on the results, the livelihood welfare factors analyzed across the Kibera villages are discussed in Section 5, before the main concluding remarks and recommendations are provided in Section 6.

2. A Food System Approach

A food system approach was applied in this study to explore a set of livelihood factors and their explanatory potential for the levels of food insecurity in the informal settlement of Kibera (Figure 1) [17,18]. In a food system approach, the outcomes can be observed alongside all of the Sustainable Development Goals (SDGs) introduced by the United Nations General Assembly (UN-GA), for which food security, safe and healthy diets, inclusiveness and equitable benefits, as well as sustainability and resiliency, are the immediate outcomes. The dynamics of food system activities related to, among others, the value-chain with production, trading and consumption, as well as banking, laws and regulations' facilities, are highly interlinked with the dynamics of socio-economic and environmental drivers. While the socio-economic drivers include specifications of the policy regime and levels of conflicts, the dynamics of the environmental drivers define the quality of water, climate adaptability, biodiversity and soil conditions, among others [19]. The drivers have strong influences in context-specific food systems. While it is generally acknowledged that the food systems are complex, it is not possible to analyze every single causal relationship in every study.

The target group of this study is the households in Kibera [20,21]. Stakeholder participation in cities is recommended to deal with the complexities involved, such as food insecurity, poverty, health problems and environmental issues [22]. The households are suffering from the substantial impacts of lacking inclusiveness and equitable benefits, lacking safe and healthy diets, suffering from food insecurity, vulnerability to lacking sustainability and resiliency, for which climate change and environmental degradation will harm the groups substantially.

The definition of the role of a household head is disputed [23], and it is unclear why some interviewees said they were household heads and others not, probably because of different interpretations about what a household head's role is. Institutional theory informs about the structures influencing the contexts for acting, involving both informal and formal rules that encourage or restrain peoples' behaviors [24]. In institutional theory, an emphasis has been put on the difference between individual and social values (see, e.g., [25]. Taking a citizen's role implies that a 'we' perspective is applied when considering the needs of your family, your community, your city or your country [26].

Institutional factors also include rural–urban interactions and inter-relationships, in relation to, among others, money flow, migration, food trade and land ownership [18]. Social capital is the basis of commitments, cooperation and trust, and has been shown to have an influencing role in Kibera as an explanatory factor for food security [21,27]. Hence, the specific relationships investigated in this study include food security, reflecting on the 'inclusiveness and equitable benefits' and 'sustainability and resilience' outcomes, following the food system approach to assist the visibility of the interrelationships of a larger system [28]. As such, food security does not operate in isolation from other factors, but is highly interrelated with other welfare factors, such as income and relations with rural areas and backgrounds. A food system approach makes such complexities visible and logical.

A food system approach investigates multiple factors, activities and outcomes of a food system; covering biophysical, economic, political and social factors, food-related production, processing, distribution, preparation and consumption activities, as well as socioeconomic, climate and environmental outcomes [12,19]. The literature on food systems conceptualizes the food system differently, including some of the literature having a strong emphasis on natural resources [29], and others focusing on consumers and diets [30]. Others again investigate the bottlenecks and opportunities with food systems [31]. Van Berkum et al. [17] provide a generic framework for food systems focusing on how different types of policy incentives or business innovations can influence the relationships between multiple stakeholders (input providers, farmers, traders, public officials, processors, retailers), and can impact on the interactions of different components (consumption, distribution, value chain, production). Several surveys explore how to support a food system transition towards sustainability and resilience following the SDGs [32], and specifically focusing on urban—rural food system interactions [18,33].

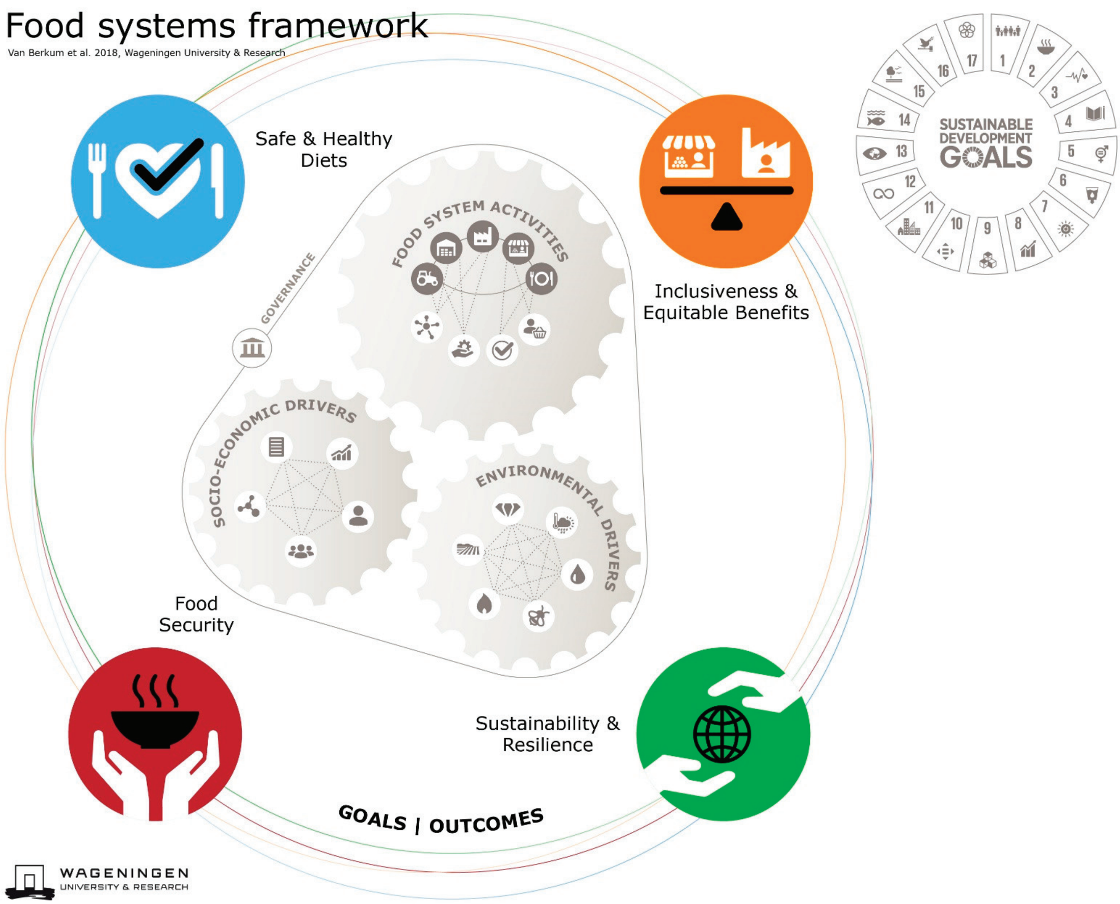

Figure 1. A food system approach involving interactional dynamics between food system activities, socio-economic drivers and environmental drivers, and the governance therein. In transitioning towards the Sustainable Development Goals (SDGs), outcomes are observed in relation to safe and healthy diets, food security, inclusiveness and equitable benefits, as well as sustainability and resilience [17].

3. Methodological Approach

In this section, the study area is presented on a map, and the data collection and the statistical analyses applied are explained. Two documentaries have been made to explain the food system dynamics in Kibera (see Supplementary Materials below: Videos S1 and S2).

3.1. Study Area

Kibera can be divided into 13 villages, for which 12 were included in this study (Figure 2). The missing village, Mashimoni, was not covered by the study because of security reasons. During the interviews, Global Positioning System (GPS) locations of the interviewed respondents were registered.

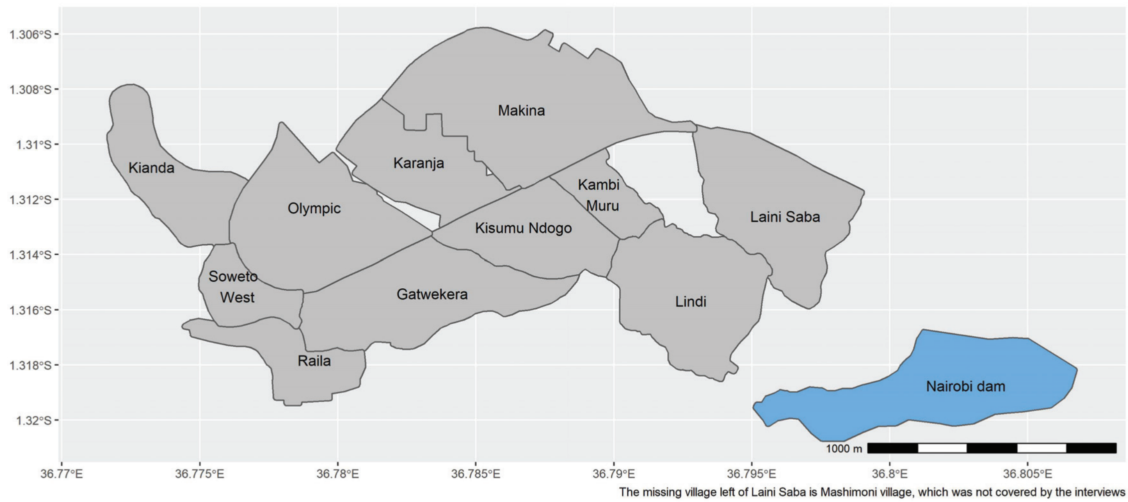

Figure 2. Map of Kibera indicating the 12 villages included in the analyses.

3.2. Data Collection and Statistical Analysis

The selection of the households to be interviewed personally by in-depth interviews in August 2020 was performed by so-called random walks. Within each village, a selection of about 30–35 households were interviewed, taking into account a spread of gender, age and tribe. Although the sample size per village was small, it was possible to determine significant differences between them. Notably, with larger samples, more significant results would have been identified. To detect locations by GPS, an Open Data Kit (ODK) mobile-phone platform was applied.

A semi-structured questionnaire was prepared, including both open- and close-ended questions. Covering livelihood factors such as income, education, background and relations with rural areas, as well as questions about trust, consumption preferences, food security and many more, the dataset is comprehensive and unique of its kind and has contributed to other studies as well [18,19]. Some of the variables were obtained as monetary units, others as percentages, numbers of people and times of travel (Appendix A). In two cases, a scale was applied; (1) to take account of trust levels, a scale of 1 to 5 was applied, for which 1 equals low trust, 2 equals some trust, 3 equals moderate trust, 4 equals reasonable trust, and 5 equals a high trust level. (2) a Household Food Insecurity Access Scale (HFIAS) was applied as a proxy for food security in this study, developed by USAID [34]. When calculating the HFIAS in this study, a total of eight questions were scored from 0 to 3, with 3 being the highest frequency of occurrence. Adding all of the scores, the total HFIAS can range from 0 to 24, indicating the degree to which respondents have inadequate access to food. Following this approach, various food consumption-related questions with different intensities were asked, including: In the past four weeks:

- Did you worry that your household would not have enough food? How often?
- Were you or any household member not able to eat the kinds of foods you preferred because of a lack of resources? How often?
- Did you or any household member have to eat a limited variety of foods due to a lack of resources? How often?
- Did you or any household member have to eat some foods that you really did not want to eat because of a lack of resources to obtain other types of food? How often?
- Did you or any household member have to eat smaller meals than you felt you needed because there was not enough food? How often?
- Did you or any household member have to eat fewer meals in a day because there was not enough food? How often?

- Was there ever no food to eat of any kind in your household because of lack of resources to get food? How often?
- Did you or any household member go to sleep at night hungry because there was not enough food? How often?
- Did you or any household member go a whole day and night without eating anything because there was not enough food? How often?

After pre-testing on 16 respondents, appropriate modifications were implemented. Stata software [35] was used for the data processing and analysis after data collection, and maps were made using a statistical program called "R" [36].

The final samples per village are provided in Table 1. The sample size per village was mostly 30 households interviewed, although in Gatwekera, Kianda, Laini Saba and Soweto West the numbers were higher, which is explained by the need to interview some more households to reduce any dominance of gender, age and tribe in the sample, and in Kisumu Ndogo the sample was lower than 30, due to the difficulty in finding people willing to spend two hours to respond to this questionnaire. The table also provides the share of households participating with male heads, and the mean age of the household head, across the different villages.

Table 1. Overview of number (N) of households interviewed, % of households represented by male, and mean age across 12 of the 13 villages of Kibera.

	Gatwekera	Kambi Muru	Karanja	Kianda	Kisumu Ndogo	Laini Saba	Lindi	Makina	Mashimoni Squatters	Olympic	Raila	Soweto West
N	34	30	30	35	28	35	30	30	30	30	33	35
% Male	0.82	0.83	0.77	0.69	0.82	0.83	0.67	0.77	0.77	0.60	0.75	0.74
Mean age	36.8	43.2	39.5	31.5	36.8	37.9	36.1	36.4	42.1	33.5	34.2	38.7

A *t*-test was performed for each variable against the average of Kibera to detect the variabilities across the villages, to test the hypothesis: Is the livelihood factor identified at village level significantly different from the average of Kibera? The livelihood factors include a series of variables listed in Appendix A, Table A1, bundled within the following categories: (1) Households origin (tribe), (2) Household practices, (3) Household characteristics, (4) Household welfare, (5) Household use of energy source, (6) Trust relations on a scale from 1 (low) to 5 (high) and (7) Food insecurity. By means of the descriptive statistical analysis, the levels of significance are presented by p-values to illustrate the exact discrepancies with the Kibera average (Appendix A, Table A1). Stars indicate the p-value of the t-test on the difference in means between the village of interest and the other villages within Kibera, where + = $p < 0.1$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, with * = $p < 0.1$ indicating some significance, ** = $p < 0.05$ indicating quite some significance and *** = $p < 0.01$ indicating high significance in the difference of the specific village value compared to the Kibera average.

4. Results

In this section, the results are presented on maps covering the 12 villages investigated in Kibera. The darker the blue color is, the higher the value of the respective variable. Note that the scale of each map is different, and as such the colors do not represent similar value categories across the maps. The results of the *t*-test and the numeric values of the estimates are presented in Table A1 in Appendix A. Each sub-section that follows addresses one of the four research questions listed in the introduction.

4.1. Who Are the People Living in Kibera, and How Are Tribes Distributed across the Villages?

Tribes. There is a large diversity of tribes in Kibera. Overall, based on the random sample of this study, the selected households consisted of 131 representing the Luhya tribe (34%) and 127 representing the Luo tribe (33%), which were the most prevalent tribes in Kibera, followed by a total of 42 households representing the Kisii tribe (11%), and a total of 30 households representing each of the Nubian and Kamba tribes (8% each), while the Kikuyus only contributed with about 15 interviews (4%) of the total sample (Table A1).

Across the villages, significant differences in the composition of tribes compared with the average of Kibera were shown for Soweto West where there were more Luos (49%) and Kisiis (26%) and fewer Luhyas (20%) (see Appendix A). Moreover, in Laini Saba there were more Kikuyus (23%) and Kambas (34%), whereas Kisumu Ndogo followed by Lindi showed a very similar composition of tribes to Kibera overall. The share of Luos was highest in Gatwekera (76%), followed by Olympic (63%) and Soweto West (49%), while the share of Luhyas was highest in Kambi Muru (77%), followed by Mashimoni Squatters (67%) and Makina (60%). Although the largest share of Kisiis was identified in Kianda (37%) and Raila (30%), the shares of Luos and Luhyas were relatively high in both these villages as well. The share of Nubians was highest in Karanja (43%) (see Figure 3).

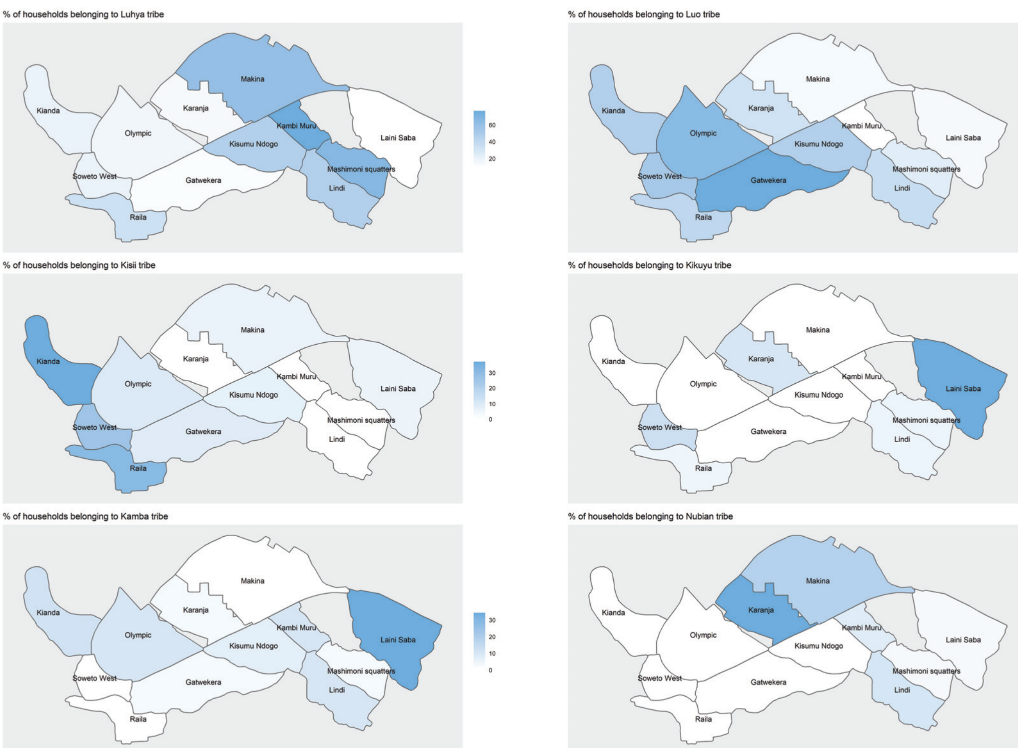

Figure 3. Main tribe distribution across 12 villages in Kibera.

Household practices. On average in Kibera, the number of years a household head has lived in Kibera is 21 years. The share of household heads indicating they adopt the same practices as their neighbors, was estimated to be 45% on average. The average a household head visited the rural area of belonging was 1.6 times a year, whereas the share of household heads who feel connected to Western Kenya was as high as 75% on average. (Table A1).

Karanja showed a relatively high significant discrepancy across most of the household practice factors compared with the Kibera values on average (see Appendix A). This is not surprising, given that Nubians who are born in Kibera and do not originate from Kenya dominate this village. Accordingly, the inhabitants have lived longer in Karanja (32 years) than Kibera on average, they share fewer cultural practices with their neighbors (40%) and connect less than average to Western Kenya (40%). The number of visits to the rural area was higher because they perceive Kibera as their ancestral land and refer to this as their 'rural area'. Notably, the area also has an influx of other tribes who have strong linkages with their rural homes and hence influence the outcome.

Comparing the differences in values across the villages, the household heads in Raila and Kianda on average moved to Kibera most recently (13 and 15 years, respectively). Moreover, the share of neighbors sharing the same cultural practices was highest in Gatwekera (67%) compared to the other villages, followed by Lindi (50%). The lowest sharing of cultural practices is in Laini Saba, where the tribes do not connect with Western Kenya, i.e., where the Kikuyus and the Kambas were dominant (38%). Looking at the differences between the villages, Makina's inhabitants visited their rural areas less frequently (0.9 times per year) in comparison with the other villages. Overall, in all of the villages the share of people who connected with Western Kenya is high, between 63% in Makina and 97% in Gatwekera, except for Karanja (20%) and Laini Saba (20%). This is logical, given the estimates of tribe dominance across the different villages which do not originate from the west (see Figure 4).

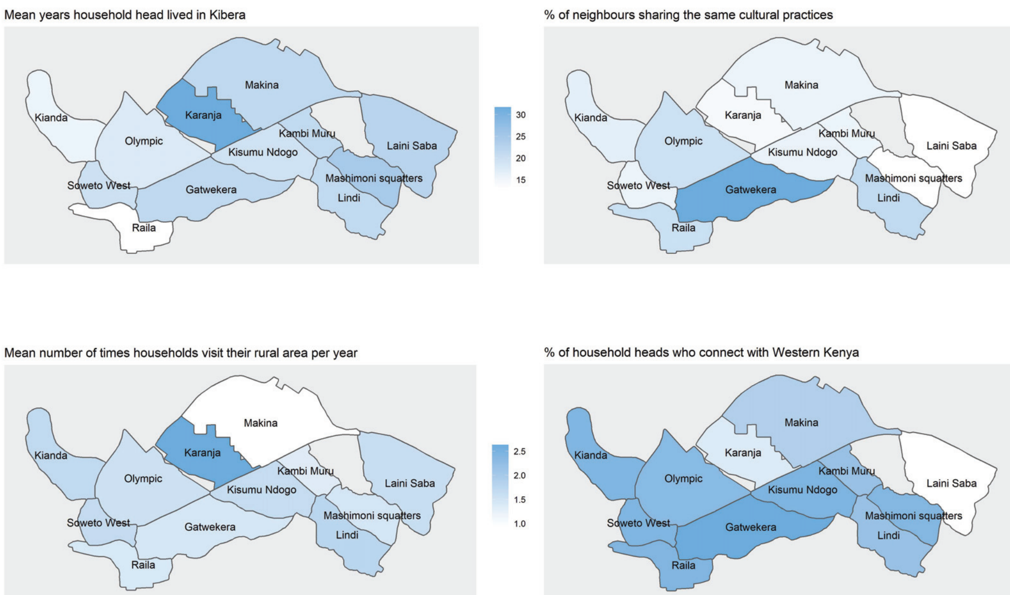

Figure 4. Household practices across 12 villages in Kibera.

Household characteristics. Some core household characteristics variables included household size, which on average was 4.6 people in Kibera, and education level of household heads, with an average of 49% who achieved secondary education (4 years or higher). While on average 67% of the household heads in Kibera are married, only 3% of the household heads interviewed were women. (Table A1).

Across the villages, it appears that household size varies, and in Laini Saba and Lindi the sizes were lower on average (4.0 and 3.8, respectively), whereas in Mashimoni Squatters and Olympic they were significantly higher (5.8 and 5.2, respectively). Three of these villages also differed when it came to education. Whereas in Mashimoni Squatters and Laini Saba only 27% and 29%, respectively, have achieved secondary education, in the Olympic village a total of 77% have achieved secondary education or higher, which was a lot more than average. Moreover, only in Gatwekera was the number of married household heads significantly higher with 85% of the household heads being married, compared with the average of 67%. Overall, female household heads were very rare, and there were no significant differences between the villages in the share of female-headed households, as shown in Appendix A. In some villages, no female household heads were included in the study, although a large share of interviewees were women who responded on behalf of the household head (see Figure 5).

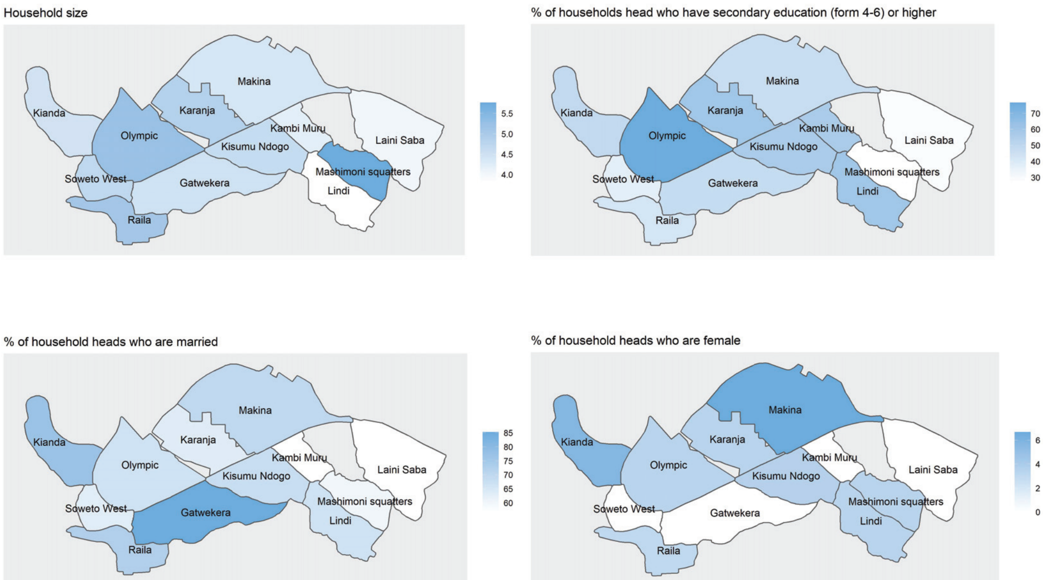

Figure 5. Household characteristics across 12 villages in Kibera.

4.2. How Do Selected Welfare Factors, such as Income, Land and Source of Electricity Vary across Kibera?

Income and landownership. In Kibera, the mean income was based on the average income of the household sample included in this study, which is KES13,166 per month (about EUR132). A total of 36% of the household heads indicated that their income was enough to cover their food needs. About 50% of the respondents indicated that they owned land in rural areas with an average size of 1.48 hectares. (Table A1).

Looking at the differences across the villages, first, the study shows that the spatial patterns regarding education level closely resemble the patterns for income. The highest monthly income was found in the Olympic village (KES17,053), whilst the lowest incomes were identified in Laini Saba (KES9,840). Second, the share of households who indicated their income was enough to cover their food needs and utilities costs was highest in Lindi (50%), followed by Makina (47%) and Gatwekera (47%). Notably, although no significant difference with the average was shown, the villages Kisumu Ndogo, Kambi Muru and Mashimoni Squatters indicated most frequently that their income was not enough (25%, 27% and 27%, respectively) (see Appendix A). Third, probably the most influencing factor for welfare in Kenya, i.e., the owning of land in rural areas, showed a lot of variability, which was shown to be significantly differentiated in Gatwekera, Kambi Muru, Karanja, Kianda, Laini Saba and Lindi. Compared with the shares of households owning land in rural areas on average in Kibera (51%), the shares were higher for Gatwekera (65%), Kambi Muru (67%) and Kianda (69%), and lower in Karanja (33%), Laini Saba (31%) and Lindi (33%). However, only in Lindi did the average size of land differ significantly from the average (3.33 hectares) (see Figure 6).

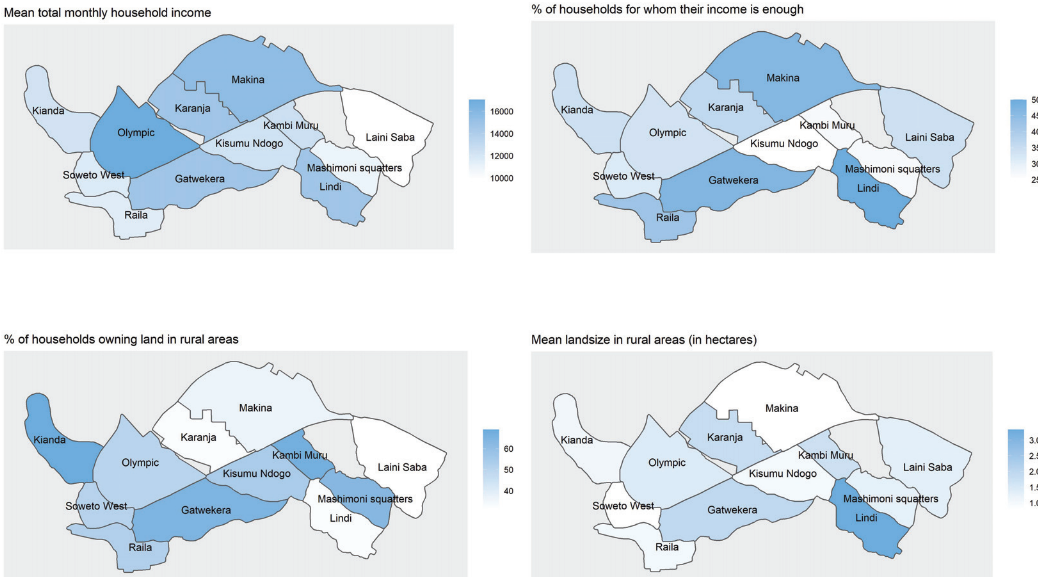

Figure 6. Comparing income and landownership welfare factors across 12 villages in Kibera.

Spending and loans. On average in Kibera overall, the share of income sent to rural areas as remittances was 6%. A total of 56% of the households received food gifts as a source to strengthen their food security. Of the respondents, 13% indicated having savings, while 35% had a loan (Table A1).

Across the villages in Kibera, the share of income sent to rural areas was significantly higher in Gatwekera (9%), and significantly lower in Laini Saba, where only 3% of income was sent to rural areas. The share of respondents who reported receiving food gifts from rural areas differed a lot across the villages. The receivers of food gifts were significantly higher than average in Gatwekera (79%) and Olympic (77%), and significantly lower than average in Karanja (20%), Kisumu Ndogo (39%) and Makina (40%) (see Appendix A). When it comes to savings, only Mashimoni Squatters is significantly different than the Kibera on average, with only 3% of households having savings. In addition, the share of households with loans was significantly higher compared to the mean in the Olympic village, where over half of the respondents had taken a loan (53%) (see Figure 7).

Energy sources. In Kibera the most used energy sources for cooking and light, among others, include: (1) accessed steady electricity network; (2) charcoal; (3) paraffin; and (4) liquefied petroleum gas (LPG). Looking at Kibera on average, a total of 49% reported having access to the electricity network, and 19% made use of charcoal, 40% made use of paraffin and 36% made use of LPG (Table A1).

First, the share of households accessing the electricity network was significantly higher than average in Makina (77%), Karanja (67%) and Kambi Muru (63%), and significantly lower than average in Laini Saba (17%) and Mashimoni Squatters (27%) (see Appendix A). Second, the use of charcoal was significantly higher than average among the households in Olympic village (33%) and significantly lower than average in Laini Saba (3%). Third, the use of paraffin was significantly higher among the households in Raila (55%) and Laini Saba (54%), while significantly lower in the Olympic (23%). Fourth, the use of LPG as energy source is only significantly different in Mashimoni Squatters where it is lower than average (17%) (see Figure 8).

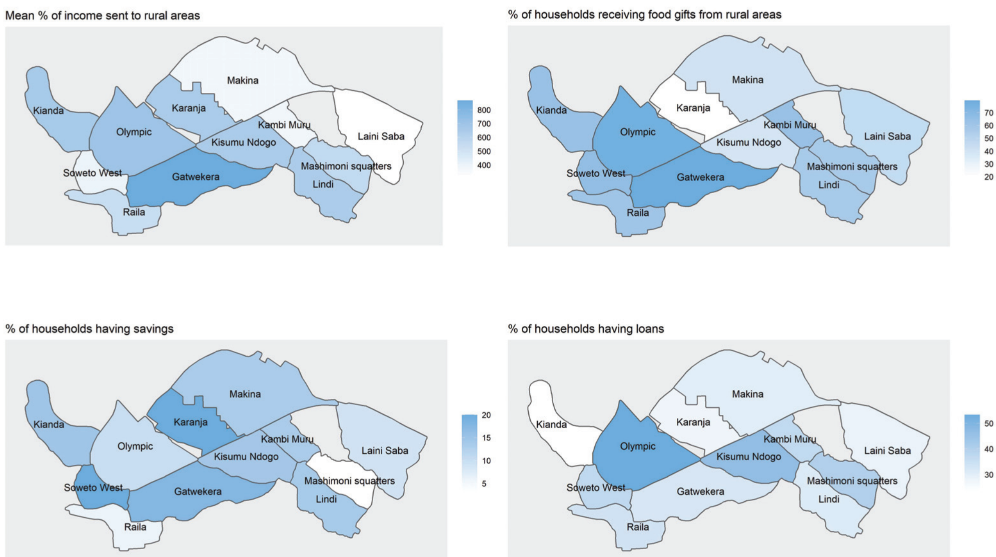

Figure 7. Comparing spending and loans welfare factors across 12 villages in Kibera.

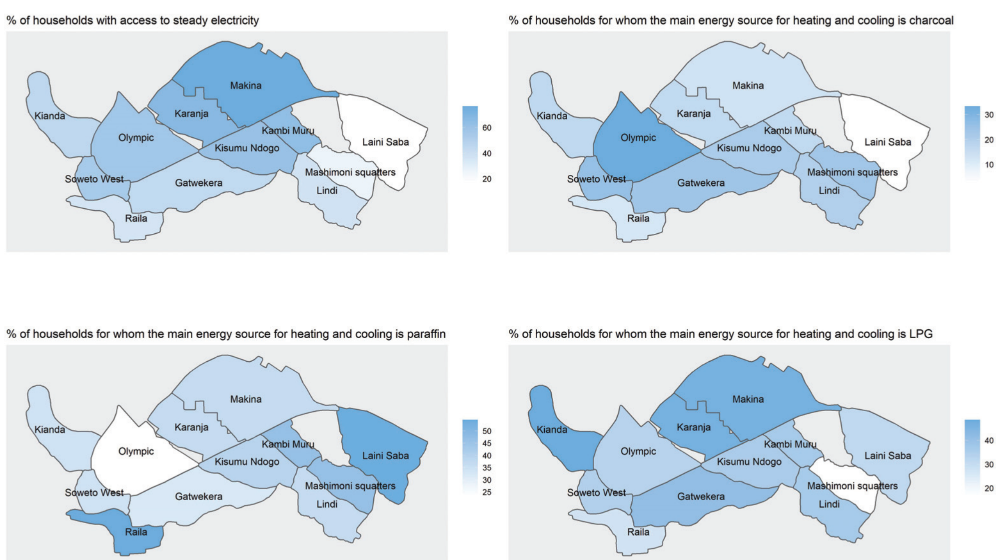

Figure 8. Comparing electricity access and sources across 12 villages in Kibera.

4.3. How Do Trust Levels Differ for Various Actors across the Villages of Kibera?

Trust levels. The level of trust was identified by asking the household heads to judge on a scale of 1–5, for which 1 is the lowest and 5 the highest trust level. On average in Kibera as a whole, people had the highest trust in people from the village (3.01), followed by trust in the national government (2.43) and the county government (2.27). The lowest trust was given to local politicians (2.01) and strangers (2.05) (Table A1).

Looking at differences across the villages, although all of the villages gave high scores to people from the village, the trust in people from the village was significantly higher in Mashimoni Squatters compared to the other villages (3.40) (see Appendix A). In addition, for the trust in national government, the Mashimoni Squatters provided a significantly higher score (2.97), whereas trust in the national government was significantly lower than average in Raila (2.06). Moreover, the trust levels of the county government varied to a great extent across the villages, with significantly higher scores compared to the average in Kibera in Mashimoni Squatters (2.62), Gatwekera (2.59) and Karanja (2.62), and significantly lower scores in Kambi Muru (1.90), Olympic (1.85) and Raila (1.91). Gatwekera informed of a significantly higher trust level of local politicians (2.32) compared with the average level in Kibera. Regarding community leaders, trust was significantly higher in Makina (2.93) but significantly lower in Laini Saba (2.06) and Soweto West (2.09). Finally, trust in strangers was only significantly higher in Laini Saba (2.54) (see Figure 9).

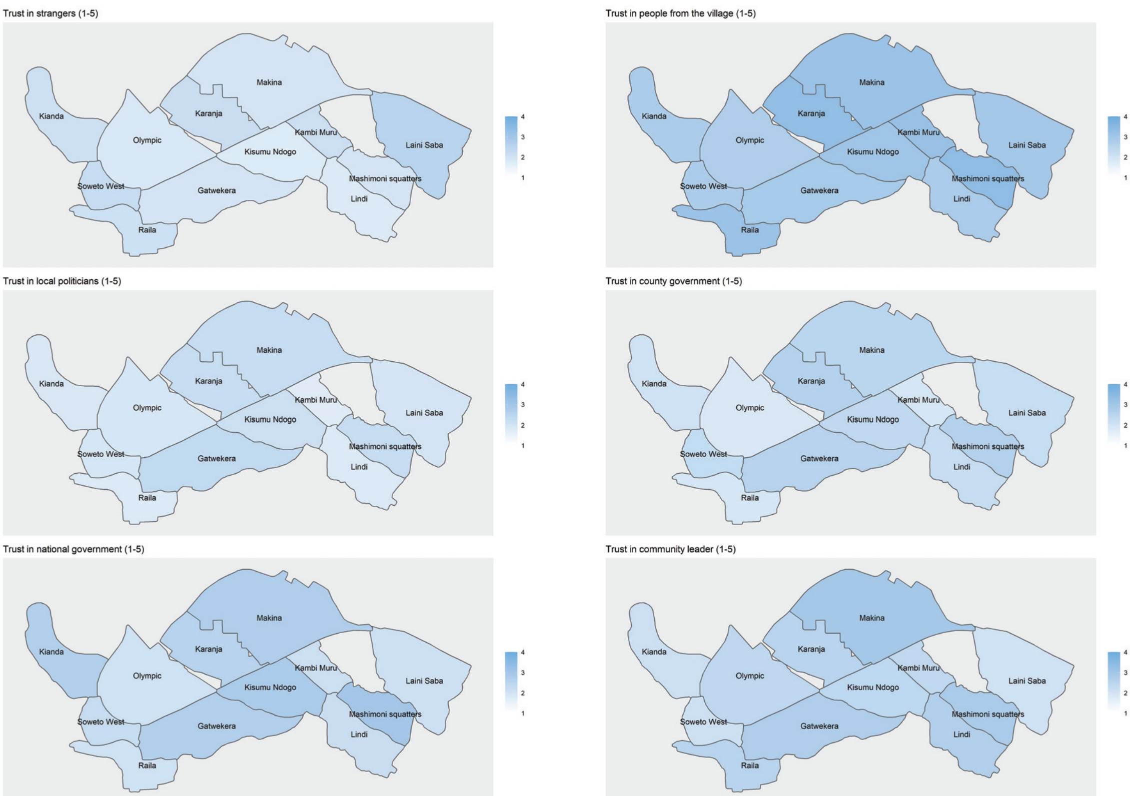

Figure 9. Comparing trust levels across 12 villages in Kibera.

4.4. To which Extent Do Levels of Food Insecurity Vary across the Kibera Villages?

Food insecurity. Looking at the food insecurity access scale (HFIAS) score in Kibera as a whole, the average was 7.93. The food security status was further classified into four groups, for which the highest shares of the population fell in the categories; mildly food insecure (41%) and moderately food insecure (43%). In the categories severely food insecure and food secure, the shares were 3% and 13%, respectively. It was significantly higher compared to the average in Laini Saba (9.40) and significantly lower in Lindi (6.13), Karanja (6.20) and Makina (6.37) (Table A1). In addition, the villages Mashimoni Squatters (9.23) and Raila (9.27) were relatively food insecure according to these estimates, although not significantly different from the average (see Figure 10).

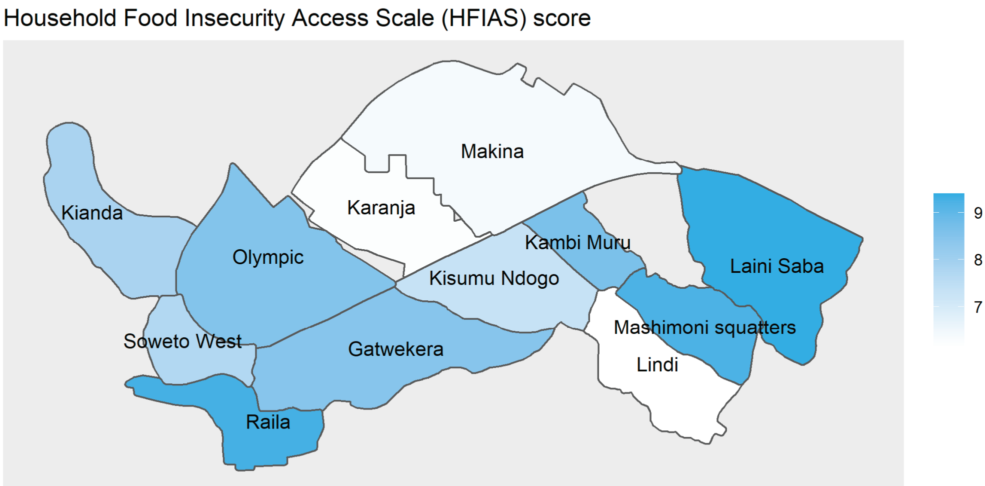

Figure 10. Comparing food insecurity across 12 villages in Kibera.

Food security is only one of several outcomes in a food system approach (Figure 1). In this study, food security is addressed in terms of access to food. As such, the outcome of a food system in terms of 'safe and healthy diets' has not been addressed directly, but the 'inclusiveness and equitable benefits' outcome has been addressed to the core, and the 'sustainability and resilience' outcome has been addressed in terms of source of energy, thus linking this with climate change.

It is unclear how to judge the average absolute HFIAS value to be low or high (7.93) on a scale from 0 to 24. Reasoning from the results of this study, however, it is confirmed that the average income (Figure 6) per household member (Figure 5) adds up to EUR0.95 per day (i.e., 95KES per day). Based on the literature, it appears that while Kibera has provided cheap housing for thousands of Nairobi residents, an endemic poverty exists in the informal settlements with more than half of the households living below the official poverty line of USD1 per day, which must also cover non-essentials such as water, healthcare and education [37]. Given this low share to be spent on food, the absolute value is thus reflected in a location with high food insecurity.

Reflecting on the 'inclusiveness and equitable benefits' outcome of a food system, it is confirmed that a large variability exists within slums such as Kibera. Note that this study was conducted during the COVID-19 epidemic, so the reasons for low food access could be explained by this. However, it appears that for Laini Saba, a total of 17 welfare factors differs from the average, including less land owned in rural areas, lower income, lower education, low household sizes, low connection with neighbors and higher trust of strangers. Laini Saba is also dominated by different tribes with less connection to Western Kenya. At the other end, the Olympic village seemed to be at the higher end in Kibera, with higher income and education levels compared to the average in Kibera, and with more loans and more food gifts. The knowledge of diversity within Kibera is critically important to projects, programs and investments targeting the most food-insecure people.

Looking at the use of an energy source as indicator of the 'environmental' and 'resilience' outcomes with a focus on climate mitigation and adaptation levels, the variability across Kibera villages is high. The use of LPG is the most sustainable alternative for an energy source in Kenya, because it emits less carbon-dioxide than most conventional fossil fuels and no black carbon, which is the second biggest contributor to climate change [38]. In Kibera, the variability of energy use is low across the villages, and the average among household users is estimated to be 36%. A large share of the households (48%) has access to steady electricity, and may tap this from the Kenyan electricity network, which is sourced from hydro and fossil fuel (thermal) and may provide the second-most climate friendly option [39]. Moreover, paraffine is used by almost equally as many households (40%), which is not a good option for the climate because it releases carcinogenic substances when it burns and creates air pollution and toxic fumes when it encounters oxygen in the water or air [40]. As many as 20% report that they make use of charcoal, which not only releases planet-warming greenhouse gases into the atmosphere, but also accelerates biodiversity loss. The potential to increase sustainability and resiliency in Kibera is huge.

5. Discussing Differences in Livelihood Welfare Factors across Kibera and Food System Outcomes

According to the literature, the food situation in Kibera is characterized by households running out of food items to feed children, reliance on a limited number of foods, running out of money to buy food, cutting the size of meals or skipping meals due to lack of money to buy food and children going to bed hungry [15]. The issue of food insecurity becomes even more critical when the issues of orphans and victims of HIV-AIDs comes into the picture [41]. Cases of lack of important nutrients and micronutrients are reported, while possible contamination of food due to poor hygiene and sanitary conditions have been reported to be the cause of high infant-mortality rates [3,41]. Poverty is further manifested in a lack of access to basic requirements including water, electricity and sanitation [7,37].

Kibera slid into poverty in the late 1930s, which to a great extent was caused by the shortage of clean water becoming the biggest challenge [37]. After World War II and after Kenya's independence from British colonial rule in 1963, rural to urban migration and the severe housing shortages in Nairobi caused an influx of Africans renting houses from the Nubians in Kibera [7,37]. Subsequently, the Government of Kenya upgraded Kibera by dividing it into villages, lowering the status of the housing units of the Nubians, and building residential housing in part of the areas, leaving the present Kibera for Kenyan tribes to settle [37]. The literature does not inform about discrepancies of food security and livelihood factors across the villages in Kibera.

Differences across the Kibera villages. Aiming at analyzing the differences in livelihood factors across the villages in Kibera, and to explain some of the existing discrepancies in food security levels among its population, this study has unraveled some critical discrepancies to consider in further transitioning towards the Sustainable Development Goal 2 (SDG2): zero hunger. Some of the differences can be explained by the different tribes in Kenya, which can be clustered according to the degrees to which their language has similarities, and traditionally join efforts during conflicts and elections. As such, the Luo, Luhya and Kisii tribes in Kibera all have roots in Western Kenya and share similar backgrounds. Likewise, the Kikuyu and Kamba tribes hold similar relationships, both originating from the mountain areas north of Nairobi and eastern part of the country, respectively. In addition, there is a tribe referred to as the Nubians, consisting of an Islamized mix of Nubian people of Sudanese, Ugandan and Congolese origin [7]. The Nubians were World War I veterans given temporary residence permits by the British colonial government between 1912 and 1934 to avoid provocations in native reserves occupied by indigenous ethnic groups of Kenya [7,42].

According to the literature, most landlords are Kikuyu and Nubians [43]. It is therefore striking that Laini Saba, with the highest share of Kikuyus, represents the very poorest of the villages. Looking at the results (Table A1), in Laini Saba the food insecurity index scored the highest, and they have the lowest ownership of land in rural areas, as well as lowest income and education level, lowest sharing of cultural practices, fewest visits to Western Kenya and lowest access to stable electricity compared with the average in Kibera. Moreover, they use almost no charcoal but more paraffin than average, while they trust strangers more and community leads less than the average household head in Kibera. The explanations of this confirm that strong links with rural areas, including ownership of land, as well as close relationships with the neighbors are increasing food security. In addition, while Kikuyus are more represented in Laini Saba (23%) than in other villages, there are more Kambas (34%), and this consequently affects the outcomes of the study.

The other tribe which highly differs from the rest is thus the Nubian tribe, who foremost live in Karanja, representing 43% of its sample population. The inhabitants of Karanja are found to have lived more years in Kibera than average (31.7 years), with the lowest connection with Western Kenya (40% of the population) and owning less land in rural areas than average (33% of the population). These findings can be explained by the literature. The Nubians were the original settlers to Kibera, for whom the original name was Kibra which means a bushy place or land of forest [7]. The initial judgement by the British who considered the Nubians a better class of African, with the Nubians themselves living with higher standards in the same way as white people at the time, created an impetus for future challenges with the Kenyan indigenous population [44]. The change of administration in the Kibera area in the beginning of 1928 from a military to civil society was lacking local authority to administer the area, which led to an administrative grey area where tax was not collected. This opened the area up to the indigenous tribes of Kenya who intensively moved into Nairobi in search of work [45]. Given the difficulties in resettling the Nubian population in Kibera, the government stopped distributing residence permits to family members of the war veterans and neglected the steady supply of water and sewerage to force the residents to resettle elsewhere, with an intention of eventually dismantling Kibera as a housing site and opening the area for the expansion of Nairobi City [6,44].

In all the other villages, the Luos or Luhyas are highest represented. Often both tribes are highly represented, although the Luos dominate the most in Gatwekera (76%), and the Luhyas in Kambi Muru (77%). The most discrepant villages in this category according to the welfare factors investigated are the villages Gatwekera, Mashimoni Squatters and Olympic. In Gatwekera, the inhabitants are more than average connecting with Western Kenya, with significantly higher ownership of rural land, sending of income and receiving food gifts in return. They are also more frequently marrying and trusting the county government and local politicians more than other villages. Looking at the income and education level, Olympic is the most well off, receiving more food gifts than average from rural areas, and having more access to loans. Both the Olympic, which is dominated by Luos, and the Mashimoni Squatters, which is dominated by Luhyas, have a significantly larger number of household members than average. However, the Mashimoni Squatters share less cultural practices among neighbors, and have lower education, lower savings, lower access to electricity, but have more trust in people from the village, the national government and the county government than average. The village most in line with the average of Kibera is Kisumu Ndogo, for which only two variables differed significantly from average, namely stronger connection with Western Kenya and receiving food gifts more frequently.

Food system outcomes. Following the logic of the food system approach, the vulnerability of the urban population to food insecurity can be compounded by climate change, rising food prices, emergencies and shifting demographics [4]. A food system approach is designed to cover interrelationships and complexities, for which food security is only one of several outcomes explaining its resiliency (Figure 1) [17,18]. The complexities in Kibera must be regarded as relatively high [27]. In the following, the reasoning covers the main outcomes of the food system: (1) food security, (2) sustainability and resiliency and (3) inclusiveness and equitable benefits.

First, *food insecurity* variability across the villages was confirmed in this study (Figure 10), with Laini Saba counting as the most food insecure, and Lindi as the relatively most food secure village. The rural inhabitants of Kenya are migrating into Kibera in search of employment and cheap housing. The villagers of Kibera confirm the strong correlations between income, employment and food security. Informal micro-enterprises help the Nairobi slum residents fight their way against poverty [7]. Although Kibera is regarded as a settlement with high poverty levels, it has been projected that more than 7300 enterprises exist [16]. Income is largely derived from wage employment and small businesses or micro-enterprises which include selling of groundnuts, fish, or fresh vegetables, preparing and selling street foods, making shoes and furniture, sewing, brewing alcohol, prostitution, selling drugs and medicinal plants, operating kiosks and construction [7,16,46].

Some households practice farming as a source of income, although this is prone to pollution and theft [37,47]. Chickens are the most kept livestock, although ducks, sheep and goats are also common [48]. Sack gardening has been identified as a viable livelihood strategy in Kibera which can improve household food security [37,47]. Most farmed crops include maize, beans, arrow roots, Irish potatoes, pigeon peas, pumpkins, cassava, bananas and sugar cane. As such the main activity for women is self-employment selling vegetables or fish, and cooking local food. On average the income of women is 42% lower than that of men [16]. Furthermore, despite the high levels of poverty in Kibera, studies show that the Kibera population make sacrifices to take their children to low-cost private schools and even pay extra tuition and buy books [7]. Access to viable income, employment and finance to invest are among the main critical factors for change towards increased food security among the inhabitants of Kibera.

Second, to obtain *sustainability and resiliency*, it is necessary to investigate the environmental drivers that are evidently influential to the livelihood of Kibera. The food system approach, integrating sustainability and food security, and addressing rural–urban interrelationships in terms of migration, food access and remittances, is highly useful to increase the understanding of such complex systems [18]. Food insecurity is a matter of sustainability and is highly interwoven with the SDGs [49]. According to the literature, the poverty levels have pushed residents to resort to using sources of fuel such as firewood and charcoal, exposing them to further poor living conditions [42]. In this study, the differences in use of energy source have been analyzed across the villages, showing that Laini Saba has a very different consumption pattern than the other villages, with more use of paraffin, less use of charcoal and with less access to steady electricity. Use of paraffin is also shown to be higher in Raila village, and lower in the Olympic village. Note that the Olympic village reported using more charcoal than any other village based on the sample of interviews. Use of LPG as energy source is rather stable, with only the Mashimoni Squatters using less than average.

Offering alternative sources of energy, for instance such as solar based, could have a large climate impact given the large number of households, if first the households currently using paraffin and charcoal as energy source are targeted. Obviously, poverty alleviation and climate adaptation strategies must go together, as it is not sufficient to target the climate challenges by, for instance, restraining use of charcoal without accessibility to alternative green energy sources for these vulnerable groups [50]. In other words, the bill to pay for climate change lies with the countries and companies who caused it, not the people who have been excluded from the welfare caused by climate change, with no equitable benefits whatsoever [51]. The enhancement of welfare for the people of Kibera should be ensured by zero climate emissions.

Third, *inclusiveness and equitable benefits* are related to the formality of settlements. In Sub-Saharan Africa, 86% of all employment consists of an informal workforce [52]. Based on the literature, informal settlements consist of informal businesses, and informal workers, for which the informal businesses can be defined along three criteria [53,54]: (1) legal informality referring to not officially being registered, (2) fiscal informality referring to non-payment of taxes, an operational bank account and maintenance of bookkeeping, and (3) labor informality referring to lacking contracts and benefits for employees. The informal workforce is employed by the informal businesses. In Kibera, all of these dimensions of informality exist, although informality in this context also covers formality applications in the forms of, for instance, use of a mobile telephone banking and payment system, and registration of companies. However, most residents work for an informal occupation, which is never recorded by official employment statistics.

The explanatory factors of the role of the informal businesses in the economy have been distinguished by the following factors in the literature [53,54]: (1) Exclusion, when businesses are excluded from state benefits due to high entry costs, (2) Exit (escape), when businesses voluntarily choose to operate informally after assessing the costs and benefits of formalization, (3) Dualism, when businesses are forced to operate informally due to the lack of an established formal sector, and (4) Structuralism, when businesses provide low-cost inputs and flexibility to the formal sector. For the Kibera case, the structuralism judgement is highly valid, given the duality in the Kenyan economy, with affordable and accessible food products made available by the informal economy to millions of the inhabitants in Kenya. Moreover, formality is often linked with foreign influence, grounded in the public administration system defined by the colonists, thus outsiders [27]. Notably, in the apparent chaos which externals cannot fully understand, in Kibera the norms and rules are the driving forces, maintaining order and supporting development.

Notably, the informal sector is a container term comprising everything from traditional communities with high social capital, as well criminal gangs, although this share is expected to be very low. This study confirms high levels of social capital in Kibera [21], based on the trust levels confirmed, which are shown to differ across the villages. Cooperation with the informal sector, to strengthen the resiliency of future food systems, will require insights into where and when the social capital is high. This is because with high trust levels, the impacts towards the realization of the SDGs can become significantly stronger.

This survey has contributed to filling an information gap apparent in the Kibera informal settlement. However, because of the informality of Kibera, some challenges appeared with the data collection. For instance, in a few cases, discrepancies existed between the detected location of households by means of a GPS and the village definition. The reasons why include that households belong to villages outside of the defined borders. Note that the areas are small, the whole of Kibera is about 2.5 km^2, and the borders of villages are not formally defined, so human relations appear more definitive than the borders on the ground. Based on the reasoning that the respondents identify with the village of their response more than the physical location of their house, the village names as reported by the respondents themselves were applied instead of the GPS locations in unclear cases. Another limitation of the study is related to the sample size in each village. The average is 32 households per village, which is relatively small to claim the answers are fully representative. However, compared with existing data, the data collected in this study fill urgent data gaps.

6. Concluding Remarks

Kibera can be described as a densely populated informal settlement where residents face a range of challenges including high levels of poverty, food insecurity, insecure land tenure, lack of adequate housing, poor infrastructure and drainage, frequent threats of violence, high crime rates, poor environmental conditions and inadequate access to basic goods and services that include sanitation, health care and education and frequent outbreaks of water-borne diseases [6,9,47].

In this study a food system approach [17,18] is applied to deal with the high complexity levels, to resolve some of the misunderstandings of informal settlements by investigating differences in livelihood factors across the villages in Kibera, and to explain some of the existing discrepancies in food security levels among its population. To reach the Sustainable Development Goals (SDGs), including SDG1: No poverty, SDG2: Zero hunger and SDG11: Sustainable cities and communities, the application of the food system approach in this study assists by providing a holistic approach addressing the complexities of interrelationships of the different factors in Kibera. In a series of maps, it is illustrated that livelihood factors differ across the 12 villages, including income levels, food insecurity levels, access to electricity, ownership of land in rural areas and food gifts received. (Appendix A).

The results of this study, aimed at analyzing differences in livelihood factors across the villages in Kibera, and at explaining some of the discrepancies in food security levels among its population, have shown that:

- The differences across villages in Kibera are large and can be linked with the dominant tribe in the specific village. For instance, two villages (Laini Saba and Karanja) are dominated by tribes with less connectivity to rural areas in Western Kenya, with Laini Saba having a majority of Kamba and Kikuyu tribes who relate to the region of Mount Kenya and Eastern Kenya, and Karanja having most of the Nubians, who are not originally from Kenya, but were World War I veterans given temporary residence permits by the British colonial government between 1912 and 1934 [7,44]. The Luos and Luhyas are tribes from Western Kenya who in varying degrees dominate the other villages. Notably, also within these villages a series of welfare factors differ significantly, for instance, connection with Western Kenya, owning land in rural areas, access to steady electricity and trust in county government;
- The selected income factors differ across the villages, with Laini Saba having the lowest, and Olympic having the highest average income levels. The variability in owning land in rural areas is high, ranging from a total of 69% owning land in Kianda, to only 33% owning land in Laini Saba. In addition, access to electricity varied highly across the villages, for which Makina ranged the highest, with 77% having access, to only 17% having access in Laini Saba;
- The trust levels, ranging from 1 to 5 on a scale where 1 refers to lowest level of trust, and 5 the highest, was shown to be highest for 'people from the village', followed by 'community leader in Kibera'. However, looking at the variability across the villages, the trust in the county government was significantly different from the average for a total of six villages. Only in Laini Saba was the trust in strangers higher than average;
- Food insecurity measured on a HFIAS scale showed variability, with Laini Saba ranging the highest and Karanja, Makina and Lindi lowest, confirming higher food security in these three villages than average.

This study puts the informal settlements high up on the agenda as an area for fighting poverty and hunger, and to shape useful strategies with real impacts on the millions of people living in urban slums all over the world. People from rural areas are confronted with less land available to be split among family members due to generations with large numbers of children, resulting in extensive migration into cities in search for work. Eventually, Africa's population is expected to double by 2050, for which two-thirds of this increase is projected in urban areas [55]. At the same time, the largest share of the world's undernourished people is living in Eastern Africa [56].

With a new world order as a result of the war in Ukraine, it is further of interest to investigate how self-sustainable Kenya is, to feed its future population with reduced grain imports, increased grain and fuel prices because of this war, and the expectation of more frequent draughts threatening future crops.

To reach the millions of people living in informal settlements, it is advised that research and implementation go hand in hand. The approach in this survey can be replicated in future in Kibera to take account of changes over time, or be conducted in any other informal settlement to learn more about the differences in livelihood factors on a larger scale, across Kenya, or Sub-Saharan Africa, to assist any future investment programs aiming at zero hunger. This implies that solutions are searched for in close cooperation with local communities to arrive at affordability and accessibility of food products for low-income groups. To obtain real impacts, an in-depth understanding of the food system, including food security and resiliency and sustainability interrelationships, can ensure today's policies and programs will contribute to fight poverty and hunger in a sustainable manner in future. Against this background, further research is advised on the following selected topics:

- Outcomes of the food system were investigated in this study along with food security, inclusiveness and equitable benefits and sustainability and resiliency, but did not directly take safe and healthy diets into account. Although this was covered more substantially in the paper by Ayuya et al. [20] on fish nutrition in Kibera, it is recommended to further investigate safe and healthy diets, including the consumption of indigenous vegetables in informal settlements;
- To achieve higher welfare with no increase in climate emissions it is recommended to investigate bottlenecks such as access to finance and access to affordable green energy-based innovations and their differences across villages, as well as to analyze the climate and welfare impacts of such innovations;
- To achieve real impact, the informal economy must be understood and recognized as an equal partner. It is advised to investigate the potential to invest and set up business opportunities among the lowest income groups, in communities with high social capital [21].

Supplementary Materials: The following supporting information can be downloaded online. Video S1: Documentary of Kibera (Kibra): https://www.youtube.com/watch?v=K_goJu2encg&t=7s; Video S2: Documentary of Nyeri-Kibera food system: https://www.youtube.com/watch?v=b4oGoYuCnJ0.

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Institutional Review Board Statement: The data collection adhered to the Egerton University Data Policy.

Informed Consent Statement: The research sought informed consent from respondents by using a consent form during the interviews. Further, all research assistants were trained on ethical procedures and measures to protect confidentiality.

Data Availability Statement: All the data used in this survey is listed in Appendix A.

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Appendix A. Statistical Tests of Discrepancies between Livelihood Factors in a Village and the Average in Kibera

Table A1. Means of livelihood factors across 12 villages of Kibera. Stars indicate the p-value of the t-test on the difference in means between of the village of interest and the other villages within Kibera, where + = $p < 0.1$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

	Kibera (total)	Gatwekera	Kambi Muru	Karanja	Kianda	Kisumu Ndogo	Laini Saba	Lindi	Makina	Mashimoni Squat-ters	Olympic	Raila	Soweto West
Figure 3: Households (hh) origin (tribe)													
% of hh belonging to the tribe Luhya	34%	12% **	77% ***	13% *	20% +	46%	9% ***	47%	60% **	67% ***	17% *	33%	20% +
% of hh belonging to the tribe Luo	33%	76% ***	0% ***	27%	43%	43%	6% ***	30%	7% **	17% *	63% ***	36%	49% *
% of hh belonging to the tribe Kikuyu	4%	0%	0%	7%	0%	0%	23% ***	3%	0%	3%	0%	3%	9%
% of hh belonging to the tribe Kisii	12%	9%	0% *	0% *	37% ***	7%	6%	0% *	7%	0% *	10%	30% ***	26% **
% of hh belonging to the tribe Nubian	8%	0% +	10%	43% ***	0% +	0%	3%	13%	23% ***	3%	0%	0% +	0% +
% of hh belonging to the tribe Kamba	8%	3%	10%	3%	11%	7%	34% ***	10%	0% +	3%	10%	0% +	0% +
Figure 4: Household (hh) practices													
Mean years hh lived in Kibera	20.7	21.47	21.2	31.7 ***	15.4 *	19.4	22.4	21.1	21.4	24.5	17.9	12.8 **	19.9
% of neighbors sharing the same cultural practices	45%	67% ***	42%	40%	44%	43%	38% +	51%	42%	38% +	48%	49%	42%
Mean number of times hh visit their rural area per year	1.60	1.44	1.33	2.63 **	1.69	1.64	1.60	1.77	0.93 +	1.47	1.57	1.42	1.66
% of hh head who connect with Western Kenya	75%	97% **	77%	40% ***	89% *	89% +	20% ***	77%	63%	87%	83%	88% +	89% *
Figure 5: Household (hh) characteristics													
Household size	4.63	4.50	4.20	4.90	4.50	4.60	4.00 +	3.80 *	4.40	5.80 **	5.20 +	5.10	4.70
% of hh heads who have secondary education (from 4–6 years) or higher	48%	47%	57%	60%	49%	57%	29% *	60%	47%	27% *	77% **	42%	37%
% of hh heads who are married	67%	85% *	57%	63%	77%	68%	57%	67%	70%	60%	67%	73%	63%
% of hh heads who are female	3%	0%	0%	3%	6%	4%	0%	3%	7%	3%	3%	3%	0%

Table A1. *Cont.*

	Kibera (total)	Gatwekera	Kambi Muru	Karanja	Kianda	Kisumu Ndogo	Laini Saba	Lindi	Makina	Mashimoni Squat-ters	Olympic	Raila	Soweto West
Figure 6: Household (hh) welfare													
Mean monthly income (KES)	13,094	14,726	12,555	14,827	12,267	12,411	9840 *	14,703	15,578	10,843	17,053 *	11,506	11,684
% of hh for whom their income is enough	36%	47%	27%	37%	34%	25%	34%	50%	47%	27%	33%	42%	31%
% of hh owning land in rural areas	51%	65% +	67% +	33% *	69% *	54%	31% *	33% *	37%	63%	50%	52%	51%
Mean land size in rural areas (hectares)	1.41	1.97	1.74	1.85	1.10	1.03	1.31	3.33 **	0.83	1.27	1.43	1.06	0.78
Figure 7: Household (hh) spending and loans													
Mean % of income sent to rural areas	6%	9% *	4%	6%	7%	6%	3% *	6%	4%	6%	7%	5%	4%
% of hh receiving food gifts	56%	79% **	63%	20% ***	63%	39% +	46%	57%	40% +	57%	77% *	61%	66%
% of hh having savings	13%	18%	13%	20%	15%	14%	9%	14%	13%	3%	10%	6%	20%
% of hh having loans	35%	32%	37%	28%	24%	46%	29%	31%	30%	40%	53% *	33%	37%
Figure 8: Household (hh) use of energy source													
% of hh having access to steady electricity	48%	44%	63% +	67% *	46%	61%	17% ***	37%	77% **	27% *	57%	36%	54%
% of hh using of charcoal as energy source	19%	24%	17%	17%	17%	21%	3% *	20%	13%	23%	33% *	12%	26%
% of hh using paraffin as energy source	40%	32%	47%	37%	34%	39%	54% +	37%	37%	47%	23% +	55% +	34%
% of hh using LPG as energy source	36%	41%	37%	47%	49%	36%	31%	37%	47%	17% *	33%	27%	34%
Figure 9: Trust relations on a scale from 1 (low) to 5 (high)													
Trust in strangers (1–5)	2.06	1.97	2.13	2.17	2.11	1.75	2.54 **	1.79	1.97	1.97	1.87	2.09	2.26
Trust in people from the village (1–5)	3.01	2.88	3.20	3.30	2.77	3.04	2.94	2.83	3.13	3.4 +	2.73	3.15	2.77
Trust in national government (1–5)	2.42	2.64	2.130	2.57	2.66	2.79	2.09	2.17	2.72	2.97 *	2.07	2.06 +	2.24
Trust in county government (1–5)	2.27	2.59 +	1.90 +	2.62 +	2.06	2.39	2.23	2.27	2.47	2.62 +	1.85 +	1.91 +	2.30
Trust in local politicians (1–5)	2.01	2.32	1.70	2.23	1.86	2.14	1.97	1.83	2.27	2.23	1.89	1.82	1.91
Trust in community leader (1–5)	2.46	2.73	2.37	2.53	2.15	2.44	2.06 +	2.63	2.93 *	2.80	2.43	2.52	2.09 +
Figure 10: Food insecurity													
Hh Food Insecurity Access Scale (HFIAS) scores	7.97	8.47	8.63	6.20 *	7.89	7.36	9.40 +	6.13 *	6.37 +	9.23	8.50	9.27	7.71

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Article

The Contribution of Oil Palm Smallholders Farms to the Implementation of the Sustainable Development Goals-Measurement Attempt

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Abstract: Smallholder oil palm plantations play an essential role in the Indonesian economy, both on a national, regional, local, and household scale. However, no data or studies show how much smallholder oil palm plantations contribute to achieving in each sustainable development goals (SDGs). The development of smallholder oil palm plantations, like other economic developments, wherever conducted needs to provide benefits to the community such that it exceeds the costs incurred, including the costs of preserving and protecting the environment. To assess its contribution, it is essential to examine the Sustainable Development targets in which smallholder oil palm plantations contribute. Therefore, this study is aimed at examining sustainable development goals to which smallholder oil palm plantations can contribute. Based on focus group discussion and the literature review, there are 13 SDGs for smallholder oil palm plantations that contribute and play a role in achieving the targets set by the United Nations in sustainable development. These results are significant as a basis for further studies to prove the presumption concerning the role and positive contribution of smallholder oil palm plantations in each of the existing SDG targets.

Keywords: palm oil; SDGs; smallholders

1. Introduction

According to data from the Indonesian Central Statistics Agency [1], plantations are an important sub-sector in the Indonesian economy, contributing around 3.27 percent in 2019. In total, the export value of plantations reached US$25.38 billion, and palm oil and its derivative products constituted the main contributor. Even ref. [1] reported that the increase in exports of processing industrial products by 20.67 percent was contributed by an increase in exports of palm oil. A wealth of data proves that oil palm expansion into poor and remote areas lifts these areas from poverty and becomes centers of local economic growth. Now, the spread of oil palm covering 26 provinces from 34 provinces makes oil palm plantations an essential component in economic growth and sustainable village development, especially in reducing poverty in villages. BPS data also informs that poverty and inequality in Indonesia tend to decrease. In March 2021, the poverty rate in Indonesia was 10.14%. The percentage of the rural poor was 13.10%, down from 13.20% in September 2020. However, this poverty reduction performance has not been able to clearly show the contribution of oil palm plantations, especially in the achievement of other Sustainable Development Goals (SDGs). One of the main reasons is the variety of sources of household income in rural areas, not only from oil palm. This question needs to be answered because governments uses the SDG to combat extreme poverty by ensuring sustainable environmental, economic, and social development [2].

Various literature reveals that the SDG aims to eliminate poverty in all its forms by 2030. For example, refs. [3,4] explain that the SDG goal is a step of change to improve the welfare of the poorest people in the world. This concept provides a reasonable justification for assessing the impact of oil palm plantations, especially for oil palm farmers who are the main actors in developing oil palm plantations. Several studies have been conducted to examine the contribution of oil palm in achieving the SDG, which has also been discussed qualitatively and macro, among others by [5–9]. However, this study has not revealed in detail and comprehensively the contribution of oil palm plantations to poverty alleviation, let alone for other relevant SDGs goals. For example, although they quantitatively reveals the role of oil palm plantations in reducing inequality and poverty, they do not show the role of oil palm plantations in other SDGs targets. As shown by TNP2K, oil palm plantations contribute to achieving other SDGs targets, such as eliminating hunger and fighting climate change.

The studies that specifically examines the contribution of oil palm plantations to achieving the SDGs goals is challenging to find. The studies conducted by [5,7,8] reveal more about the role that oil palm plantations plays in achieving the SDGs, including in absorbing labor and initiating the regional economy. However, their research does not explain the role or contribution of smallholder oil palm farmers to any sustainable development goals. In other words, their research does not clearly explain the contribution of smallholder palm oil to any of the SDGs. In addition, a study conducted by Saragih et al., (2020) [10] on the sustainability of oil palm development has not revealed clearly and in detail the link between the dimensions used and the SDGs. However, several studies related to the achievement of the SDGs have also been conducted, including the analysis of [11] on cement companies in Mexico, [12] on gender equality in Tanzania, and [13] on the role of sustainable financial innovation in Europe. Once again, these studies examine the role of sectors in achieving one of the SDGs, except for [13] survey on more complex goals. This information shows the importance and openness of exploring the role of oil palm plantations, especially smallholder oil palm plantations, in achieving the SDGs comprehensively. Furthermore, this is important, according to [14], SDGs and the effectiveness of policies designed and implemented to achieve each goal are also interrelated. Ref. [15] added that interactions between the SDGs could be positive and negative, usually influenced by key factors such as geographic context, resource support, time horizon, and governance.

This study examines and discusses the role of smallholder oil palm in the achievement of sustainable development goals, more precisely, examines what sustainable development goals (SDGs) are to which smallholder oil palm can contribute. The following section briefly describes the methodology used to identify the relevant SDGs, and is followed by a discussion of the literature review on the development of smallholder oil palm and the role of the agricultural sector in achieving the SDGs. The next section of this study discusses the relevant SDGs in which smallholder oil palm plantations can play a role in achieving the SDGs. The last section presents conclusions and recommendations for future research.

2. Methods

The method used in this study is focus group discussion (FGD) among the authors. This FGD was directed to identify the relevant SDGs to which smallholder oil palm is possible to contribute to their achievement. This FGD also invited two competent resource persons to provide a broader picture of sustainable development in Indonesia, particularly an overview of the role of oil palm plantations in achieving sustainable development goals. The results of this FGD activity are complemented by various literatures that are most relevant to the identified SDGs. The literatures used were obtained from various publications, both published in Indonesia and/or from other sources.

3. Literature Review

3.1. The Development of Indonesian Oil Palm Smallholders: A Brief Overview

Oil palm originates from the tropical rain forests of West Africa, where this plant has been commercially cultivated in Indonesia since 1911 on the east coast of Sumatra under Dutch rule [16]. Ref. [17] reported that the area of the first plantation, established in 1910–1914, was 2620 ha. This oil palm plantation area increased to 6920 ha in 1919 and continued to increase until 1936, when the total planted area reached 75,000 ha, of which 63,234 ha were productive crops. After that, there was no significant development of oil palm plantations until the 1970s, when state plantations and large private plantations controlled oil palm plantations.

Indonesia's oil palm plantations increased significantly after the 1970s, following the implementation of the Perkebunan Inti Rakyat (PIR) development scheme (PIR or NES = Nucleus Estate Scheme). This scheme was developed for one reason, as [18] stated, namely that establishing an oil palm plantation requires a large amount of capital that is affordable by only large companies. In this scheme, refs. [19–21] explain that state-owned plantation companies (called nucleus plantations) assist smallholders such as plasma smallholders in developing oil palm plantations. The core company provides seeds, technical assistance, and financing to plasma farmers and purchases the plasma farmers' produce. This PIR pattern was developed with three designs, namely PIR-local, PIR-special, PIR-trans, and integrated with population redistribution policies through resettlement or transmigration schemes to provide labor for new plantations [22]. Furthermore, according to [23], the PIR pattern continues to develop with various partnership patterns, including the Primary Cooperative Credit to Members (KKPA) pattern and plantation revitalization.

Along with the ease of plating and the promising prospects of oil palm, people around large plantations have begun to learn to grow oil palm independently. Furthermore, this has led to the rapid development of smallholder oil palm plantations in Indonesia. Ref. [24] publishes that of Indonesian oil palm plantations covering an area of 16,381,959 ha, 40.79% are people's plantations, while 54.94% are large private plantations and the rest are state plantations. The people's plantation area has increased sharply compared to 1982, which only reached 2% of Indonesia's total oil palm plantations. Of the total oil palm plantations, 80% are mature plantations, while the remaining 14.76% are immature plantations, and 3.22% are non-yielding plantations. These community plantations involve 4,427,273 farmers or 2,566,066 farmer households [24].

Furthermore, these oil palm plantations create no less than 12 million indirect jobs. In terms of production, in 2021, the contribution of large private plantations is estimated to be still the main contributor with a share of 62% or 30,728,504.00 tons, followed by smallholder plantations at 16,755,437.00 tons or 34% of the total production in 2018 [24]. However, smallholder oil palm plantations also face problems, especially low productivity besides the age of the oil palm plantations.

According to [25,26], smallholders' average oil palm production is significantly lower than large oil palm plantations. [27] also reports that Indonesia's CPO productivity is around 3–4 tons/ha, much lower than Malaysia's 4–10 tons/ha. Ref. [27] also added that from 5.61 million ha of smallholder oil palm area, 2.4 million ha consisting of 1.5 million ha of independent oil palm and 0.9 million ha of plasma oil needed to be immediately rejuvenated.

3.2. Agriculture and Sustainable Development Goals (SDGs)

Ref. [28] expressed that Sustainable Development has become a ubiquitous development paradigm that is often used as a slogan for international aid agencies, jargon for development planners, conference themes, academic papers, and slogans for development and environmental activists. The implementation of sustainable development based on a new approach to how to regulate and organize the economy should become an essential and natural part of everyday practice [29–31] added that the concept of sustainable development had attracted widespread attention compared to other development concepts, refs. [32–35] argue that sustainable development ensures that the current use of resources does not deprive future generations of social, economic, and environmental benefits. In contrast, ref. [36] views sustainable development as development that meets the needs of the present generation without compromising the needs of future generations.

Furthermore, sustainable development was measured using a three-dimensional approach, namely social, economic, and environmental. Specifically related is the conservation of ecosystems and biodiversity, production systems, population control, human resource management, preservation of progressive culture, and community participation [37]. Sustainable development results are an increase in economic growth, social justice, good environmental management, and better governance. Measuring sustainability is very important because it helps assess whether a country or company progresses or vice versa in a certain period [38].

In 2015, the United Nations General Assembly adopted the Sustainable Development Goals (SDGs), which form the core of the 2030 Agenda for Sustainable Development. The SDGs agenda has 17 goals and 166 targets used as the basis for the world to carry out sustainable development and direct global development strategies until 2030 [39]. The seventeen goals include SDG1: No poverty, SDG2: No hunger, SDG3: Healthy and prosperous lives, SDG4: Quality education, SDG5: Gender equality, SDG6: Clean water and proper sanitation, SDG7: Clean and affordable energy, SDG8: Jobs sustainable development and economic growth, SDG9: Industry, innovation, and infrastructure, SDG10: Reducing inequality, SDG11: Sustainable cities and communities, SDG12: Responsible consumption and production, SDG13: Addressing climate change, SDG14: Marine ecosystems, SDG15: Land ecosystems, SDG16: Peace, justice and strong institutions, and SDG17: Partnerships to achieve the SDGs.

In more detail, it is known that the achievement of the SDGs cannot be separated from the agricultural sector. Several SDGs out of 17 SDGs are directly or indirectly related to agriculture, as stated by [40–42], who also concluded that food and agriculture are the core issues of the 17 SDGs. It also shows the multidimensional role of the agricultural sector in achieving the SDGs. Furthermore, ref. [43] explains that food and agriculture are essential for achieving the 2030 Agenda for Sustainable Development. The important role of food and agriculture in achieving the SDGs starts from SDG1 and SDG2, namely ending poverty and hunger. Food and agriculture also have a role in SDG11 and SDG14, namely tackling climate change and preserving natural resources. Ref. [44], by adapting [40], explains that there is at least a link between the eight goals in the SDGs and agriculture. These eight goals are SDG1: No poverty; SDG2: No hunger; SDG6: Clean water and sanitation; SDG7: Affordable and Clean Energy; SDG12: Responsible consumption and production; SDG13: Action against climate change; SDG14: Life underwater; and SDG15: Living on land. In contrast to [40,44,45] of the SDGs, this study also proves that each commodity in the agricultural sector contributes to the achievement of different SDGs.

Several studies have tried to examine the contribution of the agricultural sector to the achievement of the SDGs; however, none of these studies have quantitatively and in detail analyzed the contribution of the agricultural sector. The contribution of agriculture to the eight SDGs, as expressed by [44], has also never been performed. Some of the studies conducted are still partial, namely only on a few SDGs. For example, study [46] reviews the role of smallholders concerning the Sustainable Development Goals (SDGs). The dual function of smallholders in adopting the SDGs and their socio-economic limitations make it difficult for them to meet expectations as drivers of sustainable development. Ref. [46] shows that 13 SDGs and their respective targets address these socio-economic limitations. Nevertheless, this study does not quantitatively explain the contribution of smallholders in achieving the SDGs.

Furthermore, a study in South Africa conducted by SADC (2013, 2016) [47,48] suggests that economic growth, poverty reduction, and food security are significantly affected by the performance of the agricultural sector, which is an essential source of livelihood both directly and indirectly for more than 60% population in South Africa. This finding also confirms the importance of the agricultural sector to the achievement of the SDGs. The results of this literature review also indicate the importance of assessing the role of agriculture, especially smallholders, including oil palm smallholders, in achieving the SDGs.

4. The Contribution of Indonesian Palm Oil Smallholders in SDGs: An Overview

As previously stated, the number of oil palm smallholders is quite large, with the second-largest land area after large private companies. In terms of employment, small farmers also involve more than 4.4 million people or 2.5 million households. This data shows the important role of smallholder oil palm farmers in alleviating poverty and increasing food security, as mandated in the SDGs. Ref. [49] discussed the importance of smallholders where these planters are the backbone of food security in developing countries. According to [49], they contribute up to 70% of national food production and 30–34% of total world food production.

Regarding plantations, including smallholder oil palm plantations, Law No. 39 of 2014 concerning plantations mentions the multifunctionality of plantations. Based on this law, ref. [9] stated that there are three functions of plantations, namely economic, ecological and socio-cultural functions. Thus, the role of smallholder oil palm plantations in sustainable development is clear. This role was also seen from the objectives of organizing plantations, including improving the welfare and prosperity of the people, providing employment, developing responsible and sustainable plantation resources, providing sources of raw materials for downstream industries, and maintaining local wisdom and environmental sustainability.

The above discussion indicates the importance of smallholder oil palm plantations in achieving the SDGs. However, a study that focuses on the contribution of independent and plasma oil palm smallholders to the achievement of the SDGs is challenging to find. The main reason is allegedly that it is unclear on which SDGs oil palm plantations, especially small oil palm plantations, contribute. Many studies have discussed the significance of oil palm plantations in achieving the SDGs, but focus on only one or two SDGs, including the [6]. Whereas the studies of [46,50–52] suggests that there are multiple goals of SDGs that small farmers play. However, according to [53,54], sustainable development is relative and location- or country-specific for each sector and industry.

Starting from the 17 SDGs and 169 target indicators, this study discusses and examines the 13 SDGs that have the potential to be contributed and played by small oil palm plantations, both independent and plasma plantations in Indonesia. The 13 SDGs consist of (1) No Poverty (SDGs 1); (2) Zero Hunger (SDGs 2); (3) Good Health and Well-being (SDGs 3); (4) Quality Education (SDGs 4); (5) Gender Equality (SDGs 5); (6) Clean Water and Sanitation (SDGs 6); (7) Affordable and Clean Energy (SDGs 7); (8) Decent Work and Economic Growth (SDGs 8); (9) Industry, Innovation, and Infrastructure (SDGs 9); (10) Reduced Inequalities (SDGs 10); (11) Climate Action (SDGs 13); (12) Life on Land (SDGs 15); and (13) Partnerships for the Goals (SDGs 17). Furthermore, the thirteen SDGs are classified into three pillars of the four pillars of sustainable development, namely (1) social development pillar, (2) economic development pillar, and (3) environmental development pillar. The fourth pillar, namely legal development and governance, is less relevant for oil palm plantations to contribute to the achievement of the SDG16 target. The three pillars of development and related SDGs will be briefly discussed as follows.

4.1. Social Development Pillars

The social development pillars in the SDGs are directed at realizing the fulfillment of quality fundamental human rights in a fair and equal manner to improve welfare for the entire community. These pillars include SDG1: No poverty, SDG2: No hunger, SDG3: Healthy and prosperous lives, SDG4: Quality education, and SDG5: Gender equality. As many studies have revealed, the existence of oil palm is enjoyed directly or indirectly by the people of Indonesia, including the world community. For oil palm farmers, the oil palm plantation business that has been conducted has helped them a lot to escape poverty, which is also free from the problem of hunger. Ref. [55] study concludes that the expansion of oil palm plantations has reduced poverty and income inequality in the districts with the largest oil palm plantations. Oil palm plantations have also contributed to poverty reduction by 2.6 million people in rural areas [56,57]. One of the reasons why oil palm grows rapidly is because of its profitability hence, it continues to grow and is difficult to stop [58]. These studies demonstrate the important role of oil palm in achieving SDG1 and SDG2.

Some results, such as [59]'s study using BPS data, discovered that oil palm plantations have improved the welfare of oil palm farmers in Sambas Regency by 172% compared to before the existence of oil palm plantations. Ref. [60] also discovered the same result, where 77% of oil palm farmers in the Central Mamaju Regency were included in the prosperous category using indicators developed by BPS. The State Electricity Company (PLN), and the Regional Drinking Water Company (PDAM) provides easy access to health, fulfill food and non-food needs, as well as provide access to education. Two studies inform the contribution of smallholder oil palm plantations in SDG3 and SDG4.

From a gender perspective (SDG5), smallholder oil palm plantations also provide a place for females to contribute to every on-farm and off-farm activity. The study conducted by [61] discovered the contribution of females in every oil palm farming activity, both in decision making and the implementation of farming activities. In the case of North Sumatra and West Kalimantan, a study by [62] discovered that females are actively involved in working in the garden for approximately 2–3 h per day until the oil palm plants bear fruit at the age of 3–4 years. However, there is gender discrimination in some aspects, especially in access to resources and capital.

Based on the discussion above, possible targets and indicators that were developed and used to assess the contribution of smallholder oil palm plantations to the achievement of the SDGs targets in the pillars of social development are presented in Table 1.

Table 1. Tentative targets and indicators for the contribution of palm oil in achieving the social development pillars of the SDGs.

Targets *	Indicators
SDG1: No Poverty	
By 2030, eradicate extreme poverty for all people and gender, and have equal rights to economic resources and access to basic services.	The poverty rate of oil palm farmers (as percentage of oil palm households living below the poverty line in the survey area).
	Poverty Rate by gender and age group (as percentage of oil palm smallholders living below the poverty line in the survey area, by sex and age group).
	Oil palm smallholder households with access to basic services (Proportion of oil palm households that can access basic services (such as health and education) by gender and age group category).
	The status of the oil palm land obtained is based on legal documents (Proportion of oil palm smallholders who have land rights based on legal documents and who have land rights based on gender and type of ownership).

Table 1. *Cont.*

Targets *	Indicators
SDG2: Zero hunger	
By 2030, eliminate hunger and ensure access for all to safe, nutritious, and sufficient food all year round and achieve sustainable food production and adopt agricultural practices tough that increases production.	The ratio of per capita normative consumption to food availability (the amount of food availability is above the average cutting day of the population and or the proportion of oil palm farmers who have a frequency of eating 3 times a day).
	The proportion of household expenditure on food to total household expenditure (Percentage of household food consumption expenditure for palm oil to total household expenditure).
	The Pola Pangan Harapan (PPH)/Desirable Dietary Pattern (DDP) score indicates the quality of food consumption (composition of food diversity based on the energy contribution of the main food groups and measured by scores).
	The proportion of ownership of agricultural area for productive and sustainable food (Percentage of land ownership planted with food crops, non-oil palm).
SDG3: Healthy and Prosperous Life	
By 2030, ensure universal access to sexual and reproductive health services, including family planning, information, and education, and free from epidemic disease.	Accessibility of oil palm farmers to public health facilities and conditions and the non-existence of epidemic diseases from within the household (Number of palm oil household members infected with HIV, tuberculosis (TB), malaria, hepatitis, and/or leprosy per uninfected household member and the proportion who use health facilities for their disease).
	Proportion of underage married women and ever-married women aged 15–49 years whose last delivery was (a) assisted by trained health personnel; (b) in health facilities (Percentage of underage married women to the number of female family members and the utilization of reproductive health access).
	Oil palm farmer household expenditure on health as part of total household expenditure or income (Percentage of allocation or expenditure on health costs to total palm oil household expenditure).
	Insurance Ownership Health insurance (Percentage of palm oil household members who have health insurance).
SDG4: Quality Education	
By 2030, ensure that all girls and boys complete a minimum, equal, and quality primary and secondary education and have skills relevant to the world's development.	The level of education for members of the oil palm farmer household at the elementary school/equivalent, junior high school/equivalent, and senior high school/equivalent levels (proportion of palm oil household members who have completed education at the elementary/equivalent, junior high/equivalent, and high school/equivalent levels).
	The number of adolescent/adult oil palm farmer household members in a certain age group, proficient/capable of (i) reading and (ii) counting, by gender (Proportion of oil palm household members who achieve at least the minimum proficiency level in: (i) reading, (ii) counting).
	Accessibility of oil palm smallholder household members to formal and non-formal education facilities (proportion of household members who attend available formal and non-formal education).
	The number of adolescent household members (age 15–24 years) and adults (aged 15–59 years) with information and communication technology (ICT) skills (Measured as a percentage of all palm oil households).
SDG5: Gender equality	
End all forms of discrimination against females everywhere.	Females participation in oil palm plantation activities (the proportion of female oil palm household members who work on their own oil palm plantations or not).
	Recognition and appreciation of Females who participate in oil palm (The ratio of the wages received by women working in oil palm plantations compared to the wages of men in the same type of work).
	Life quality of Females in the household (the proportion of female household members who experience domestic violence).

Note: * target and indicators are modified according to FGD results and the scope of the study, namely household scale.

4.2. Economic Development Pillars

Oil palm plantations have provided economic benefits, not only for plantation owners and the economy of the area where oil palm farmers live. Furthermore, this indicates that one of the SDG targets played by smallholders of oil palm plantations is their contribution to the achievement of SDG 8, namely decent work and economic growth. The study conducted by [63] concluded that the development of private and/or state oil palm plantations involving smallholders had improved the regional or regional economy in infrastructure development in rural areas. Although it does not specifically mention smallholder oil palm plantations. However, the expansion of oil palm plantations in West Kalimantan, as reported by [64], has changed the regional economy and social welfare structure as indicated by the increase in the Human Development Index (HDI) and Gross Regional Domestic Product (GRDP) per capita. Even [65] empirically discovered that the development of oil palm plantations in rural areas created a multiplier effect, especially employment and business opportunities, of 3.03. Furthermore, refs. [66–68] concluded that smallholder oil palm plantations have the potential to spur development in rural areas.

Besides increasing rural economic growth and job creation, smallholder oil palm plantations also have considerable potential in achieving SDG 10, namely reducing inequality. Refs. [55,60] state that smallholder oil palm plantations have reduced inequality in the Central Mamaju and districts dominated by oil palm plantations. The same finding shows that the palm oil industry contributes to economic growth, employment, and income distribution [69]. Ref. [70] also discovered that income distribution in oil palm plantation centers is quite good, with a Gini index of around 0.36. Furthermore, to improve the rural economy, the development of smallholder oil palm plantations has created and increased the purchasing power of oil palm farmers in rural areas. This, in turn, will increase the demand for public goods, including energy, and the importance of developing rural infrastructure to improve the accessibility of the area and farming communities. Subsequently, this means that improving the economy and welfare of oil palm farmers allows them to access the resources needed to support their lives. Improving the economy and welfare of oil palm farmers certainly cannot be separated from the role of farmer institutions, such as farmer groups, cooperatives, or extension institutions [68,71–73]. Cooperation between farmers and farmer organizations is also an essential factor for the creation of sustainable oil palm plantation development (SDG17).

Many studies also prove that oil palm plantations developed by the community independently or on a plasma have provided benefits for them. Not only high returns from land planted with oil palm, but smallholder oil palm plantations also provide high benefits from the aspect of labor [74,75]'s study, refs. [68,76] also show that oil palm is more profitable to cultivate than rubber and rice. These studies indicate the role of smallholder oil palm plantations in achieving the SDGs targets, particularly in the pillars of economic development. Table 2 below presents potential targets and indicators in assessing the contribution of smallholder oil palm plantations in achieving the SDGs targets.

4.3. Environmental Development Pillar

Many environmental issues in sustainable development are related to the expansion of oil palm plantations, including deforestation accompanied by loss of biodiversity [77,78]. However, oil palm plantations also contribute to environmental aspects, which includes reducing emissions and absorbing carbon dioxide, and producing oxygen [79–81] having natural biopori to absorb and hold water, rainwater infiltration and reduce surface water runoff [82,83]. Oil palm is also a water-efficient plant compared to several other types of plants [84,85] and oil palm is the most efficient crop (after sugarcane) in water use for every giga joule (GJ) of the resulting bioenergy [86]. These studies conclude that there are many positive aspects that oil palm contributes to environmental development. In other words, oil palm plantations positively contribute to the pillars of environmental development, particularly in both SDG13 and SDG15.

Table 2. Targets and tentative indicators of palm oil contribution in achieving the economic development pillars of the SDGs.

Targets *	Indicators
SDG7: Clean and affordable energy	
Ensure universal access to affordable, reliable, eco-friendly, and modern energy services by 2030.	Access of oil palm farmer households to electrification (Oil palm household electrification ratio).
	Household electricity spending, including electricity consumption per capita (Electricity consumption per capita).
	Accessibility to the use of gas (LPG) for households (Proportion of palm oil households using LPG for energy needs).
	Oil palm farmer households using non-environmentally friendly fuels for their household (Proportion of palm oil households whose main energy source is technology and non-environmentally friendly fuel).
SDG8: Decent work and economic growth	
Promoting supportive development policies productive activities, creative decent employment, entrepreneurship, creativity, and innovation, and encouraging and growing micro, small and medium enterprises (MSMEs), through access to financial services.	Increase employment opportunities in the village through labor absorption in oil palm plantations owned (Proportion of oil palm household members working in the oil palm sector by age and gender).
	Accessibility of oil palm farmers to new growth centers of the economy, including job opportunities outside of oil palm (Proportion of oil palm household members working outside the oil palm sector by age and gender).
	Non-food household consumption of household expenditure (Percentage of household non-food consumption expenditure for palm oil to total household expenditure).
	Accessibility of oil palm farmer households to financial/economic institutions/village-owned enterprises/cooperatives (Proportion of palm oil households that use nearby financial services).
SDG9: Industry, innovation, and infrastructure	
Develop infrastructure that quality, reliable, sustainable, and resilient, including regional and cross-border infrastructure, to support economic development and human well-being, with focus on affordable and fair access for all.	The distance of the oil palm farmer's house to the roadworthy-(The distance of the house from the road suitable for motorized vehicles is categorized as far, medium and close).
	Practices to increase oil palm production through the use of production inputs and waste utilization (GAP = Good Agricultural Practices) (Number of types of good agricultural practices available by oil palm farmers).
	Development of a biomass processing unit through the utilization of available palm oil waste (Number of households utilizing available palm oil biomass).
	Accessibility of oil palm farmer households to ICT facilities, specifically broadband facilities (Number of households using ICT facilities, especially the internet).
SDG10: Decrease discrepancy	
By 2030, progressively achieve and sustain population income growth and reduce inequality and promote social, economic, and political inclusion for all.	Oil palm farmers live below the poverty line by gender and age group (Number or proportion of oil palm households below the poverty line).
	Distribution of income among oil palm farmer households-(measuring using a Gini Index).
	Involvement of female oil palm farmers in social, economic, and cultural activities or institutions (the proportion of women who are active members of social, economic or cultural groups in their area).
SDG17: Partnerships to achieve sustainable development goals.	
Increase local and regional cooperation and partnerships between smallholders and oil palm farmer institutions for the achievement of sustainable development goals.	Membership of oil palm farmers in economic, extension, and other institutions related to oil palm, either directly or indirectly (the proportion of oil palm households that are active members of extension, economic and social activities related to oil palm development).
	The level of farmer participation and benefits in the institutions they follow (The activity level of palm oil farmers in the group is measured by the level of their presence and the level of benefits derived from their participation).
	Availability and accessibility of oil palm smallholder institutions (Number of groups or institutions that can participate and receive benefits).

Note: * target and indicators are modified according to FGD results and the scope of the study, namely household scale.

Ref. [87] defines the environmental development pillars of the SDGs as the achievement of sustainable management of natural resources and the environment as a support for all life. In the case of oil palm, it is clear that environmental sustainability aspects cannot be separated between oil palm cultivation and oil palm farmers themselves. Through oil palm cultivation by farmers, the village economy grows and develops. Hence, the number of poor farmers and the number of hungry people in rural areas was reduced or eliminated, as previously discussed. Furthermore, the development of the rural economy certainly impacts the ease of access to clean water and proper sanitation (SDG6). Thus, potential targets and indicators that was developed to assess the contribution of oil palm smallholders to the achievement of the SDGs is summarized and presented in Table 3

Table 3. Tentative targets and indicators for the contribution of palm oil in achieving the environmental development pillars.

Targets *	Indicators
SDG6: Clean water and proper sanitation	
By 2030, achieve universal and equitable access to safe and affordable drinking water for all.	Oil palm households using safe drinking water services (Proportion of palm oil households using clean water from formal institutions).
	Farm households use safely managed sanitation services, including bathing, washing, and latrine facilities (Proportion of palm oil households owning and using safe sanitation).
	Oil palm farmer household activities in water conservation (Proportion of oil palm households participating in activities related to water conservation).
	Household clean water consumption per capita (Total water expenditure spent per capita).
SDG13: Action against climate change	
Actions to anticipate climate change, as well as improve education, raise awareness, as well as human and institutional capacities related to climate change mitigation, adaptation, impact reduction, and early warning.	The actions of oil palm farmers to increase the absorption of CO_2 emissions through planting ground cover on their land-(the proportion of the area of oil palm owned which is planted with cover crops).
	Actions by smallholder households to increase production without clearing new land (Number of good agricultural practices carried out by smallholders for their oil palm plantations).
	Oil palm farmers' perceptions and experiences of climate change caused by oil palm (measured or analyzed based on the experience of oil palm farmers related to the phenomenon of climate change over the past year).
SDG15: Land ecosystem	
Ensuring the conservation, restoration, and sustainable use of terrestrial and inland aquatic ecosystems and their environmental services, by taking action and significantly to reduce the degradation of natural habitats, loss of biodiversity.	The legality of oil palm plantations owned by farmers indicated by a certificate of ownership of plantation land.
	Smallholders organization and management of independent smallholders and the compliance of oil palm smallholders with organizational commitments (Measured by the level of eligibility of oil palm smallholders against their membership commitments).
	Environmental management and monitoring including compliance with biodiversity conservation (the proportion of oil palm area owned within the conservation area).
	Continuous improvement of smallholder plantation business (Number of good agricultural practices in oil palm plantations owned).

Note: * target and indicators are modified according to FGD results and the scope of the study, namely household scale.

By carefully following the classification of the broader dimensions of the SDGs, namely people, prosperity, planet, partnership, and peace, as classified and discussed by [88–90], the contribution of smallholder oil palm plantations is also clear and significant to the achievement of the SDGs targets. These five dimensions, known as the 5 Ps, are in principle not much different from the pillars of the SDGs developed in Indonesia. To be sure, for sustainable development, these five Ps are also interrelated such that the achievement of one P need to contribute to the achievement of the others. Briefly, the relevance of the 13 SDGs to smallholder plantations are explained as follows:

a. People

The SDGs clearly state to end poverty and hunger in all their forms and dimensions and ensure that all human beings fulfill their potential in dignity, equity, and a healthy environment. Related to this dimension, smallholder oil palm plantations contribute to the achievement of SDG1 targets: No Poverty; SDG2: Zero Hunger; SDG3: Good Health and Well-being; SDG4: Quality Education; SDG5: Gender Equality; and SDG6: Clean Water and Sanitation. Obviously, SDG1 to SDG5 are also pillars of social development that aim to meet basic human needs, even SDG1 and SDG2 fulfill needs, including the basic needs of oil palm farmers. The fulfillment of these basic needs, in turn, will make it easier for oil palm farmers to access SDG3, SDG4, and SDG6, namely health and education needs. Meanwhile, for SDG5, gender equality in smallholder oil palm plantations cannot be ignored. Therefore, the role of females in smallholder oil palm plantations is quite essential or not [61,62]. Furthermore, [91] explained that oil palm plantations also provide opportunities for females to work in the oil palm industry.

b. Planet

Regarding the planetary dimension, the target of the SDGs is to protect the earth from degradation. Furthermore, this shows the importance of smallholder oil palm plantations being managed with Good Agricultural Practices (GAP) principles. The implementation of GAP correctly and adequately will lead to the achievement of environmental protection and sustainable development, which is part of climate action, SDG13. The application of GAP to oil palm plantations, including smallholder oil palm plantations, is also to answer the criticism that the expansion of oil palm plantations, including smallholder oil palm plantations, is correlated with the risk of environmental damage, thereby reducing the capacity of the environment to provide environmental services [92,93].

c. Prosperity

Sustainable development is directed at achieving the level of welfare of each individual without compromising environmental sustainability. In line with that, the development of smallholder oil palm plantations is also directed at achieving sustainable development goals that promote the welfare of farmers, promote economic and social development in rural areas without compromising environmental sustainability. One of the efforts to preserve the environment is the use of clean and affordable energy sources (SDG7). This indicates that access to clean energy sources is essential to achieve sustainable development goals, especially SDG7 targets. This is important because ref. [94] reports that 3–4 billion people in developing countries depend on solid fuels, mainly traditional wood fuels, which are generally obtained from natural forests for cooking and heating. Therefore, improving the welfare of oil palm farmers is expected to increase oil palm farmer households' access to clean energy sources.

Equally important, rural economic growth dominated by smallholder oil palm plantations also eliminates inequality, especially economic inequality, compared to other villages [55,60]. The target of SDG10 is to reduce inequality in income and inequalities based on age, gender, ethnicity, origin, disability, religion or economic status, or otherwise. This inequality reduction will occur quickly when oil palm plantation development also grows job opportunities to reduce unemployment (SDG8). A review conducted by [95] discovered that smallholder oil palm positively impacted income and employment, although not as large as large private or state plantations. Equally important, smallholder oil palm plantations have triggered the growth of new village economic centers that provide convenience for oil palm farmers to access economic centers, health, and social services.

d. Partnerships and Peace

Oil palm is also widely cultivated by local communities in various forms of production organization, enabling them to continually adapt to changing local and economic contexts. The studies [96–98] also add that these organizations, such as farmer groups and cooperatives, have integrated local communities with large-scale economies of oil palm companies. These studies show the importance of cooperation between farmers, farmer groups, and other institutions, both formally and indirectly, to achieve the welfare of oil palm farmers' households and the sustainability of their oil palm plantation business. This is an implementation of SDG17: Partnerships for the Goals.

5. Conclusions

The Sustainable Development Goals (SDGs) are global goals for equitable and sustainable development at every level, from local communities to more macro levels. Furthermore, the goal is to end poverty, protect the planet and ensure that everyone enjoys prosperity, now and in the future. Despite the controversy regarding the development of smallholder oil palm plantations, it is undeniable that the development of oil palm plantations has brought prosperity and economic growth to the countryside. The above discussion and various studies have explained the SDGs targets of having the potential of contributing to smallholder oil palm plantations. Oil palm plantations have many interrelated functions that cannot be separated. For example, palm oil, which has a higher economic value than other commodities, brings farmers out of poverty and hunger. This achievement will undoubtedly have an impact on other SDGs, such as access to clean water and sanitation. The 13 SDGs in which smallholder oil palm plantations contribute are interrelated and cannot be separated. Likewise, when viewed on a broader dimension or pillar, achieving one dimension or pillar also has consequences on other dimensions.

Apart from having identified 13 relevant SDGs to which oil palm can contribute, there has not been a single study that has attempted to comprehensively examine and quantify the contribution of smallholder palm oil. In fact, there are also many claims or published data showing the important role of oil palm plantations in the Indonesian economy, as previously discussed. The question that needs to be answered is how to prove and answer the hypothesis or claim, while the main challenge to the solution is how to generate the data that is essential in proving the extent to which smallholder oil palm plantation claims contributes to each of the relevant SDGs. It is possible to use a household survey of oil palm farmers to generate the necessary data among the various methods. However, in the case of Indonesia, which has a very large area, this is a challenge in itself in producing data. Therefore, this requires a comprehensive survey study, which is also currently being conducted.

Finally, while this study theoretically highlights and identifies sustainable development targets that smallholder oil palm can play and contribute, not all indicators can be measured at the level or scale of smallholder households. The SDGs indicator framework, which globally includes 231 unique indicators for the 5 SDGs pillars, for this study can only identify 47 identifiable indicators that are relevant for the 3 sustainability, economic, social and environmental pillars. Another weakness is that the impacts or phenomena produced by oil palm may not be due to the impact of smallholder palm oil alone. The impact of water, for example, the impact may not be due to the behavior of people's palm oil, but to the behavior of large oil palm plantations or the behavior of other large plantations or other global phenomena that have an impact on Indonesia. Therefore, additional empirical research is needed that broadens the time horizon to capture the dynamics and improve understanding of the impact of oil palm plantations, not only on smallholder oil palm, but also on large private and state plantations.

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Socioeconomic Relations of Food Waste in Selected European Countries

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Abstract: The present paper deals with the issue of food waste in selected European countries, in which we have tried to analyze the socioeconomic rations. The main aim of our research was to analyze food waste quantity and compare the amount of wasted food in European Union countries (except Cyprus due to the unavailability of food waste data). The analysis was based on a dataset provided through the Food Waste Index Report 2021 by the UN environment program and complemented by socioeconomic variables obtained from EUROSTAT. For a deeper analyses of the obtained results, we formulated three assumptions, which have been tested with the use of several statistical methods—Pearson's correlation coefficient, linear regression, the distance from a fictitious object method, and hierarchical clustering. Our results show that the amount of food wasted in different sectors (retail, food, households) is not correlated, and any of the analyzed socioeconomic variables do not influence the ranking of countries by the crucial variable.

Keywords: food loss; food waste; European Union countries; consumption; sector; household

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1. Introduction

Food loss and waste can be considered as the amount of food intended for human consumption that does not fulfil its purpose. Under the term food loss, we refer to spills, spoils, an abnormal reduction in quality such as bruising or wilting, or food otherwise getting lost before it reaches the consumer. On the other hand, food waste corresponds to non-consumed food of good quality, which is suitable for consumers. While food loss is unintended, food waste results from conscious decision (Lipinski et al. 2016). Approximately 1.3 billion tons of food is lost or wasted, roughly corresponding to about one-third of food produced for human consumption (Gustavsson et al. 2011).

Waste of food can be considered as an interdisciplinary problem, including economic, environmental, and ethical issues. Loss of caloric intake is only one side of the problem supplemented with the destruction of finite resources (Payne 2014). From an ethical point of view, the existence of food waste is problematic in itself as there are resources to waste nutrition sources, and on the other hand, there are millions of people who are starving or malnourished, while one-quarter of wasted food could feed them (OLIO 2020). FAO (2014) estimated the total cost of food waste in 2012 as 2625 billion USD, environmental costs (emissions, water pollution, and waste, soil erosion, deforestation, and biodiversity impact) as 696 billion USD, social costs represent 882 billion USD, the economic value of wasted and lost food is estimated at 936 billion USD, and subsidies in OECD countries regarding food waste and loss are 119 billion USD. About 24% of the fresh water used in crop production, 23% of cropland area and fertilizers, and 368 mils. metric tons are wasted every year due to food losses (Joardder and Masud 2019).

Food waste is a comprehensive and multifaceted problem, interconnected across all stages of the food supply chain, from primary production to final consumption (Canali et al. 2017). Causes are different on each value chain level. Furthermore, there is evidence of product group specifics. On the other hand, later stages of the food supply chain can influence earlier ones—for instance, standards requested by retail can be considered as an essential factor of food waste on the farmers' level (Göbel et al. 2015).

Lack of purchase planning, storage, and preparation of food in connection with consumerism and abundance culture and the wide availability of food can be considered as the most critical drivers in the case of individual consumers (Aschemann-Witzel et al. 2015). Factors causing food waste in the processing part of the food supply chain are primarily losses resulting from processing operations and quality assurance, and non-compliance with trade quality demands (Raak et al. 2017). Researchers have identified the following causes of food waste—cold chain breaking, excess production, inadequate demand forecasting, inadequate packaging, inappropriate work procedures, incorrect handling, lack of coordination, lack of information sharing, lack of integrated systems, lack of knowledge, lack of operational control, lack of refrigerated transport, lack of training, poor inventory control, problems with display, problems with storage, problems with transport equipment, short shelf life, standards of appearance and shape, sudden changes in orders, and very restrictive laws (de Moraes et al. 2020). A relatively massive proportion of wasted food comes from hospitality and food services (16–28% of the amount representing 23% of the purchased value), while the preparation waste can be considered as the most significant fraction followed by leftovers and waste by customers (Papargyropoulou et al. 2019). Some studies also point out the tendency to waste in school canteens, while the amount of diner leftovers is mainly affected by the quality of meals, serving size, and availability of snacks for children during mid-morning breaks (Boschini et al. 2020). It is unforgettable that socio-demographic characteristics of the consumer and his consumer behaviour play a key role in food waste drivers (Fanelli 2019), while factors as motives, financial attitudes, planning routines, food surplus, social relationships also influence the tendency to wase food (Aktas et al. 2018).

Reducing food waste is considered as an essential factor in ensuring food security at a global level, as it will allow the use of limited resources for other purposes, reduce environmental risks, and avoid financial losses (Priefer et al. 2013). Changes in behaviour towards the minimization of food waste can be achieved due to price consciousness, environmental concern, and time management (Pellegrini et al. 2019), while embedding community perspectives into policy instruments can bring value in preventing food waste (Benyam et al. 2018). It is necessary to connect stakeholders to food waste optimization, mainly to utilize PPP at the global level and improve communication and bring more efficient packaging connected with a better interpretation of food labels by consumers (Halloran et al. 2014). "Food waste is an exemplar of the challenge we face; if we both see it as a resource opportunity rather than a waste threat and apply our creative science and technological energies to its valorization, we show the way to other waste-to-resource opportunities. European Union countries are committed to reducing food waste by 50% (amount of wasted food per capita) by 2030 (European Commission n.d.). The European Union also established a Farm-to-Fork strategy to secure enough affordable and nutritious food, promote more sustainable consumption and healthy eating, halve the use of pesticides and fertilizers, increase the organic farming ratio, combat food fraud in the supply chain, improve animal welfare, and reduce food losses and food waste (Horská et al. 2021).

Evaluating the current state and tracking progress on reducing food waste and losses is necessary to understand the availability of relevant data sources, which is struggling in data inconsistency and poor temporal, geographical, and supply chain coverage (Xue et al. 2017). Current methods of food waste and losses quantification include either direct measurements (physical waste surveys) or measurements based on self-reports (diaries, interviews, and questionnaires) (Elimelech et al. 2018). Hartikainen et al. (2020) consider questionnaires as an appropriate way to collect data about food waste from production and manufacturing stages (except animal production, where they suggest usage of statistics) as well as in thecase of households, while retail stakeholders and caterers should provide data collected from their operations (such as food waste diaries). Corrado et al. (2019) suggest harmonizing food waste account guidelines, increasing the quantity and representativeness of data, and developing methods for liquid waste accounting. On the other hand, Elimelech et al. (2019) point out that relying on people's estimations could be uncertain, and it is necessary to use objective measurements such as physical waste surveys.

Calculation of food waste data varies across different countries due to different collection methodologies and different definitions of food waste (Bagherzadeh et al. 2014), which causes the problematic comparability of data from local sources. International organizations provide the following databases dedicated to food waste and losses:

- Food Loss and Waste Database (FAO)
- Food Waste Dataset (OECD)
- Global Food Loss and Waste (World Bank)
- Food Waste Index Report Database (UNEP)

Food Waste Index Report Dataset (UNEP Food Waste Index Report 2021) can be considered as the most comprehensive food waste data collection that combines different local data sources. According to the report, only seven countries have high confidence in food waste estimates from sources stated below. ARCADIS (2019) published the "National Food Waste Baseline report", which provides detailed data about food waste in Australia. EPA (2020) published the "2018 wasted food report", which provides an analysis of food waste in the United States of America in 2018 using a new methodology developed by the US Environmental Protection Agency. The Danish environmental protection agency (2014) published results of a survey mapping food waste in retail, restaurants, and commercial kitchens, and the Swedish environmental protection agency (2012, 2020) published comprehensive reports about food waste based on analysis from years 2010 and 2018 (Westöö et al. 2018). WRAP (2020) published a report about food waste in the United Kingdom based on research conducted in 2019. Environment Agency Austria (2017) presented food waste statistics for Austria. Schmidt et al. (2015) published a comprehensive summary report on food waste in Germany for 2015.

2. Methodology

The paper's main objective is to analyze food waste quantity and compare the amount of wasted food in European Union countries (except Cyprus due to the unavailability of food waste data). The analysis is based on a dataset provided through the Food Waste Index Report 2021 by the UN environment program and complemented by socioeconomic variables obtained from EUROSTAT (2021). Used variables are presented by Table 1.

Table 1. Variables used in analysis.

Label	Type	Description	Year(s)
FW_R	Numeric	Food wasted in retail sector per person	2015–2020
FW_FS	Numeric	Food wasted in food services sector per person	2010–2020
FW_H	Numeric	Food wasted by household per person	2014–2020
GDP	Numeric	Gross domestic product per person in PPP (current $)	2019
Poverty	Numeric	% of people living below the poverty threshold (EU-SILC)	2019
Urban	Numeric	% of people living in towns (EU-SILC)	2019
HSize	Numeric	Average household size in a country	2019
Unempl	Numeric	Unemployment	2019

In the analysis, we mainly used the methods of multivariate statistical analysis. We used Pearson correlation coefficients to describe linear relationship between the variables, to evaluate the development of the relationships between the individual indicators. Linear regression has been used to identify relevant socio-economic variables that relate to food waste by households. Relationships and order were analyzed using cluster analysis based on hierarchical clustering using ward linkage and Euclidian distance. Data analysis was processed using MiniTab and R Studio base packages.

Where statistical significance is evaluated using *p*-value without further explanation, we assume level of significance at $\alpha = 0.05$.

In connection with the set goals, we set the following research assumptions:

- Assumption no. 1: Amounts of food wasted in the retail sector, food services, and households positively correlate.
- Assumption no. 2: Socioeconomic variables influence a country's ranking based on the amount of wasted food per capita.
- Assumption no. 3: Socioeconomic variables of EU countries impact amounts of food wasted by households.

3. Results and Discussion

3.1. Amount of Wated Food

Waste, loss, or spoilage of food are efficiency issues that have attracted increasing attention from the media, researchers, politicians, companies, and the general public in last few years. Although the food waste seems to be a "simple problem", which can be easily solved by "stopping throwing it away", it is much more complex (Eriksson et al. 2018). The complexity of the food loss and waste issue links to the three pillars of sustainable development, when on one hand the reduction of food loss and waste could help to recover the economic losses and reduce financial burdens on the world's most vulnerable people; on the other hand (from the environmental perspective), food loss and waste are an extremely inefficient use of resources; and last but not least (from a food security perspective), reduction of food loss and waste is a major opportunity to close the calorie gap between where the world is now and where it needs to be to sustainably feed the planet (Lipinski 2015). The mentioned does not mean that the reduced food waste automatically results in sustainable development, e.g., if the waste reducing measures are more recourse demanding then the savings they achieve (Eriksson et al. 2016), but reducing unnecessary food waste has the potential to make an important contribution and has a high symbolic value (Eriksson et al. 2018). Despite the fact that the food waste is primarily a moral issue of throwing away the edible food items when people elsewhere are starving (Stuart 2009), it is also associated with the unnecessary use of natural resources (Nellemann et al. 2009) and loss of monetary value (WRAP 2008). Addressing the issue of food waste and identifying its main "spoilers" is therefore necessary and urgent.

The United Nations environment program published the Food Waste Report 2021 complemented by a dataset that unites different country- and worldwide-level data on food waste per capita, separating it into three sources of waste—households, retail sector, and food services. As shown in Figure 1, the highest food waste per capita is, according to UNEP data, produced by households, followed by the food services and the retail sector.

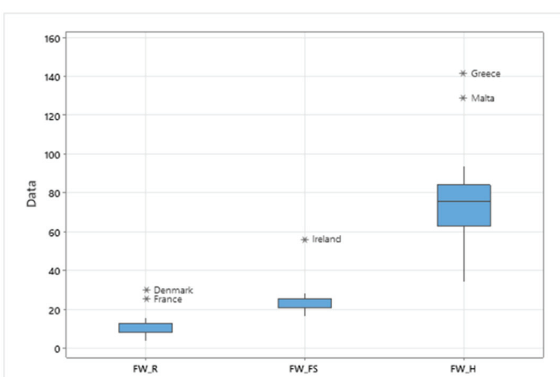

Figure 1. Box-plot charts for food waste variables.

It is also evident that countries can be identified as outliers as they have a significantly higher amount of wasted food than other countries. A visual comparison of countries is presented in Figure 2. We assumed that amounts of food wasted in the retail sector, food services, and households should be correlated, but from visual analysis based on Figure 2 it seems that this is not the case. For a deeper analysis of the formulated assumption, we have tested correlations using Pearson's correlation coefficient, which ruled out the existence of a statistically significant correlation ($\rho = 0.1$ for all pairs, non-significant at $\alpha = 0.05$). Therefore, we can conclude that amounts of food wasted from three different sources are not dependent on each other.

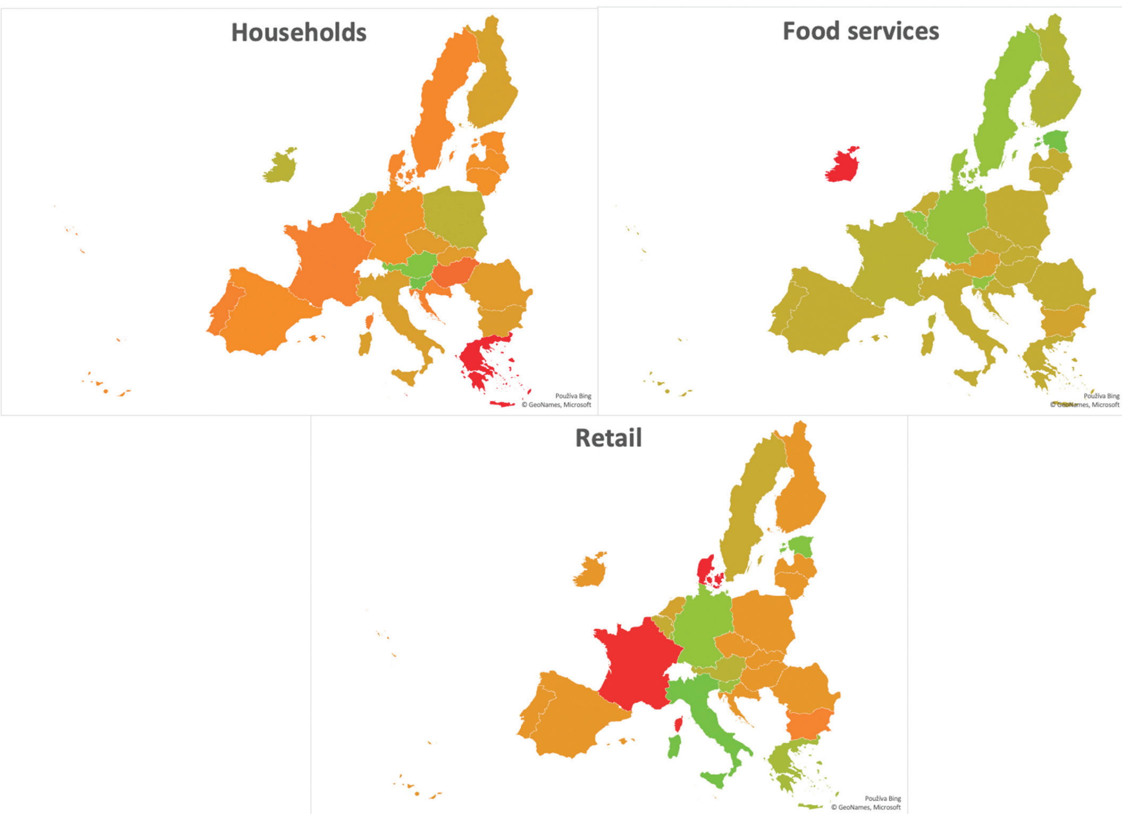

Figure 2. Relative comparison of wasted food amount (per person) in EU countries per capita according to source sector; red colour represents higher amount.

For a better comparison of countries, we have constructed integral variables using the multicriteria evaluation method (distance from the fictitious object), while the Pearson correlation matrix was used to calculate weights of individual variables. The ranking of countries is presented in Figure 3, where the lower distance represents a better position. We assumed that socioeconomic variables (GDP, Gini coefficient, Export, Urbanization, Unemployment) influence the country's ranking, but there is no statistically significant correlation between them ($\rho = <0.1, 0.2>$ for all variables, non-significant at $\alpha = 0.05$). This could be caused by globalization of retail and food services sectors and therefore differences are not present.

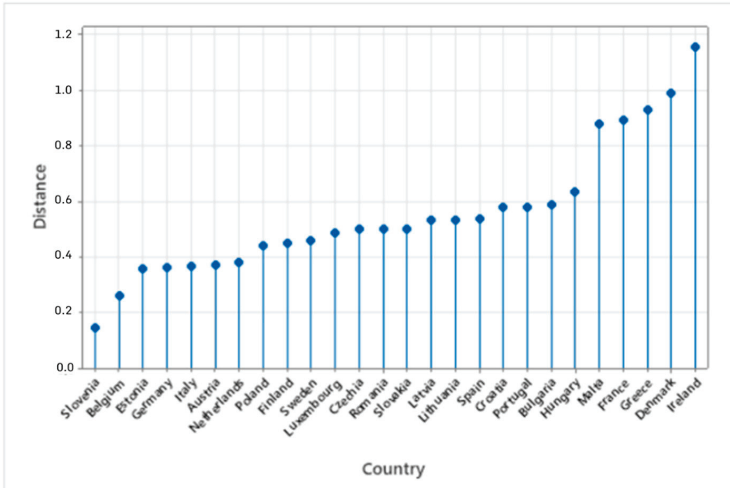

Figure 3. Ranking of food wasted in countries based on the integral variable combining all three sectors.

For a better understanding of the differences between countries, we have applied hierarchical cluster analysis using ward linkage and Euclidian distance while input variables were standardized. Five clusters resulted from analysis as optimal, while the division of countries according to clusters is presented in Figure 4.

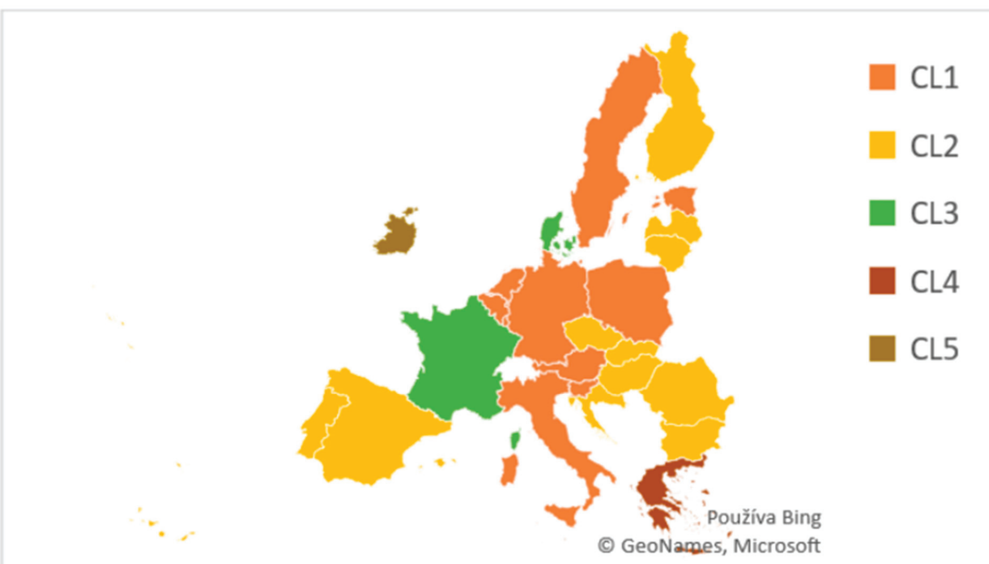

Figure 4. Affiliation of countries to clusters.

From centroids of clusters calculated as non-standardized variables (Table 2), the following groups of countries can be described. Optimal countries (CL1) are countries that reach the minimum amount of food wasted in retail and food services, while food wasted by households is not very high compared to other clusters. Ambiguous countries (CL 2) have countries that reach not bad nor best values. Retail wasters (CL3) can be described as countries that reach a high amount of food wasted in the retail sector. Household wasters (CL4) are countries that reach an extremely high amount of food wasted by households, and finally, foodservice wasters (CL 5) are represented by countries that reach an extremely high amount of food wasted in food services.

Table 2. Centroids of clusters.

Cluster	FW_R	FW_FS	FW_H
1	8.035	22.35	61.89
2	13.068	25.553	75.95
3	27.7	22.56	83.06
4	10.1	25.57	135.35
5	12.811	56.146	54.7

3.2. Predictors of Food Waste Generated by Household

The second part of the analysis focuses on analyzing whether selected socio-demographic differences among countries impact the amount of food waste generated by households, following the fact that the situation of households is a presumed factor influencing possible differences in food waste also between developed countries. As can be seen from Table 3, food wasted by households (per capita) is significantly correlated with the unemployment rate and level of country urbanization.

Table 3. Correlations between the amount of food wasted by households and selected socioeconomic variables.

Variable 1	Variable 2	N	Correlation	*p*-Value
Unempl	FW_H	26	0.419	0.033
HSize	FW_H	26	0.116	0.572
Urban	FW_H	26	0.411	0.037
Gini	FW_H	26	0.234	0.250
GDP	FW_H	26	−0.118	0.566

Following the results shown above, we have constructed a linear model using mentioning two exogenous variables. The model explains 26.5% of food waste variability, is significant on $\alpha = 0.05$, and can be described using Equation (1).

$$\begin{gathered} FW_H = 34.2 + 0.624 * Urban^{**} + 2.70 * Unempl^{**} \\ (^{**}\ p - \text{value} < 0.05) \end{gathered} \tag{1}$$

The amount of food wasted by households is influenced by levels of both country urbanization and unemployment, while the first predictor can be described by the fact that the countryside provides opportunities for food residuals in farming activities. On the other hand, the explanation of the effect of the unemployment rate is not straightforward. We can presume that employed people eat outside the household during the working week and therefore waste produced by them is counted to food services instead of households.

As a response to the urgent need to address food waste, a mass of evidence was created based on the quantities of food wasted and the related emissions along the food production–consumption chain (Edjabou et al. 2016). The results of many research studies and evidence show that the largest food-waste faction is represented by private households. Given the high amounts of food waste occurring on the household level, identification of the factors affecting the food waste, leading "people" to waste the food, as well as the prevention of food waste at the final stages of the supply chain, is of utmost importance (Parfitt et al. 2010).

4. Conclusions

This paper has studied the state of food waste and losses in selected European countries, emphasizing inter-community comparison and the impact of sociodemographic variables. The study was based on data divided into three categories, considered to be the main sources of wasted food—retail, food sector, and households. Our analysis shows that amount of food wasted in different sectors is not pairwise interconnected in terms of amounts. Moreover, there is no influence of sociodemographic characteristics, represented by selected variables, on the ranking of examined countries; this is based on the integral wasted amount of food, which we assume can be caused by the globalization of the retail and food services sectors. Therefore, differences are not present at the country level. On the other hand, we found that a higher unemployment rate and higher urbanization at the national level cause the increase. This is due to the continuous population growth, environmental impacts, and the fact that there are still people who suffer from malnutrition. We consider it appropriate to start monitoring the real state of food waste within the member states of the EU, which would contribute to a better understanding of the given issue following a more detailed analyses and ultimately facilitate the setting of public policies to reduce food waste.

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Article

Prosumer Behavior Related to Running a Household in Rural Areas of the Masovian Voivodeship in Poland

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Abstract: The subject of research is a phenomenon of prosumption, i.e., the intertwining of consumption and production processes, until the differences between them are blurred. When consumers produce goods and services for their use, they become prosumers. The article aimed to assess consumer behavior in terms of various forms of prosumer activity on the market of household-related services. The types of prosumer activity of rural households and their size were determined during the analyses. The article uses primary sources from a survey conducted among residents of rural areas of the Masovian Voivodeship in Poland in 2017. Statistical, descriptive, and comparative methods were used. The research shows that consumers are very active in the field of prosumption, rationally running their households. The study used principal component analysis (PCA) and selected descriptive statistics. The research results showed that the services performed can be grouped into three categories, i.e., the index of basic living self-sufficiency of households, the index of renovation and repair self-sufficiency, and the index of professional self-sufficiency of farms. Consumers usually prepare meals at home and clean, iron, and wash clothes, thus reducing the costs of running a household. It is also popular to carry out repairs oneself or to carry out repairs of equipment at home.

Keywords: prosumption; rural household; principal component analysis

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1. Introduction

The modern consumer more and more often does not want to be just a passive recipient of goods and services offered by producers but wants to be more active and creative during the consumption process [1]. The consumer wants to participate not only in consuming but also in creating products and services, he wants his voice to be heard by producers not only at the stage of use but also at the stage of creation [2,3]. Prosumer behavior related to running a household is part of the model of green economic growth and contributes to the practical implementation of the concept of sustainable development [4].

A phenomenon of the intertwining of consumption and production processes until the boundaries between them are blurred is called prosumption, therefore consumers become producers at the same time [5]. The term "prosumption" comes from the combination of the two words "production" and "consumption" and means the interpenetration of production and consumption [6]. Units become producers—they design or modify products to their liking [7]. Prosumer is a creative and active consumer who disseminates his knowledge of good and bad experiences related to products or services among consumers, thus affecting their purchasing decisions, as well as exerting influence on the quality of goods and services produced [8]. Prosumption is an expression of consumer opposition to mass, standardized production. The consumer wants to be treated individually because everyone has different needs, preferences, and tastes [9].

The consumer is faced with the choice between buying goods and services on the market and prosumption, which is the most effective way of meeting the needs of household members, minimizing the effects of inflation, and helping to protect the level of meeting needs [10]. Prosumers are people who choose to produce or coproduce specific goods and services. Some of them pursue their passions in this way. Others wish to become independent from mass production in the process of meeting their own needs. Various factors lead to buyer involvement in prosumption. These are, among others: shortening the working time, reluctance of educated people to take up boring jobs, rising costs of qualified labor, increased interest in physical activity as a method of mental rest, the desire to improve the quality of goods, and the need for self-expression [11].

The main factors of prosumption development include general determinants related to consumption (biological, economic, social, cultural, and technological factors), as well as specific factors that can be attributed only to prosumption. They can be distinguished among [12]:

- increasing the amount of free time and the need for its management,
- the opportunity to perform professional work at home and intertwine it with consumer activities,
- development and dissemination of education,
- changes in work organization and reevaluation of its role in human life,
- evolution of work towards creativity.

There are also other divisions of specific factors of prosumption development, which include economic and social trends, technological progress, development of knowledge and research methods as well as the activity of enterprises [13]. Prosumption affects the dissemination of a new life model and a new style of work. The traditional division into working time and free time disappear, and the increase in free time favors the development of prosumption. According to Zalega (2014), prosumer consumption is also affected by the rising costs of many services, the collapse of the bureaucratic system of second-wave services, and the development of new technologies [14]. A factor in the development of prosumption is the decline in real household income. This can be particularly visible in times of crisis when the decreasing purchasing power of households forces them to take up activities, produce products on their own, or limit the use of services to perform them yourself. This form of prosumption is associated with natural consumption and the self-production of products [15].

An additional factor affecting home production and service activities in households are the consumer’s skills. Virtualization of life, easier access to new technologies, such as the internet or mobile phone, means that consumers can communicate with each other, sharing their skills and opinions about products and services by uploading photos and videos of things they made [16].

Prosumer behavior not only applies to tasks taken over by active consumers from enterprises, but also to non-marketable forms of work and production that can only be carried out in the household sector. Such activities include preparing food, cleaning, raising children, and maintaining a social life. They play a key role in the entire economy because they largely determine the physical and mental characteristics of employees, as well as the number and structure of supply on the labor market [17].

On television and the internet (especially in social media), you can find instructions and videos on how to perform actions yourself at home [18]. An important effect of prosumption is also the creation of (often virtual) communities with similar interests, jointly developing new concepts, cooperating, and cocreating new solutions [19].

The recognition of farmers as food prosumers from Toffler’s Third Wave made the topic re-emerge. In the era of globalization and the phenomenon of overconsumption, considering the conditions of sustainable development and sustainable consumption, consumers think about returning to nature and following such a consumer trend [20].

The importance of the role of self-supply in the concept of sustainable development is supported by the fact that food obtained from self-supply is fresh—without the need to undergo industrial preservation processes, does not lose nutrients during storage, and does not contain food additives (e.g., preservatives). In addition, it does not generate costs in long-distance transport, energy costs during refrigerated storage and does not pollute the environment with an excess of organic and packaging waste [21]. Self-grown food does not go through the industrial processing phase and the market. This means that the supply chain is the shortest possible in this case [22]. It also helps to reduce unethical food waste [10].

One of the first detailed studies on self-supply in agriculture was conducted in Poland by Chmielewska [23]. The author showed that the level of self-supply of food differs due to the socio-economic characteristics of households. Interesting research on the role of food self-supply in the theory of sustainable development and sustainable consumption was presented by Głowicka–Wołoszyn and coauthors [21]. The study by Strzelecka, where the source of data was the FADN database, is also noteworthy. Research showed that during the economic crisis, as a result of a decrease in income from conducted activity, there is an increase in self-supply of farms [24].

In Poland, research on the prosumer activity of consumers in terms of both the production of goods and services by the same group of respondents was, so far, carried out only by Nowak [25] and Murawska and Długosz [26].

Nowak in his research on consumption and prosumption in housekeeping in Kujawy and Pomerania Region in Poland defines prosumption as "replacing the use of market services through their performance". His research showed that households predominated that more than 50% of services were performed as part of their household (57%), while 43% of households commissioned over half of the work to professionals. Simple but time-consuming activities such as washing and organizing nutrition were most often performed at home. The organization of special events constituted a significant part of services performed on their own. Over half of the respondents carried out the renovation of the apartment on their own. A small percentage of people performed on their own: home appliances repair, furniture repairs, hairdressing services, radio, and TV equipment repair, house construction, or sewing. This meant giving up specialized services as part of the household [25].

The research carried out by Murawska and Długosz shows that consumers are active in the field of prosumption. They express their opinions on products and services, using modern technologies and devices offered on the market of goods and services, i.e., they often design the interior of the apartment on their own, renovate it, run a garden, or prepare preserves, and thus reduce costs. [26].

According to Czuba, consumers decide to limit the use of certain types of services and products on market terms for proecological reasons and indicate the great importance of such activities for the practical implementation of the concept of sustainable development [4].

Other reasons for prosumption are given by Veen, Dagevos, and Jansma. The respondents of their research indicate personal and pragmatic reasons, such as the pleasure of producing food or the enjoyment of gardening, as reasons for engaging them in some form of prosumption. These motivations are not due to concerns about sustainability or the creation of an alternative food system. The authors argue that it is more appropriate to take a pragmatic approach to the concept of prosumption in the field of food than to combine it with themes related to power, capitalism, or activism [27].

Kosnik in her research dealt with the ethical issues of undertaking various forms of self-supply by farmers in Central Europe and New Zealand [28].

Community gardens are also one example of prosumer behavior [29,30]. Establishing community gardens is a long-term process without an imposed project where the local community collaborates. During cyclical meetings of all those interested in the subject, the area is tidied up, the garden infrastructure is created, and plants are planted. All activities are made by hand, and the items that are handled are made by hand using recycled materials.

Do-it-yourself (DIY) housework is another manifestation of prosumer behavior related to running a household. According to the DIY concept, consumers relatively often demonstrate prosumer activity in the scope of running a household; they design and modify products according to their preferences and needs [31–33]. Therefore, a new type of consumer was created—a consumer-craftsman who designs and manufactures products himself, using his skills, knowledge, and passion, while being motivated by the desire for self-expression [34–36].

Since 14 March 2020, an epidemic threat was announced in the Republic of Poland in connection with SARS-CoV-2 virus infections. The appeal of the authorities to stay at home led to the mobilization of the population for prosumer activities in the household. For many people, it turned out to be the time to do all the things that were put off at home for later. General cleaning at home, window cleaning, refrigerator, washing machine, oven, etc., as well as furniture, renovations, replanting flowers on the balcony, or garden care.

The main goal of this research is to assess consumer behavior in terms of various forms of prosumer activity on the market of household-related services. The study used principal component analysis (PCA) and selected descriptive statistics. During the survey, the respondents indicated the level of prosumer activity related to running a household. On this basis, using selected statistical methods, the division of services related to running a household into three categories was made.

The paper contributes to the existing literature in several ways. First of all, it concerns rural households, and secondly, it concerns various forms of prosumer activity.

The novelty of these studies is the characterization and evaluation of the phenomenon of prosumption in the category of goods, including food production, but also the provision of services on one’s own, which is not analyzed by researchers at the same time. In this case, both the prosumption of goods and services were treated comprehensively, using the PCA method to evaluate individual indices, which were separated based on the conducted analysis. The research results have shown that the services performed can be grouped into three categories, i.e., the index of basic living self-sufficiency of households, the index of renovation and repair self-sufficiency, the index of professional self-sufficiency of farms. Another interesting element of this study is the fact that the surveyed group of respondents lives in rural areas. It is a group of farmers, as well as agricultural and labor farms, and farms not related to agriculture at all.

The authors chose the following logical structure of the article. The first part of the article contains an introduction that includes justification of the relevance of the topic, the purpose of the research, and the structure of the article. In addition, provides an appropriate theoretical basis for the development of prosumption and the importance of this form of consumption for both consumers and producers. Section 2 contains research methodology. The results of the research are discussed in the section Results, which consists of three subsections: Section 3.1, Section 3.2, Section 3.3. The paper ends with conclusions containing the most important research findings.

2. Materials and Methods

To analyze prosumer behavior related to running a household, direct research was conducted regarding the self-supply of food and household services. The empirical material contained in the work comes from surveys conducted in rural areas of Masovian Voivodeship, in the form of a questionnaire on a sample of 302 respondents in 2017 in Poland. The group of respondents is a non-representative sample. A questionnaire survey of the incident group was conducted, from which only respondents from the area of Masovian Voivodeship were selected. The research was conducted during an on-site interview. The respondents filled in a paper questionnaire, which was later entered into the database at SPSS.

Masovian Voivodeship was selected as the area of empirical research on purpose. Although it is the richest region in Poland, assessed according to the level of GDP per capita, it is also the most spatially diversified region in terms of socio-economic development. In turn, the self-supply of households, according to the Central Statistical Office data, in Masovian Voivodeship is at the average level for the entire country.

During the survey, the respondents indicated the level of prosumer activity related to running a household, choosing respectively: lack of services, low, average, high. The types of services that respondents were asked about in the questionnaire were identified based on a literature review [25,26] and previous authors' research [37].

The collected research material was further coded, while the data set created on the basis was processed with the SPSS statistical package. Statistical analysis was performed in SPSS. Then, after grouping, counting, and initial description of the collected data, they were analyzed. For this purpose, among others, the principal component analysis method.

Principal component analysis (PCA) is one of the statistical methods of factor analysis. The first use of the principal component analysis method was initiated by Pearson in 1901 [38]. However, the main development of this method (the 1930s) is due to the work of the American statistician Harold Hotelling, who used it to analyze school achievement tests [39]. Principal components analysis (PCA) is used among others to reduce the number of variables describing a phenomenon or to discover patterns between variables. It consists of determining components that are a linear combination of the variables studied [40].

The algorithm for proceeding in the principal components analysis is as follows [41]:

- Stage I—checking assumptions

Before starting the analysis of principal components, one should check the basic assumption to assess the legitimacy of its application, namely, the correlation of variables—the higher the correlation between primary variables, the more justified the use of this analysis. The correlation is examined by analyzing the correlation matrix for variables taken for analysis.

Assumptions:

1. Normality of distribution—this assumption is not necessary when analyzing a large data set.
2. Size and representativeness of the sample—analysis is started when the sample has at least 50 observations. The sample should be taken at random. The set of observations must be homogeneous.
3. Outliers—often distort true relationships between variables. It is good to detect such points at the beginning of the analysis and remove them from the data.
4. Missing data—in the case of missing data in the analyzed sample, the missing values should be replaced by means or the cases with missing data should be removed.

- Stage II—choosing the right matrix

If the analyzed variables are comparable (they are expressed in the same units and are of the same order), then the covariance matrix is used in further analysis. However, if the variables have different units or are of a different order, the principal components analysis is performed using the correlation matrix. This is an important step to start the whole analysis because the main components obtained for the covariance and correlation matrix do not have to be the same.

- Stage III—determination of main components

$X = (X_1, \ldots, X_p)^T$ is a vector of variables used for analysis. Principal components are a linear combination of initial variables:

$$\begin{gathered} Z_1 = a_{11}X_1 + a_{21}X_2 + \ldots + a_{p1}X_p \\ Z_2 = a_{11}X_1 + a_{22}X_2 + \ldots + a_{p2}X_p \\ \vdots \\ Z_p = a_{1p}X_1 + a_{2p}X_2 + \ldots + a_{pp}X_p \end{gathered}$$

The next step is to determine the matrix of coefficients a_{ij} for $i, j \in \{1, \ldots, p\}$ for the given observation vector $\boldsymbol{X}$.

- Stage IV—dimension reduction—selection criteria

Important information is that each subsequent determined main component explains a smaller and smaller part of the variability of the initial variables. At some point, it turns out that one component determines a negligible part of the variability. Therefore, components should be reduced, using only the most important ones in further considerations.

The most commonly used reduction criteria are:

1. The criterion of sufficient proportion—the degree of explained variance of the original variables must be at least 75%. In practice, usually with 2–3 main components, the degree of explanation of variance is sufficient.
2. Kaiser criterion—elimination of principal components whose eigenvalues are less than 1.
3. Scree plot—determination of further eigenvalues on the line graph. The interpretation consists in finding a place from which a slight decrease in eigenvalues occurs to the right. No more factors should be considered than those to the left of this point. The selection of the appropriate criterion is the subjective decision of the researcher.

- Stage V—interpretation

Interpretation of the results obtained is carried out using factor loadings. Factor loadings are the correlation coefficients between a given variable and components.

If the above analysis is performed based on the covariance matrix, then the correlation coefficient between the *i*-th variable X_1 and the *j*-th component Z_j for $i, j \in \{1, \ldots, p\}$ is calculated from the formula:

$$r_{X_i,Z_j} = \frac{cov(X_i, Z_j)}{s_i\sqrt{\lambda_j}} = \frac{\lambda_j a_{ij}}{s_i\sqrt{\lambda_j}} = \frac{\sqrt{\lambda_j} a_{ij}}{s_i}$$

where:

s_i—the standard deviation of the variable X_1,

λ_j—the variance of the main component Z_j, as well as the *j*-th eigenvalue of the correlation matrix (covariance), on which the entire analysis is based,

$\sqrt{\lambda_j}$—component standard deviation Z_j.

However, if the components are generated from a correlation matrix, then:

$$r_{X_i,Z_j} = \sqrt{\lambda_j} a_{ij}$$

The sum of all eigenvalues of the correlation matrix (covariance) $\lambda_1 + \ldots + \lambda_p$ is the total variance of the system. This allows you to define a part of the total variance determined by the *j*-th component:

$$h_j = \frac{\lambda_j}{\lambda_1 + \ldots + \lambda_p} \cdot 100\%$$

The percentage share of total variation explained by the first *K* components is calculated as follows:

$$H_K = \sum_{j=1}^{p} h_j$$

Accurate analysis of the principal components allows indicating those initial variables that have a large impact on the appearance of individual principal components, i.e., those that form a homogeneous group. The main component (in which variance is maximized) is then a representative of this group [42].

3. Results

3.1. Descriptive Statistics

Table 1 presents the structure of the studied population. A total of 58.9% women and 41.1% men participated in the study. The most numerous age group were people aged 45–54 (29%). In the sample of respondents, according to the adopted research assumptions, people were living in rural areas from ten municipalities in the Mazowieckie voivodship in Poland. The survey asked respondents about their level of education. The interview questionnaire presents seven categories of education: primary, lower secondary, basic vocational, general secondary, vocational secondary, postsecondary, and higher. The most populated group was people with general secondary education, comprising about 38% of respondents. Almost one-in-five respondents had higher education (18.2%). In the sample examined, the smallest group consisted of people with basic education (4%) and basic vocational education (4.3%). The researched farms are mainly two- and three-generation families, where four-person households predominate. In the structure of households according to a number of people in a household, the largest group was constituted by 4-person households—29%. Approximately 32% of households surveyed had children up to the age of 14. Households without children up to 14 years old constituted 68% of respondents, with one child 18%, with two—10%, with three and more—4%. The largest group among the respondents were people whose monthly income was in the range of EUR 119.00–237.00 (28.8%). For 9.3% of respondents, the monthly household income per capita did not exceed EUR 118.00. The group of respondents for whom the income was over EUR 474.00 per month constituted 17.9% of the surveyed population.

Table 1. Structure of respondents and their families.

Features of the Respondents	Number of Respondents	%
In all:	302	100.0
Sex:		
Women	178	58.9
Men	124	41.1
Age:		
up to 24 years old	28	9.3
25—34 years old	74	24.5
35—44 years old	80	26.5
45—54 years old	88	29.1
55 years old and more	32	10.6
Education		
Primary	12	4.0
Lower secondary	53	17.5
Basic vocational	13	4.3
General secondary	114	37.7
Secondary vocational	41	13.6
Postsecondary	14	4.6
Higher	55	18.2
Number of people in the household:		
1	8	2.7
2	23	7.7
3	43	14.5

Table 1. *Cont.*

Features of the Respondents	Number of Respondents	%
4	86	29.0
5	76	25.6
6 and more	61	20.5
Number of children under 14 in the household:		
0	200	67.8
1	54	18.3
2	29	9.8
3 and more	12	4.1
Average household income per person per month:		
Below EUR 118	28	9.3
EUR 119–237	87	28.8
EUR 238–355	68	22.5
EUR 356–474	47	15.6
Above EUR 474	54	17.9
No answer	18	6.0

Source: own calculations.

Respondents were asked to specify to what extent they perform services related to running a household, and to what extent they outsource these activities to third parties, and how important this form of satisfying consumer needs is for them. To measure the level of household self-supply in services, a service consumption structure meter was used to determine the share of services performed alone in total services. The declared level of service (lack of services, low, average, high) was a subjective answer of respondents. Household members participating in the survey showed great interest in performing home services themselves (Table 2).

The number of respondents who do not undertake the provision of household services at all is shown in column 2 in Table 2. The least frequently outsourced activities are preparation of meals, cleaning the house, ironing, and laundry. These are simple but time-consuming activities. Laundry services are primarily subject to availability. A small number of laundries are noticeable in the villages, and the use of facilities offering this type of service is unpopular. The respondents used laundries mainly for items requiring specialized washing or cleaning (85%).

In response to a question about preparing meals at home, 55% of respondents indicated that they prepare meals only on their own, which is mainly associated with family tradition. Eating together at a time when society is very busy with work allows you to meet together at least at a shared meal. A significant part of services performed on their own was the organization of special events, i.e., birthdays, name days, anniversaries, child's communion, etc. About 20% of the respondents performed the renovation of the apartment (painting walls and ceilings and wallpapering).

The results of research on tailoring services showed that every fourth respondent does not deal with sewing on their own. This may be mainly due to a decrease in interest in learning to sew. Fewer households have sewing machines, and the tradition of passing on sewing skills from generation to generation is not continued. Besides, the market is flooded with all kinds of clothing, which significantly reduces the need and desire for self-sewing. Many stores offer various types of modifications—shortening, narrowing, and this frees you from having to do it yourself. Nearly 30% of respondents can sew and do this type of tailoring at home.

Table 2. Declared level of services performed independently as part of managing a household.

Specification	Lack of Services		Low		Average		High		Total	
	Amount	%	Amount	%	Amount	%	Amount	%	Amount	%
X1—childcare	95	32.5	37	12.7	35	12.0	125	42.8	292	100.0
X2—elderly care	98	34.0	32	11.1	36	12.5	122	42.4	288	100.0
X3—repair of home appliances, electronics in the home	81	28.3	104	36.4	78	27.3	23	8.0	286	100.0
X4—repair of means of transport	101	35.3	112	39.2	56	19.6	17	5.9	286	100.0
X5—transport service (passenger car)	46	16.0	63	21.9	70	24.3	109	37.8	288	100.0
X6—transport service (lorry)	192	67.1	43	15.0	32	11.2	19	6.6	286	100.0
X7—preparing meals	20	6.9	32	11.1	79	27.4	157	54.5	288	100.0
X8—arranging special events	39	13.7	87	30.6	72	25.4	86	30.3	284	100.0
X9—washing	28	9.6	28	9.6	46	15.8	189	64.9	291	100.0
X10—cleaning the clothes	42	14.7	48	16.8	64	22.4	132	46.2	286	100.0
X11—ironing	24	8.2	33	11.3	48	16.5	186	63.9	291	100.0
X12—cleaning the house	23	7.9	41	14.1	38	13.1	188	64.8	290	100.0
X13—sewing	68	23.6	64	22.2	73	25.3	83	28.8	288	100.0
X14—agricultural machinery repair	128	45.2	65	23.0	69	24.4	21	7.4	283	100.0
X15—filling out applications for direct payments	136	47.7	64	22.5	49	17.2	36	12.6	285	100.0
X16—plumbing services	103	36.0	98	34.3	56	19.6	29	10.1	286	100.0
X17—flat renovation (e.g., wall painting)	57	19.8	80	27.8	90	31.3	61	21.2	288	100.0

Source: own calculations.

Concerning running a household, respondents most often use truck transport services (67%). Research has shown that it is very difficult for farmers to complete their applications for direct payments. While completing the application documents (applications to the Agency for Restructuring and Modernization of Agriculture), over half of the respondents used the help of another person—public or private agricultural advisory. Only 13% of respondents did not have any problems completing the documents themselves.

3.2. Correlations

In the first step of the statistical analysis, correlations between input variables were calculated (Table 3). Correlations between most questions are quite high, but there are no statistically significant correlations between some questions. The presence of a large number of statistically significant correlations suggests the use of the principal component analysis method (PCA), however, it is expected to isolate more than one component, as the relationships between questions are not uniform.

Table 3. Pearson's correlation coefficient between input variables.

Pearson's Correlation	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P17	P19	P20
P1	1	0.730 **	0.260 **	0.166 **	0.290 **	0.049	0.423 **	0.343 **	0.491 **	0.506 **	0.536 **	0.520 **	0.340 **	0.245 **	0.256 **	0.240 **	0.342 **
P2	0.730 **	1	0.429 **	0.306 **	0.459 **	0.221 **	0.526 **	0.477 **	0.559 **	0.578 **	0.593 **	0.589 **	0.464 **	0.395 **	0.383 **	0.377 **	0.497 **
P3	0.260 **	0.429 **	1	0.558 **	0.457 **	0.206 **	0.384 **	0.420 **	0.438 **	0.435 **	0.445 **	0.395 **	0.472 **	0.360 **	0.325 **	0.555 **	0.513 **
P4	0.166 **	0.306 **	0.558 **	1	0.486 **	0.380 **	0.305 **	0.338 **	0.373 **	0.327 **	0.368 **	0.296 **	0.339 **	0.454 **	0.395 **	0.505 **	0.423 **
P5	0.290 **	0.459 **	0.457 **	0.486 **	1	0.316 **	0.526 **	0.453 **	0.570 **	0.496 **	0.547 **	0.526 **	0.411 **	0.372 **	0.334 **	0.486 **	0.524 **
P6	0.049	0.221 **	0.206 **	0.380 **	0.316 **	1	0.183 **	0.143 *	0.136 *	0.192 **	0.180 **	0.117 *	0.229 **	0.429 **	0.336 **	0.259 **	0.244 **
P7	0.423 **	0.526 **	0.384 **	0.305 **	0.526 **	0.183 **	1	0.602 **	0.730 **	0.592 **	0.669 **	0.666 **	0.507 **	0.337 **	0.272 **	0.384 **	0.468 **
P8	0.343 **	0.477 **	0.420 **	0.338 **	0.453 **	0.143 *	0.602 **	1	0.528 **	0.603 **	0.576 **	0.535 **	0.540 **	0.307 **	0.296 **	0.434 **	0.487 **
P9	0.491 **	0.559 **	0.438 **	0.373 **	0.570 **	0.136 *	0.730 **	0.528 **	1	0.716 **	0.889 **	0.863 **	0.549 **	0.308 **	0.254 **	0.403 **	0.502 **
P10	0.506 **	0.578 **	0.435 **	0.327 **	0.496 **	0.192 **	0.592 **	0.603 **	0.716 **	1	0.770 **	0.726 **	0.552 **	0.293 **	0.277 **	0.417 **	0.479 **
P11	0.536 **	0.593 **	0.445 **	0.368 **	0.547 **	0.180 **	0.669 **	0.576 **	0.889 **	0.770 **	1	0.891 **	0.626 **	0.291 **	0.284 **	0.429 **	0.528 **
P12	0.520 **	0.589 **	0.395 **	0.296 **	0.526 **	0.117 *	0.666 **	0.535 **	0.863 **	0.726 **	0.891 **	1	0.602 **	0.258 **	0.243 **	0.410 **	0.531 **
P13	0.340 **	0.464 **	0.472 **	0.339 **	0.411 **	0.229 **	0.507 **	0.540 **	0.549 **	0.552 **	0.626 **	0.602 **	1	0.353 **	0.378 **	0.537 **	0.521 **
P14	0.245 **	0.395 **	0.360 **	0.454 **	0.372 **	0.429 **	0.337 **	0.307 **	0.308 **	0.293 **	0.291 **	0.258 **	0.353 **	1	0.501 **	0.451 **	0.349 **
P17	0.256 **	0.383 **	0.325 **	0.395 **	0.334 **	0.336 **	0.272 **	0.296 **	0.254 **	0.277 **	0.284 **	0.243 **	0.378 **	0.501 **	1	0.396 **	0.354 **
P19	0.240 **	0.377 **	0.555 **	0.505 **	0.486 **	0.259 **	0.384 **	0.434 **	0.403 **	0.417 **	0.429 **	0.410 **	0.537 **	0.451 **	0.396 **	1	0.622 **
P20	0.342 **	0.497 **	0.513 **	0.423 **	0.524 **	0.244 **	0.468 **	0.487 **	0.502 **	0.479 **	0.528 **	0.531 **	0.521 **	0.349 **	0.354 **	0.622 **	1

Source: own calculations. **. Correlation is significant at 0.01 level (two-sided). *. Correlation is significant at 0.05 level (two-sided).

3.3. Principal Component Analysis

In the second step, the actual PCA was started. Firstly, the number of extracted components was determined. For this purpose, the scree plot and the size of variance extracted by individual components were used. The scree plot (Figure 1) indicates that three components should be distinguished, as the eigenvalues obtained for them are greater than 1.

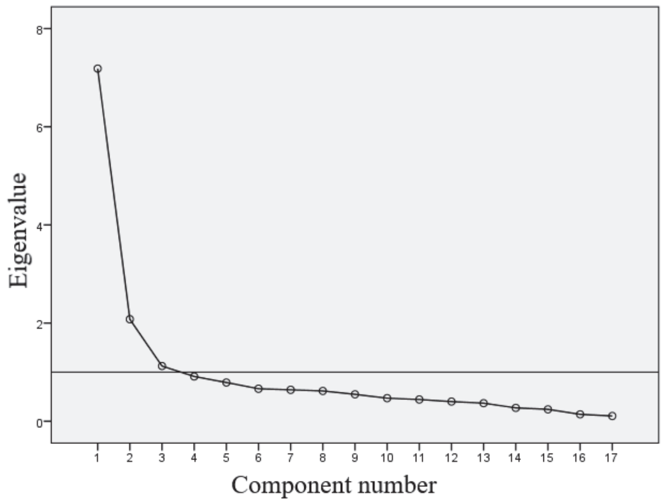


Figure 1. Scree plot. Source: own calculations.

Similar conclusions are provided by the graph showing the extracted percentage of variance (Figure 2). It is quite high for the first 3 components, but for the fourth one, it falls below 5%. Based on this criterion, one can postulate the separation of 2 or 3 components. The third component has interesting content to interpret, so the solution with three components was left.

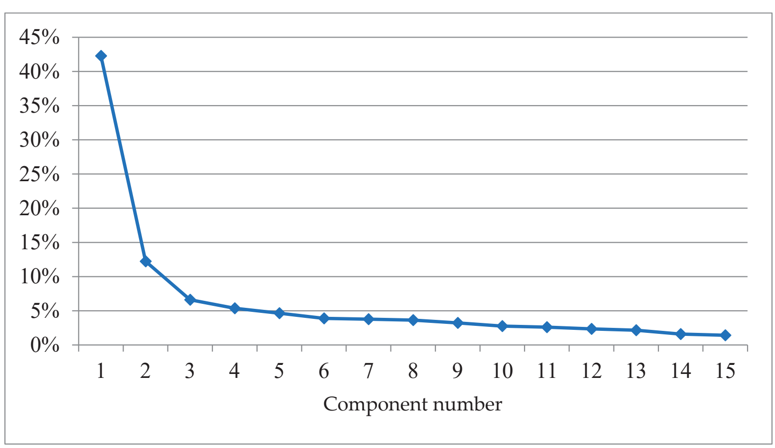


Figure 2. Extracted % of variance. Source: own calculations.

Overall, the solution retains 61% of the data set variance, which is a satisfactory result [41]. Most information is provided by the first component (31% after rotation); the next components, 18% and 12% (Table 4).

Table 4. Statistics for total explained variance.

Component	Sum of Squares of Loadings after Extraction			Sum of Squares of Loadings after Rotation		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
C1	7.186	42.270	42.270	5.312	31.247	31.247
C2	2.078	12.225	54.495	3.006	17.685	48.931
C3	1.124	6.614	61.109	2.070	12.178	61.109

Source: own calculations.

Table 5 presents the share of extracted variance in each of the input questions. For most of them over 50% was identified. There are no questions about the low share of isolated variance, so all can be left in the analysis.

Table 5. Statistics for common variation resources.

Resources of Common Variation	
	After Extraction
X1—childcare	0.656
X2—elderly care	0.697
X3—repair of home appliances, electronics in the home	0.567
X4—repair of means of transport	0.571
X5—transport service (passenger car)	0.456
X6—transport service (lorry)	0.459
X7—preparing meals	0.560
X8—arranging special events	0.455
X9—washing	0.787
X10—cleaning the clothes	0.660
X11—ironing	0.829
X12—cleaning the house	0.811
X13—sewing	0.514
X14—agricultural machinery repair	0.613
X15—filling out applications for direct payments	0.560
X16—plumbing services	0.653
X17—flat renovation (e.g., wall painting)	0.542

Source: own calculations.

The next step of the analysis presents the interpretation of the isolated components. Table 6 show the relationship between original questions and components. The higher the ratio, the stronger the relationship. On this basis, we proceed to component interpretations.

The selected varimax rotation method minimizes the number of factors needed to explain each variable. This method simplifies the interpretation of the observed variables.

The first component (C1) has a strong relationship with the variables X1, X2, X7, X8, X9, X10, X11, X12, X13, i.e., with most variables. There is no link with variable X6 describing the scope of transport services for truck transport, variable X4 (repair of means of transport), X14 (agricultural machinery repair), X15 (filling out applications for direct payments), X16 (plumbing services), i.e., so more specialized services related to business and professional activities. Therefore, the first component (C1) can be interpreted as an index of basic household self-sufficiency. This index describes simple housework related to physical work directly related to running a household.

Table 6. Statistics for rotated component matrix. Rotation method—Varimax with Kaiser normalization.

Variables	Component		
	1	2	3
X1—childcare	**0.723**	−0.078	0.357
X2—elderly care	**0.711**	0.056	0.433
X7—preparing meals	**0.720**	0.203	0.036
X8—arranging special events	**0.553**	0.385	0.031
X9—washing	**0.838**	0.292	−0.020
X10—cleaning the clothes	**0.772**	0.246	0.053
X11—ironing	**0.861**	0.298	0.011
X12—cleaning the house	**0.864**	0.250	−0.046
X13—sewing	**0.510**	0.483	0.143
X3—repair of home appliances, electronics in the home	0.208	**0.711**	0.136
X4—repair of means of transport	0.037	**0.658**	0.370
X5—transport service (passenger car)	0.399	**0.506**	0.201
X16—plumbing services	0.184	**0.753**	0.227
X17—flat renovation (e.g., wall painting)	0.375	**0.616**	0.146
X6—transport service (lorry)	−0.057	0.163	**0.655**
X14—agricultural machinery repair	0.129	0.264	**0.726**
X15—filling out applications for direct payments	0.133	0.202	**0.708**

Source: own calculations.

The second component (C2) has strong connections with the questions X16 (plumbing services), X17 (flat renovation), X3 (repair of home appliances, electronics in the home), X4 (repair of means of transport), and X5 (transport service (passenger car). These are more technically advanced services, requiring some technical knowledge and physical strength, commonly known as "men's works". These are not the basic tasks necessary for the survival of a household, they do not respond to basic living needs. This component can be defined as an index of self-sufficiency in renovation and repair. This index describes activities related to professional knowledge and skills, and it sometimes supported tips that can be found in professional magazines or the internet on special blogs and forums.

The third component (C3) has clear connections with three variables: X6 (transport service (lorry)), X14 (agricultural machinery repair), and X15 (filling out applications for direct payments). These are not living needs, but specialized needs typical of farms, necessary not for the survival of family members, but the economic functioning of these farms. Therefore, this component can be defined as the index of professional self-sufficiency of farms.

Three indexes were obtained as a result of the analysis:

- C1—the index of basic living self-sufficiency of households,
- C2—the index of renovation and repair self-sufficiency,
- C3—the index of professional self-sufficiency of farms.

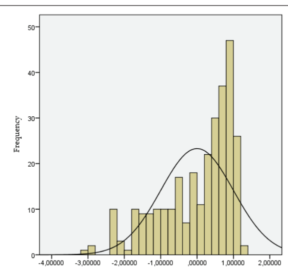
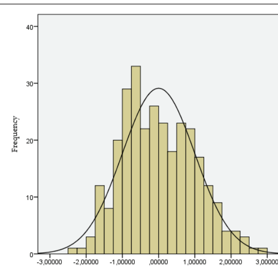
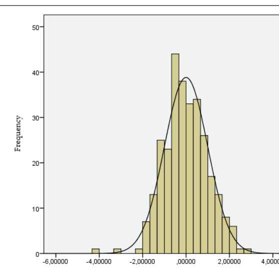
Descriptive statistics and histograms for all three indexes are presented below (Tables 7 and 8).

Table 7. Descriptive statistics for separated three components.

		The Index of Basic Living Self-Sufficiency of Households	The Index of Renovation and Repair Self-Sufficiency	The Index of Professional Self-Sufficiency of Farms
N	Valid	292	292	292
	Missing data	287	287	287
Average		0×10^{-7}	0×10^{-7}	0×10^{-7}
Median		0.3614053	−0.1350337	−0.0606378
Dominant		−0.223061	−0.20301	−0.42462
Skewness		−0.940	0.294	−0.060
Standard Error of Skewness		0.143	0.143	0.143
Kurtosis		−0.059	−0.430	0.636
Standard Error of Kurtosis		0.284	0.284	0.284
Minimum		−3.10785	−2.46059	−4.19332
Maximum		1.26319	2.77830	2.75763
Percentiles	25	−0.6445440	−0.7650325	−0.6468101
	50	0.3614053	−0.1350337	−0.0606378
	75	0.8155446	0.7498512	0.6591177

Source: own calculations.

Table 8. Histograms for separated three components.

The Index of Basic Living Self-Sufficiency of Households	The Index of Renovation and Repair Self-Sufficiency	The Index of Professional Self-Sufficiency of Farms
C1	C2	C3
N = 292	N = 292	N = 292
		

Source: own calculations.

Indexes have different distributions. In terms of living self-sufficiency, most households record high and very high self-sufficiency. In terms of repair and renovation self-sufficiency, most farms are below average; they use the services of external entities. The last index seems to be quite uniformly distributed.

The conducted analyses show that consumers are active in the area of prosumption related to running a household and, in the case of farmers, also of a farm.

The level of satisfying consumer needs in such a way is so high that in the era of excessive consumption and striving for sustainable development practices, it can be assumed that this is good practice.

4. Discussion

The current article is devoted to the problem of prosumption, which can be considered as a phenomenon not often analyzed by the researchers; in particular, when it comes to the scope of selection of prosumer activities—in our study, these are behaviors related to running a household.

The conducted research shows that households are still active in designing, producing, and delivering goods and services necessary to meet consumer needs. Only farms participated in the study, which can be divided into three groups: typically, agricultural farms, agricultural and labor farms, and rural farms not associated with agriculture at all. Taking into account the criterion of linking farms with agriculture, the respondents were also asked about services related to running a farm.

The level of self-supply of households with goods and services was very high. Similar results were obtained by Nowak in their research, but also by Murawska and Długosz. Statistical analysis showed that individual categories of services can be divided into three groups of prosumer behavior. The first group is prosumer behavior related to the basic living self-sufficiency of households. These are simple household chores related to manual work directly related to running a household: cooking, washing, ironing, cleaning the house, and caring for children and the elderly. The second group of prosumer behavior is basic renovation and repair work. They require more work, technical knowledge, and physical strength. These are not essential jobs for the survival of a household but are part of a lower-order need. Not every person has the range of knowledge and skills to perform such tasks on their own, hence you can often use the advice contained in special blogs and internet forums. This group of services includes plumbing services, apartment renovation, repair of household appliances, electronics, and means of transport. The third group of prosumer behaviors are specialist needs typical of farms, necessary not for the survival of family members, but the economic functioning of these farms. This type of prosumer behavior is typical of agricultural or agricultural-worker households. Typical agricultural services can be distinguished: scope of transport services for truck transport, repair of agricultural machinery, and filling out applications for direct payments.

The obtained research results show that Polish consumers are interested in prosumer activities related to running a household, and the time of the COVID-19 pandemic is now even more conducive to such behavior [43].

The conducted research, in the context of its political consequences, are important for creating activities supporting small family households producing food for self-supply. This type of prosumer behavior is part of the theory of sustainable development, sustainable consumption, and responsible consumption.

Prosumer behavior is important both from the point of view of caring for the natural environment, but also for economic reasons. They save money if done on their own, especially during economic crises, rising inflation, and higher costs.

In subsequent research activities, it would be interesting and worth analyzing if the research sample consisted of both rural and urban households and to investigate how prosumer behavior changed during the COVID-19 pandemic. The planned future research on the impact of the COVID-19 pandemic on the prosumer behavior of households will also take into account the energy aspect (prosumption on the energy market).

The limitation of the conducted studies is that they are not representative and cannot be generalized to the entire Polish population. But a sample of 302 respondents is appropriate for a correct statistical analysis from which correct conclusions can be drawn.

5. Conclusions

Prosumption is defined as the activity of consumers in the selection and creation of products and services tailored to their needs. Prosumption requires consumers to be involved, devote time, contribute their effort, a specific commitment, and create not only for themselves, but also for others.

Based on the analyses, prosumption is popular among consumers living in rural areas. Only a few households outsource their basic domestic services. Only 7% of the respondents do not prepare meals at home, but eat meals in restaurants or bars, or buy ready-made meals. Ironing and cleaning the house 8% of respondents outsource to companies specializing in these services on the market, which means that the remaining group of respondents (92%) perform them entirely or partially at home. The most frequently outsourced services are truck transport services, filling out applications for direct payments, agricultural machinery repair—these are more specialized services related to running a farm.

Most of them do household work on their own and in the future also intend to exhibit such forms of prosumer activity. Prosumer voluntarily and willingly participates in the processes of cocreating and improving products and services, creating new ideas and solutions related to running a home. This is due to the inclusion of prosumption in new consumer trends, but also the economic aspect. A factor in the development of prosumption in recent years was also the economic crisis, which forced consumers to take up more activity, to manufacture products on their own, or to limit the use of services to perform them themselves. The PCA method assessed the level of prosumer activities related to running a household. The types of services performed were grouped into three categories: the index of basic living self-sufficiency of households, the index of renovation and repair self-sufficiency, and the index of professional self-sufficiency of farms. This means that as part of running a household, simple household activities are carried out, such as washing or cleaning, but also renovation work that requires more skills or work strictly related to running a farm. Obtained conclusions can be a valuable source of knowledge about a phenomenon of prosumption, both for producers of goods and enterprises providing services. There are areas of activity in which prosumers are the most active, and knowledge of this allows better tailor the company's offer to the needs of households. It may translate into the development of an innovative economy in coexistence with rational and responsible consumption.

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foods

Article

Multi-Scenario Simulation Analysis of Grain Production and Demand in China during the Peak Population Period

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Abstract: The transformation of dietary structure brought about by economic development in populous countries is expected to trigger an increase in grain demand, which will put enormous pressure on the grain supply in these nations and even globally. We simulated nine demand scenarios for 2020–2050 based on China's dataset for 15 kinds of grains from 1961–2018. The results show that the maximum difference between the predicted grain demand is 323.8 Mt, equal to the total grain consumption of approximately 600 million Chinese people in one year. To capture which demand scenarios will be met when grain productivity gradually improves within reasonable ranges, we present three projections from the production side. In particular, Projection 1 (P1), which maintains productivity at the current level, only fulfills the projected demand for Scenarios 1-LL, 2-LM, 4-ML, and 7-HL and falls short of the maximum value (Scenario 9-HH) by 117 Mt, which requires an additional 250,000 ha of arable land resources to fill the gap. After raising the preset value of grain yield, the productivity of Projection 2 in turn satisfies the demand scenario 5-MM. When both set variables (grain yields and arable area) increase simultaneously, the output of Projection 3 increases by 15.3% over P1. However, it still lags behind the demand of 68 million tons in Scenario 9-HH, thus implying uncertainty in China's vision of meeting the goal of 95% grain self-sufficiency. Rather than pursuing a single outcome, we discuss multiple possibilities for China's future grain balance and emphasize the adjusting and compensating role of grain trade and storage in the whole system. Ultimately, this paper calls for a better understanding of the supply–demand gap therein and its future trends to support national grain security as well as global sustainable food policies.

Keywords: demand scenarios; production projections; gap; population peak; China; food security

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1. Introduction

The past half-century has seen rapid economic growth, urbanization, population expansion, and dietary structure shifts, all of which have led to profound changes in global and regional grain demand [1–3]. The advancement of grain production, processing, and storage technologies and the increasingly powerful and globalized grain industry effectively support the global grain supply system [4,5]. However, profound changes in supply and demand have not only resulted in the continuous evolution of global and regional grain systems but have also become a major challenge facing the world [6,7]. By the mid-century, the global population will likely stabilize at approximately 9 billion people, and global grain production will have to increase by 50% by then to meet their needs [8–11]. This trend will be accompanied by a transition of the grain system from producer to consumer and the forces that control it. Currently, grain production is experiencing greater competition for land, water, and energy, and the need to curb its negative environmental impacts is becoming increasingly evident [12–15]. Beyond these, climate change, extreme natural disasters, and COVID-19 are also emerging as uncertainties that affect the grain supply system [16–18].

As the world's most populous country, any change in China's grain demand is likely to profoundly impact the global food system [19]. Arable land was only 8% of the world's total, and water availability per person accounted for 1/4 of the global average, but China fed approximately 20% of the world's population, which was both a remarkable achievement and a huge challenge [20,21]. The nutritional transition has led to a dramatic shift in the Chinese diet away from staples and increasingly toward livestock and dairy products, vegetables and fruit, and fats and oils [22]. However, the diversification of grain uses has caused a structural shortage of domestic grain supply, making China's grain supply and its security issues of major interest to international markets and trading partners [23,24]. The main characteristic of China's grain demand is that the consumption of food has been decreasing annually, but the increase in consumption of meat, egg and milk have caused the growth of feed. In light of the rapid economic development and population growth trends, Wang argued that the gap between grain supply and demand in China would further widen, thus putting new strains on the national grain supply [25]. In addition, recent rising wages significantly increased the cost of grain production, lowered agricultural competitiveness in the global market, and exacerbated food insecurity concerns in China [26]. With the gradual penetration and control of China's grain production and trade system by international agricultural monopoly capital attempts, ensuring food security under the red line of resource constraints has become the main challenge to be addressed. When China's population peaks, grain balance issues will put enormous pressure on its resources and environment and have a major impact on global agricultural markets and food security.

Over the past two decades, many existing studies and analyses have addressed the Chinese food security challenge ahead [27–29]. Some scholars have focused on growth drivers of China's grain demand and prospects for grain production responses, projecting grain demand (cereal and soybean only) to be approximately 600–700 Mt in 2030 [30–32]. Some further projected Chinese grain demand to 2050, with assumptions on population growth and dietary shifts, estimating the volume of additional grain demand over the next 30 years [33–35]. According to UN estimates, China's population is predicted to peak at 1.4–1.5 billion in 2025–2043, and the size of the population directly determines the total demand for grains [36,37]. Although previous studies analyzed the issue of "food safety" and "food security" in China from multiple perspectives, a comprehensive study to articulate the issue was absent. In this context, we review the historical grain production and demand trends in China, relate these changes to global trends, and simulate multiple scenarios using varying factors to discuss potential challenges to China's future food security.

In this study, we attempt to develop a "past-present-future" research framework to match China's future grain demand and production. Based on historical trends in grain supply and demand, we discuss grain supply from domestic production as well as grain storage, and analyze grain demand depending on grain use, dietary shifts, and grain waste. This study combines various possibilities of grain production and demand to examine the matches and uncertainties between these two sides. However, in the most important simulation section, we first estimate China's grain demand multiplex scenarios at the peak population in combination with the per capita grain demand. Then, three different projections are used to predict domestic grain production, including two influencing variables, yield and the amount of arable land. Finally, we addressed forecasts and global implications by setting up different variable scenarios [38]. An analytic framework for food security in China is thus developed, and policy measures to regulate the supply–demand relationship are proposed. Specifically, this study focuses on the following issues:

1. Simulating China's grain demand under different scenarios and analyzing their diversity and uncertainty.
2. Predicting potential projections for China's grain production, with a stepwise overlay of factors affecting productivity.
3. Calculating the gaps between the grain demand scenarios as well as the production projections and proposing options to fulfill the balance.

2. Methods and Materials

Based on the economic theory of supply and demand, we designed this study to match its basic elements. The simulation of grain demand and supply in China during the population peak involves a large number of variables and a complex model structure, which requires a combination of several research methods.

(1) In the demand theory, the influencing factors, including income, grain price, preference, and population size, are adequately considered. In this regard, the price is inversely correlated with the quantity demanded. However, as grain is essential to meet the necessities of human beings, the elasticity of demand is small and the effect of price is not significant. Due to the diversity of grain uses, we employed a functional decomposition analysis to decompose grain demand into food (direct consumption), industrial use, feed, seeds, and losses. The direct consumption is extrapolated from the historical change trend. The indirect consumption was calculated based on the conversion rate estimation method, because feed and industry consume grain in a certain ratio. The per capita grain demand was estimated by combining the parameter debugging method.
(2) In the supply theory, the technological development, factor input and natural resource endowment are the main influences. Therefore, we chose the two main factors affecting production—yields and arable land area—to analyze the changes in the time series using panel data and a stepwise approach to increasing control variables.
(3) The demand side is less elastic than the supply side in this balance. Thus, the domestic production capacity, grain imports and stocks are the vital externalities to regulate supply. Comparing the demand and supply scenarios in an integrated manner, we addressed China's potential risks and challenges in balancing grain supply and demand when facing the population peak.

In this way, the research contents are presented in three parts, including scenarios of grain demand, projections for grain supply, and simulations of the supply–demand balance. Each part has a corresponding analyzing path and specific methodologies and is jointly formed into a complete research framework, as detailed in Figure 1.

2.1. Grain Demand Model

Clarifying the structure of grain consumption is a prerequisite for forecasting grain demand. Based on the classification standards of Food and Agriculture Organization of the United Nations (FAO), grain demand can be divided into food, feed, industrial use, seed and losses [39]. The total grain demand (D) is calculated as follows:

$$D = D_1 + D_2 + D_3 + D_4 + D_5 \tag{1}$$

where D_1, D_2, D_3, D_4, and D_5 indicate grains for food, feed, industrial use, seed and losses, respectively.

2.1.1. Food Use

Food use is the portion of grain demand used for direct consumption. It accounts for 61% (using the multi-year average) of total grain demand. Taking into account the differences in ration consumption between urban and rural residents as well as the noticeable trend of eating out in China, we employed the following calculation:

$$D_1 = \sum_{i=1}^{2} P_i E_i + \sum_{i=1}^{2} P_i F_i \tag{2}$$

where D_1 represents food use, P_i refers to urban and rural populations, E_i denotes the per capita grain demand of food use, and $\mathrm{F_i}$ is the frequency of urban and rural residents eating out.

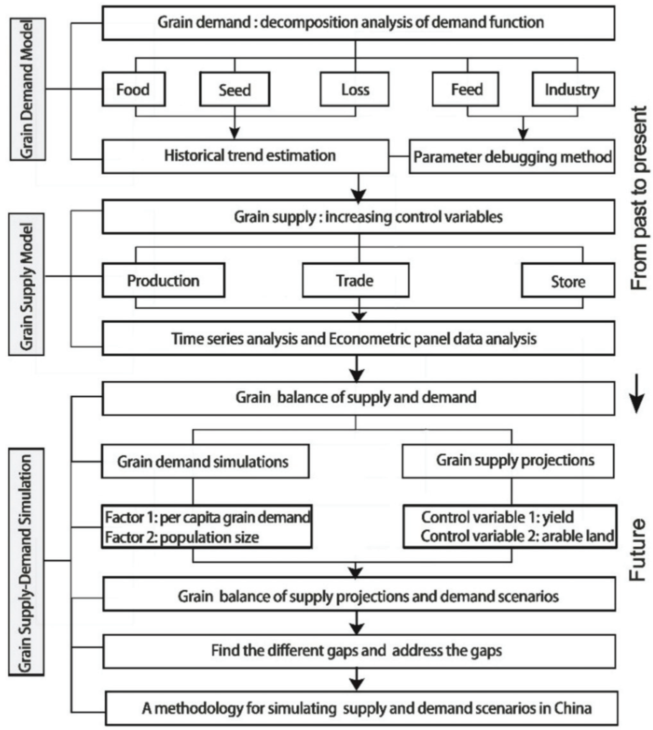

Figure 1. Research methodology.

2.1.2. Feed Use

Feed grains are the portion of grain demand used to produce meat, eggs, milk, and aquatic products and represented 24% of the total demand. Owing to the improving residential living standards and the shifting dietary structure, the demand for feeding grains has altered as well, and it was calculated as follows:

$$D_2 = \sum_{i=1}^{4} C_i T_i \quad (3)$$

where D_2 represents the demand for feed grains and C_i represents the consumption of meat, eggs, milk and aquatic products. T_i is the coefficient of grain consumption per unit of these products, which we converted according to the current Chinese ratios for meat (1:2.7), eggs (1:1.7), milk (1:0.4) and aquatic products (1:1). Since the production of livestock products indirectly consumes grains, the conversion of livestock products into indirect demand for grains is calculated.

2.1.3. Industrial Use

Industrial grains mainly include grains demand for brewing, starch, soybean crushing and biofuel ethanol, which has strongly occupied 5% of the total demand in recent years. Along with the continuous development of China's processing industry, the demand for industrial grains has become the third largest type of grain demand in China, and it was calculated as follows:

$$D_3 = \sum_{i=1}^{5} U_i T_i \quad (4)$$

where D_3 represents the demand for industrial grains and U_i refers to the grain consumption of the five main related industries in wine brewing, alcohol production, starch processing, soybean crushing, and non-staple food processing. T_i indicates the grain consumption coefficient per unit of industrial product *i.* Industrial grain is also a form of indirect use, so we use the conversion rate to calculate it.

2.1.4. Seed Use

Seeds are used as raw material for the following year's sowing, whose demand is mainly determined by scales of sown areas and advances in storage or breeding technology, and accounted for less than 5% of the total. It was calculated as:

$$D_4 = \sum_{i=1}^{15} S_i G_i \tag{5}$$

where D_4 represents the grain consumption for seeds, S_i is the sowing volume per unit area of the fifteen kinds of grains, and G_i is the sown area. Grains for seed use is a way of indirect use that can be calculated using the conversion rate.

2.1.5. Losses

Grain losses are the amount lost during the production, storage, circulation and consumption of grains and were counted as follows:

$$D_5 = \sum_{i=1}^{15} L_i \tag{6}$$

where D_5 represents the total amount of grain losses and L_i indicates the loss of cereals, soybeans, potatoes, etc.

The above five different uses together constitute China's total grain demand.

2.1.6. Per Capita Grain Demand

To simulate the grain demand at the demographic peak in China, we considered two major factors (using factor analysis): per capita grain demand and population size. In particular, per capita grain demand is determined by income, grain prices and individual characteristic factors, e.g., gender, ethnicity, and dietary preference, which can be calculated as:

$$Y_t = \alpha I_t + \beta R_t + \gamma O_t + \varepsilon_t \tag{7}$$

where Y_t represents per capita grain demand in year t, I_t stands for per capita income, R_t for the grain prices, O_t for individual characteristics, and ε for random error.

2.2. Grain Supply Model in China

The improvement in the grain supply capacity is essential to satisfy grain demand. The grain supply model was thus proposed based on grain production, imports, exports, and stores in accordance with the FAO classification standards [39]. The model incorporated non-linear time trends, which comprised a combination of linear terms, all modeled hierarchically. The first level was the calculation of grain production, to which we progressively added the grain trade acting as a critical factor affecting total supply at the next level. However, the unique situation in China was a massive grain store, an influencing factor with a significant elasticity factor for grain supply. Employing the selected data, the grain supply model was calculated as follows:

$$GSQ_i^t = GPQ_i^t + I_i^t - E_i^t + VS_i^t \tag{8}$$

where GSQ_i^t is the grain supply of *i* crops in year t and GPQ_i^t is the grain production of *i* crops in year t. $I_i^{(t)}$ and $E_i^{(t)}$ represent the volume of grain imports and exports, respectively, and $VS_i^{(t)}$ represents the change in grain store reserves.

As a key component of the grain supply, grain production volume means the actual amount of grain output in one year and refers to a function of the grain yield level (per unit area), cultivated area, and multi-cropping index. Here, grain productivity relates to the proportion of irrigated farmland, the use rate of fertilizers, agricultural films and improved varieties as a production function, expressed as:

$$Y_1 = \beta_0 X^{\beta_1} X^{\beta_2} X^{\beta_3} \ldots X^{\beta_k} \tag{9}$$

$$GPQ_i^t = P_i Y_i \tag{10}$$

where Y_i^t is grain yield, X is factors affecting Y, GPQ_i^t is the production of *i* crops and P_i^t denotes grain acreage.

2.3. The Analysis Framework of Grain Supply and Demand Scenarios

This paper proposes an analytical framework based on supply and demand balance. On the demand side, 3 population sizes and 3 per capita demand levels are combined into 9 demand scenarios.

The per capita demand was calculated by three methods: (1) the low scenario is based on the dietary balance theory and estimates the per capita demand of meeting the minimum nutritional standards; (2) the medium scenario is based on extrapolating the historical grain demand changes in China over the past 58 years; and (3) the high scenario is based on the reference per capital grain demand of some Asian developed countries or regions, i.e., Japan, Korea, Taiwan of China, and Hong Kong of China, which have similar dietary structures as mainland China, and intercepted the same period of gross domestic product (GDP) change (China's GDP is expected to increase from USD 8772 to USD 37,877 in 2020–2050).

Considering three different per capita grain demand situations (high, medium, and low) and three varying population size situations (low, medium, and high), we build a 3-by-3 scenario matrix (Figure 2): to begin with, we build the demand scenarios 1-LL, 2-LM, and 3-LH projected based on different per capita grain demands under low population size situations; next, by altering the population size to the medium level, we predict demand scenarios 4, 5, and 6 corresponding to low (ML), medium (MM), and high (MH) per capita situations, respectively; finally, scenarios 7, 8, and 9 present various demand possibilities of per capita grain demand under the high population scenario.

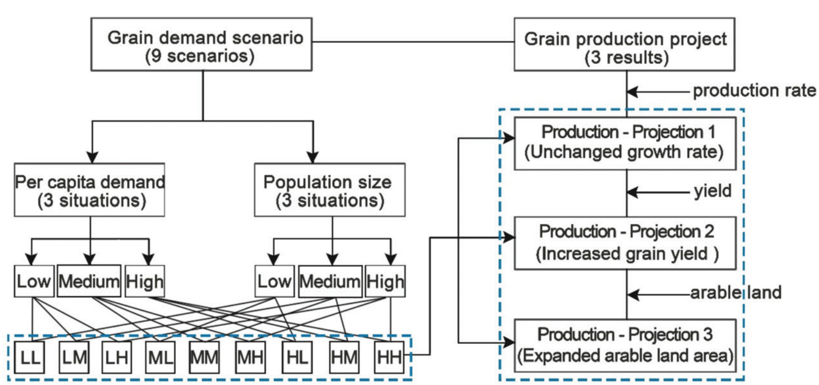

Figure 2. The analysis framework of grain demand scenarios and production projection.

In the grain supply side, we set up three prediction plans based on time series analysis: (1) Projection 1 assumes that China's grain production maintains constant growth rate; (2) projection 2 is considering the yield increase potential based on Projection 1; (3) Projection 3 is further added to the arable land area expansion potential on the basis of Projection 2.

In the demand–supply balance section, we focused on the following issues: (1) which demand scenarios will be met if the current growth rate of grain output in China remains unchanged (Projection 1)? (2) Which demand scenarios will be further satisfied if grain yields are set to be enhanced (Projection 2)? (3) Will all the demand scenarios be fulfilled if the cultivated area is further enlarged from P2? If not, which scenarios will be considered risky for China's grain self-sufficiency and even global food security? Overall, a bidirectional multi-scenario projection model is employed to analyze the gap between grain production and demand during the peak population period in China.

2.4. Data Source

We employed grain production, trade, and store data from Food and Agriculture Organization (FAO) databases and the China Statistical Yearbook, dated up to 2018, which describe the availability of different categories of grains for human consumption [39–41]. We used annual population, cultivated area, crop yields, and harvested area for the years 1961–2018 from the China Statistical Yearbook and proofread all data combining the World Bank databases. We employed all data from the provided data from 1961–2018 to analyze the Chinese grain system from the viewpoint of production and demand and predict future trends and global implications [42,43]. In particular, two sectors of data are needed to quantify the relationship between supply and demand as follows:

(1) China population projection data from World Population Prospects 2019 were drawn to simulate three different population scenarios [37].

(2) Recent studies have shown that more grain losses in consumption were objectively present in China, and the data were mainly from the FAO food balance sheets [44,45]. We will not discuss the impact of changes in the databases; for example, the data balance sheet was updated in 2014, so there are two different sets of data from 1961–2013 and 2014–2018.

What needs to be pointed out is that the definition of grain in China differs from the general international understanding. The FAO defines grains to include mainly wheat, maize, rice, and other cereals, while China also included potatoes and soybeans in its calculation [39–41]. This is because China is the world's largest producer of potatoes and has recently implemented a policy to promote potatoes as a national staple food, and meal from soybeans is the main feed source for the Chinese breeding industry. Hence, according to the Chinese Statistical Yearbook, potato and soybean are converted into unprocessed grains at ratios of 5:1 and 1:1, respectively. With this, we analyzed the demand and production components of the grain in simulations.

3. Results

3.1. China's Grain Demand during 2020–2050 under Different Scenarios

3.1.1. Per Capita Grain Demand for the Period 2020–2050

Considering a range of assumptions about China's per capita grain demands, we modeled three scenarios: high, medium, and low. In the low scenario, we assumed that China would only need to meet the basic nutritional requirements in 2050. According to the standards published by the Chinese Nutrition Society, this implies a daily per capita intake of 250–400 g of cereals and potatoes, 40–75 g of livestock and poultry meat, 40–75 g of aquatic foods, 40–50 g of eggs, 300 g of milk, 25–35 g of soybeans, and 25–30 g of edible oil, corresponding to revised grain consumption coefficients of 1, 3, 1, 1.8, 0.5, 1, and 3, respectively. Calculatedly, this scenario's per capita grain demand is 389 kg, which does not account for grain losses and possible additional consumption due to individual diets and habits. The results estimated by this method are slightly lower than those of existing studies [34], but it can be regarded as the bottom line of per capita food demand in China (Table 1).

Table 1. Comparison with the results of existing studies.

Scenario	Method	References	Result	Difference
Low	Dietary balance estimation	Tang et al. [34]	386	−3
		Xin et al. [30]	386	−3
Medium	Historical trend extrapolation	Feng et al. [46]	450	−67
		Lin et al. [47]	470	−47
High	International Experience Study	Xin et al. [48]	517	0
		Huang et al. [33]	531	14

In the medium case, referring to historical trends and existing studies, we counted five categories of grain consumption and estimated China's per capita grain demand at 517 kg. In particular, the per capita demand for food is predicted to be 170 kg, and its decreasing trend is expected throughout the projection period. Grains for feed reach 236 kg. Industrial grains represent 87 kg based on the consumption of the five major processing industries. Seeds and per capita grain losses account for 12 kg, with the latter showing a more distinct decline from the current amount (19 kg). We attribute this to improving the grain management system and implementing the Anti-Food Waste Law in China. The high scenario was designed taking into account the growth of developed East Asian economies, i.e., Japan and South Korea, featuring similar dietary structures.

We hypothesized that GDP primarily influences the increase in per capita grain demand. Combining the World Bank and scholars' projections of GDP growth rates for 2020–2050 [41], we speculated that China's GDP per capita would grow from USD 8772 to USD 37,877. For the same amount of GDP growth, Japan and South Korea raised their per capita food demand by 2% and 3.8%, respectively. For the past 60 years (1961–2020), China's per capita grain demand has grown at an annual rate of 1.6%, compared with 0.4% in Japan and 0.5% in South Korea. As a result, we predicted that China's per capita grain demand in 2050 in the high scenario would increase by 10% from 2020 to 546 kg. Using this approach, we mainly consider the influence of economic factors and dietary habits on per capita grain demand [35]. As the calculation was bound to the previous production technology of the reference subjects, we possibly overestimated the amount of grain for feed and processing. Nonetheless, it will not affect its role as an upper limit value for China's per capita grain demand in our design scenarios.

3.1.2. Population Size Projections from 2020 to 2050

We projected demographic data based on the World Population Prospects database, which is divided into three main scenarios: high, medium, and low scenarios (World Population Prospects 2019). The estimates are based on available sources for individual countries on population size and fertility, mortality, and migration levels. In the high scenario, China's total population grows at an annual rate of 0.2% from 2020 to 2044, peaking at 1.52 billion in 2044 and declining gradually to a total population of 1.5 billion in 2050. In the medium scenario, China's population peaks in 2031 at 1.46 billion, with the same projected trend of first increasing and then decreasing, reaching a minimum value of 1.4 billion in 2050. In the low scenario, China's population will continue to decline after 2024, with a total population of merely 1.29 billion by 2050 (Figure 3). The population size and trends in the three scenarios are significantly different. In particular, the 200 million population difference between the high and low scenarios at the end of our study period is expected to profoundly impact the projection of total grain demand.

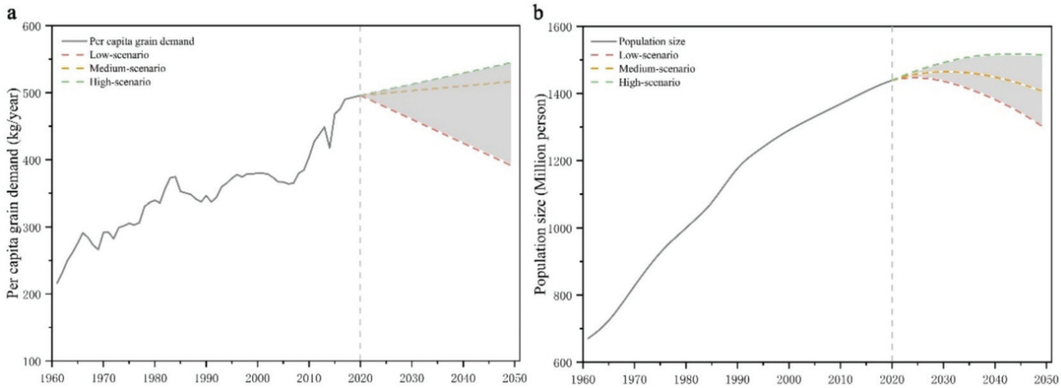

Figure 3. Scenarios of per capita grain demand (**a**) and population size (**b**) during 2020–2050.

3.1.3. China's Grain Demand during 2020–2050 under Nine Scenarios

The simulation results of grain demand show that the gap between the total demand of the nine scenarios in 2050 reaches 323.8 Mt. If we calculate the per capita demand of 517 kg according to the medium scenario, this gap is equivalent to the annual food consumption of 620 million Chinese people (Figure 4a). The estimated total grain demand in 2050 under scenario 1-LL would decline by 22.8% due to the dual coupling of low population and low per capita volume. However, scenario 9-HH suggests that a 15.8% increase in grain production (ca. 113 Mt) would be needed to meet the 2050 scenario. If demand reflected these two extremes, both the quantity and structure of China's grain production would suffer considerably.

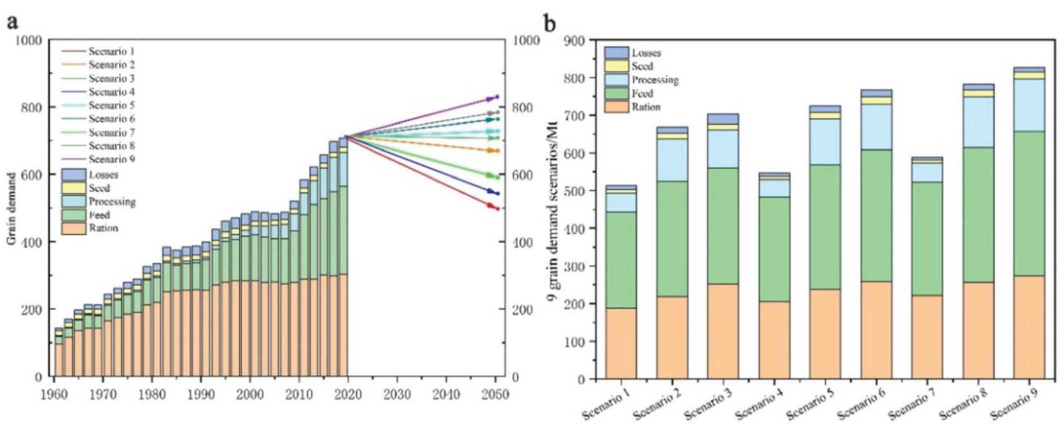

Figure 4. Scenario simulation of 9-grain demand (**a**) during 2020–2050 and comparison of 9 scenarios in 2050 (**b**).

In Scenario 1-LL, China's total grain demand in 2050 is calculated to be only 503 Mt, comprising 188 Mt for food (37.4%), 255 Mt for feed (50.7%), and 60 Mt for processing and seeds. Such a demand structure is similar to that of countries such as Europe and the US, featuring a lower total grain demand but a higher share of feed grains, and more significant consumption of meat is expected to stimulate the growth of feed grain consumption. Although per capita meat consumption in China has increased by 50% over the last 24 years, the Chinese still have a predominantly plant-based diet and are unlikely to reach the levels of Europe and the US individually. Hence, this scenario is applicable only if the food consumption structure in China is Westernized and the population size remains at a low level. In Scenario 2-LM, the set change in population size is the same as in Scenario 1, but the per capita grain demand (projected at the end of the study period) is 128 kg higher, or 21 kg above the current figure. Even so, the projection of total grain demand in 2050 falls by 45 Mt and reaches 669 Mt due to the projected decline in population. Here, food grains, feed grains, and industrial grains account for 32.8%, 45.6%, and 16.8%, respectively, comparable to China's current grain consumption structure. Specifically, food is expected to decline by 40 Mt, but feed grains are expected to increase by 53 Mt, which is compatible with the trend that meat consumption will further grow to drive a continuous increase in feed grains. In Scenario 3-LH, the total demand is 706 Mt, which is numerically comparable to the current amount. However, there are set changes in both factors, per capita demand and population size. In particular, the population size is projected to change as in the previous scenarios, while the per capita food demand increases by 50 kg compared with the current level. This increase is mainly attributed to 12% for feed and 11.7% for industrial grain, with little change in food grains. We attribute this scenario of high per capita demand and low population size to the effects of growing consumption of meat, eggs, milk and processed foods due to urbanization, on the one hand, and rising mortality due to an aging population on the other.

In Scenario 4-ML, China's total grain demand in 2050 is 546 Mt, when the total population is projected to change modestly. The shift in per capita grain demand in this scenario is similar to Scenarios 1-LL, decreasing from 496 kg to 389 kg, suggesting a Westernization of the grain consumption structure. Specifically, there is no significant variation in structural characteristics, with total food amounting to 205 Mt and feed grains to 278 Mt. Catering to this situation requires a more intensive grain consumption pattern and a series of grain policies in line with nutritional norms. In Scenario 5-MM, assuming a mid-sized demand per capita and population, the total grain demand in 2050 reaches 725 Mt, up 11 Mt compared with 2020. At the end of the projection period, the total food use decreased by 21.1% to 238 Mt, feed grains increased by 25.9% to 330 Mt, and industrial food use increased by 18.7% to 122 Mt. This scenario is comparable to the current trend in China, with total grain demand reaching a peak of 740 Mt in 2036. Such an "inverted U-shaped" variation also appears to mirror the findings of prior studies [33–35]. In Scenario 6-MH, the simulated total grain demand increases to 766 Mt, and the increase is due to a 29 kg uplift in per capita demand. Although the structural change in grain demand is not significant, the relatively rapid growth in per capita demand is not consistent with the current reality of a gradual decline in ration consumption. However, it is possible to see an increase of 51 Mt in total demand, as the indirect consumption of grain is related not only to changes in total volume but also to processing technology and farming practices.

Scenario 7-HL projected a total food demand of 589 Mt in 2050, which is the joint result of a high population growth pattern and low per capita grain demand. Admittedly, with the current population growth rate of 0.4–0.5%, it will be difficult for China's population to grow above 1.5 billion in 2050. However, the demographic growth potential released by China's gradual easing of fertility restrictions cannot be ignored either. In this scenario, feed grain demand increases to 300 Mt. Apart from the total population increase, this is also indirectly influenced by the growth in per capita meat consumption in the low scenario. In Scenario 8-HM, the per capita food demand shifts to the medium scenario, and the total amount is predicted to increase by 194 Mt to 783 Mt. This value needs to be reached at an annual growth rate of 0.5%, which is lower than the actual growth rate of China at present. However, it is still explainable when referring to Japan, Korea, and the United States. The growth rate is characterized by a rapid increase followed by saturation and then a gradual decrease. In addition, the forecasts of food and feed grains are 257 Mt and 357 Mt, respectively, where the increase in feed grains is related to the growth in total population and per capita demand. In Scenario 9-HH, total demand is the maximum of the scenarios at 827 Mt due to the combined effect of high per capita demand and a high population growth pattern. The total food demand is projected to increase by 15.8%, mainly in feed grains and industrial grains rather than in food use. In this scenario, it is difficult for China to reach the 95% self-sufficiency rate in grains proposed by the Chinese government, which would require a reduction in the nonessential demand share, including losses throughout the process.

3.2. China's Grain Production under Different Projections

3.2.1. Change Trend of Yield and Arable Land Area of China's Grain Production

The gradual improvement in grain production conditions is the basis for supporting the rapid growth in grain demand. The growth rates of grain yields of the three major categories of grain crops—cereals, potatoes and soybeans—from 1961 to 2018 were all above 90%, especially wheat, which increased 8.7 times, while yams (converted into sweet potatoes) changed relatively slowly, increasing by only 91%. Overall, rice, maize and wheat had the highest and fastest-growing yields of the three major staples, which have become the main drivers of China's soaring grain production. In contrast to the rapid growth in grain yields, the area under grain cultivation changed little, increasing by only 0.61 Mha over 58 years. From 1961 to 2014, the area under grain cultivation declined by 5% and merely rebounded with the implementation of land preservation policies such as high-standard farmland in 2013.

The significant feature of the change in grain planting area is that the proportion of the three major staple foods has been increasing year by year and accounted for 83% by 2018, which is an important support for the growth of grain production. The decrease in the area planted with potatoes and beans also shows that China has always adhered to the food security policy of "ensuring basic self-sufficiency of grain and absolute security of staple food". During the study period, China's total grain production increased 3.7 times, with the largest increase of 13.3 times for maize, mainly because the increase in demand for maize as an industrial food stimulated the expansion of production. The main reason is that the increase in demand for maize as an industrial grain stimulated the expansion at the production end. Wheat and maize increased 8.2 and 3 times, respectively, to secure the supply of food. Despite a 65% increase in potato production, the share of total grain decreased from 12.5% to 4.4%, a result of the restructuring of other grain crops due to increased production of China's three major staples. While the demand for edible soybean oil and soybean meal (for feed) has increased, soybean production has risen at a lower rate, and the supply–demand gap has relied mainly on the international market to resolve.

Overall, over the past 60 years, China's grain production capacity has increased significantly while also gradually strengthening the main position of the three staple grains, which is the combined result of current Chinese production conditions and grain policies.

3.2.2. China's Grain Production Simulation under Different Projections

This section simulates three production alternatives based on different factors affecting grain productivity. China's grain yield level has increased rapidly over six decades (Figure 5a). In the case of developed countries, although the increase in grain yields per unit is expected to slow down gradually, the overall upward trend will be maintained; therefore, the grain yield increase is taken as an influencing factor. China is currently losing its high-quality arable land resources rapidly, but the implementation of active land preservation policies in China is expected to improve this situation. Therefore, we consider improving arable land resources as the second factor affecting productivity enhancement and present the following projections.

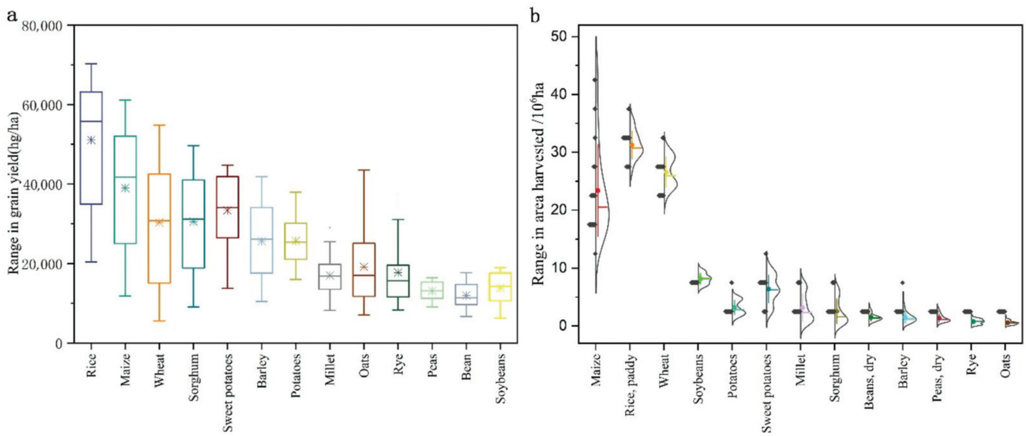

Figure 5. Ranges in grain production yield (**a**) and arable land area (**b**) during 1961–2018.

Projection 1: Here, we project that increases in grain production maintain their current pace (P1). These increases will be the combined result of various factors, mainly the adjustment of the cropping structure. Over the past 58 years, grain output in China has increased at an average rate of 1.4% per year, but the growth rate has declined to 0.62% in the last decade and has decreased at a rate of approximately 0.5% per decade. Projection 1 assumes that grain production growth rates will decrease by 0.1% per decade to reach 709 Mt in 2050, an increase of 51.2 Mt compared with the current value (Figure 6). As the base option for our proposal, we set a relatively small increment.

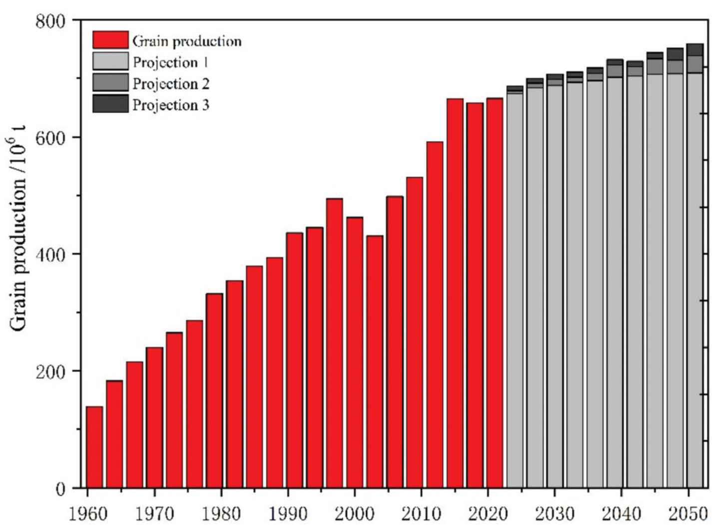

Figure 6. Projection of 3-grain production during 2020–2050.

Projection 2: This alternative enhances the setting of the grain yield variable (P2). Assuming that China's grain yields continue to grow at the current rate, calculated as between 1–2% based on the 10-year average, total grain production in 2050 will increase by 29 Mt to 738.6 Mt from P1. Projection 2 hypothesizes that the trigger for the simulation will be an increase in yield efficiency due to innovations in agricultural technologies.

Projection 3: Based on P2, we further consider the improvement of arable land resources. The amount of China's grain arable land has increased at an annual rate of 1% since 2013, while China's existing policy plans to build 1.2 billion mu of well-facilitated farmland by 2030 to guarantee grain production capacity. In Projection 3, China's grain production is predicted to increase by 20.4 Mt from P2 to 759 Mt, which are predicted to be the combined result of higher yields and arable land policy support (Figure 6).

3.3. China's Grain Demand and Production Balance during the Population Peak

A basic balance between grain supply and demand is a strong guarantee for China's food security and an important prerequisite for the sustainable development of the global food system. Although China has maintained an overall balance over the past 58 years, it is bound to break down in the future with the growth of total grain demands triggered by the dietary structural transition. The grain demand scenarios show that the total demand varies up to 323.8 Mt, which is estimated based on multiple related factors, providing more possibilities to accurately analyze the trends in the next 30 years. The three projections of grain productivity are a comprehensive analysis in which we gradually add controllable variables. Based on the matches of different scenarios and projections, we will discuss how to address the gap between grain demand and production in three comparative ways (Figure 7).

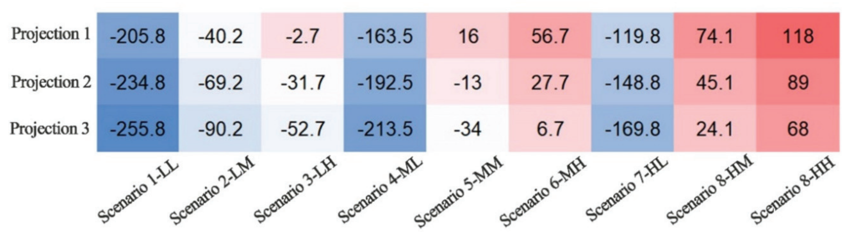

Figure 7. The gaps of demand scenarios and production projection in 2050. If demand is greater than production, the gap is positive and denoted in red. Conversely, if demand is less than production, the gap is negative, indicated in blue.

Simulation 1: With the current setting of grain output increasing at an average of 1.4% per year, Scenario 1 projects that China will produce 709 Mt of grain in 2050, which will meet the grain demand of Scenarios 1-LL, 2-LM, 4-ML, and 7-HL. The difference between the projected grain production of Projection 1 and the demand of Scenario 5-MM is only 16 Mt, while it differs from the demand of Scenario 9-HH by 117 Mt (Table 2). The gap with Scenario 9 is one-fifth of China's total grain production and the annual grain consumption of 230 million people. If it maintains the current level of grain yields, additional arable land of approximately 25 Mha will be required to address the gap, further exacerbating the shortage of arable land resources and posing a significant challenge to agricultural production in China. Assuming that China's net grain imports remain at the current level of approximately 90 Mt, over 80% of the additional demand will be filled. Only 4 Mha of additional arable land will be needed, suggesting that sufficient and stable grain imports are necessary to guarantee the production–demand balance. If net grain imports were to remain at only 75% of current levels in 2050 (equal to a scenario where import source countries exclude the US, Australia, and Canada), it would likely result in a 43 Mt grain shortage and additional requirements of approximately 9 Mha of arable land resources in domestic China. If the regulatory role of grain stocks is fully utilized, the grain supply and demand gap may be filled, and the pressure on China's land resources can also be eased.

Table 2. 9 Scenario simulation values for grain demand and production in 2050.

Indicator		Scenario Analysis								
		Scenario1 LL	**Scenario2 LM**	**Scenario3 LH**	**Scenario4 ML**	**Scenario5 MM**	**Scenario6 MH**	**Scenario7 HL**	**Scenario8 HM**	**Scenario9 HH**
Demand	Population size (billion people)	1.29	1.29	1.29	1.4	1.4	1.4	1.51	1.51	1.51
	Grain per capita demand (kg/capita/year)	389	517	546	389	517	546	389	517	546
	Total grain demand (million tons)	503.2	668.8	706.3	545.5	725.0	765.7	589.2	783.1	827.0
Production	Projection 1	709.6	709.6	709.6	709.6	709.6	709.6	709.6	709.6	709.6
	Projection 2	738.7	738.7	738.7	738.7	738.7	738.7	738.7	738.7	738.7
	Projection 3	759.0	759.0	759.0	759.0	759.0	759.0	759.0	759.0	759.0
Balance	The gap with current production (Mt)	154.8	−10.8	−48.3	112.5	−67.0	−107.7	68.8	−125.1	−169.0
	The gap with production projection 1 (Mt)	205.8	40.2	2.7	163.5	−16.0	−56.7	119.8	−74.1	−118.0
	The gap with production projection 2 (Mt)	234.8	69.2	31.7	192.5	13.0	−27.7	148.8	−45.1	−89.0
	The gap with production projection 3 (Mt)	255.8	90.2	52.7	213.5	34.0	−6.7	169.8	−24.1	−68.0
	The average gap (Mt)	232.1	66.5	29.0	189.8	10.3	−30.4	146.1	−47.8	−91.7
	The gap to fill by grain imports	-	-	-			30%		50%	100%

Simulation 2: Innovations in agricultural technologies contribute to the growth of grain yields. Assuming that the growth rate of grain yields will remain between 1–2% in 2030–2050, the grain production simulated in Projection 2 will reach 738 Mt in 2050, meeting the grain demand of Scenario 5-MM further than that of Projection 1 (Table 2). In particular, the shortage from Scenario 6-MH is merely 27 Mt and can probably be solved by domestic production or grain imports. The difference from Scenario 8-HM is approximately 45 Mt, equivalent to the annual grain demand of 87 million people. Nevertheless, the capability of net grain imports is expected to fill the shortage, and the balance of grain supply and demand can still be sustained to ensure China's food security. However, there is still a supply–demand gap of 89 Mt between Projection 2 and Scenario 9-HH. To achieve the 95% grain self-sufficiency level proposed by the Chinese government, even if yields were to increase by 1–2%, an additional 17.4 Mha of arable land resources would still be required for grain production. The additional needs are equivalent to 15% of the current total cultivated land areas. Although not all of the predicted grain demands are met by increasing yields, the raised grain production can feed an extra 56 million Chinese people. Therefore, enhancing grain yields has become one of the key measures for the Chinese government to reduce the gap between grain production and demand.

Simulation 3: Arable land is the carrier of grain production, and its quantity determines the area sown for grains. Projection 3, based on Projection 2, further assumes that the total amount of arable land for grain production increases at a rate of 1% per year, reaching a total of 759 Mt in 2050 (Table 2). Specifically, the difference between this projected volume and the grain demand from scenario 6-MH is only 6 Mt, accounting for approximately 6% of China's current total grain imports, equivalent to the output of 0.2 Mha of arable land, less than 0.2% in China. Compared with demand scenario 8-HM, a shortfall of 24 Mt of grain production is projected, representing merely a quarter of current grain imports, which can easily be filled. When the projected demand for grain reaches a maximum (Scenario 9-HH), there will be a 68 Mt production shortage for Projection 3, approximately one-tenth of China's average annual grain demand. With a 95% self-sufficiency rate as the target, an additional 14.5 Mha of arable land is needed to achieve a balance between supply and demand. This will put enormous pressure on China's agricultural production. By then, grain imports are also expected to serve as an essential means of supplementing China's grain shortage. In general, when grain productivity reaches the Projection 3 assumption, China's grain demand scenarios will be basically satisfied, and the supply–demand balance will be effectively sustained through domestic production, grain trade, and stock regulation.

4. Discussion

Addressing China's grain supply and demand over the next 30 years while ensuring the stability of the global food system is one of the key challenges facing global food sustainability [49]. China's demand for grains for human consumption and livestock feed is likely to continue to increase due to increased consumption for animal production [50,51]. The results of this study reveal that feed grain is about to overtake food grain as the largest use of grain, due to the change in diet that has come with dramatic economic reforms [52]. Therefore, following a healthy diet with moderate consumption of animal production would also reduce the pressure on cereal supply [53]. In addition, a more efficient grain supply chain is also necessary, including improving the output efficiency of water and arable land resources. The grain stocks and trade have also played an important role for China's grain supply, but the stability of the international food trade network has been greatly impacted by trade frictions and COVID-19 [54,55]. The restrictive trade system has compromised the continuity of supply and access to food [18]. Therefore, it is important for China to fulfill the grain supply by domestic production in future.

Over the past six decades, China's grain yields have increased by an average of 350%, which is the key to the improvement of grain self-sufficiency. It is also the result of a combination of agricultural production technology, the use of farm machinery, and an increase in agricultural input and policy incentives. Even so, there is a certain gap be-tween

China's grain yield levels and those of developed countries, which is partly at-tributed to the lower efficiency of China's smallholder farming system. With full consideration of topography, climate and other natural factors, China's grain yield level will have the possibility of further improvement, which is one of the future keys to solving the gap between grain supply and demand.

To explore China's grain production potential, China should strengthen the financial inputs and subsidies for grain production and establish a comprehensive assessment of its production, distribution, surplus, shortage transfer and management system. It is clear from the simulation results of grain production that increasing scientific inputs in agriculture and innovating production technologies are also not negligible. These are essential building blocks for improving grain yields. In addition, the food production process also needs to address the environmental burden caused by the overuse of chemical fertilizers, pesticides, and mulch [56,57]. Last but not least, these results also illustrate two significant problems in the current food production–consumption process: on the one hand, structural reforms on the supply side should be carried out to ensure appropriate stock levels; on the other hand, the amount of grain waste reaches 18 Mt annually, which requires economic and scientific use of grain to reduce losses and waste [58].

In the context of rapid urbanization, China is losing its well-facilitated arable land resources. In response, China practices the strictest farmland protection system and a strategy of sustainable farmland use to increase farmland productivity. In light of this, the government has also implemented a well-facilitated farmland construction policy since 2013, and in 2020, the enhanced 800 million mu of well-facilitated farmland has allowed China to raise its grain productivity by 10–20%. Although the interventions have to some extent protected arable land resources and improved its utilization rate, China's arable land is still under threat of soil erosion, sanding, salinization, and environmental pollution. In turn, these problems have become major obstacles to the further enhancement of arable land. They also set up greater difficulties for the realization of Projection 3.

With continuing economic growth and increasing aggregate demand for grain, related studies also illustrate that supply-side reforms in grain are significant in developing countries [59–61]. The paper raises additional possibilities for modeling sustainable grain demand scenarios and production scenarios to ensure food security. It is an analytical framework that can be applied to other countries with large populations. In addition, a multi-scenario simulation of grain demand and production balance is expected to enable more accurate control of the Chinese grain system during the population peak. Solutions to China's grain supply and demand problems will help shift the global food security problem to a healthier and more environmentally sustainable development.

5. Conclusions

Combining various econometric approaches, we proposed a basic framework for simulating China's food supply and demand in 2020–2050. Within this framework, we systematically modeled nine grain demand scenarios and three grain production projections by considering various relative factors such as dietary structure changes, population size, yield improvement, arable land resources, and grain imports. It can provide some references for developing forward-looking measures to ensure future food security in China and the world.

China's grain demand will be between 503 and 827 Mt from 2020 to 2050. This study simulated nine scenarios of China's future grain demand (2020–2050) based on historical population size and per capita grain demand data (provided by FAO from 1961 to 2018) in this study [62–64]. The results show a difference of 323.8 Mt between scenario 9 (the highest demand) and scenario 1 (the lowest demand) and 221.8 Mt higher than scenario 5, the most stable demand. These large differences are the great openness of our simulation projects, where we consider multiple scenarios and discuss the possibilities. In scenario 9-HH, China's total grain demand will increase by 113 Mt (15.8%) compared with 2020, and this scenario is the result of a combination of rapid population growth and dietary transition. However, among the other six scenarios (except scenarios 1-LL, 9-HH, and

5-MM), scenario 8-HM had the largest increase in total volume at 9.7%, and scenario 4-ML had a decrease rate of 23.6%.

Among the nine scenarios, Scenario 1-LL, Scenario 4-ML, and Scenario 7-HL, which have low total demand, are formed by the population size and low per capita grain demand. These requirements are calculated in full compliance with nutritional standards and do not consider the actual excess consumption. Therefore, all three scenarios serve as the bottom line of demand, albeit with probable occurrence. Scenario 2-LM, Scenario 3-LH, and Scenario 3-MM show moderate predictions, more in line with the current trend of China's grain demand. Scenario 6-MH, Scenario 8-HM, and Scenario 9-HH are assumptions based on China's high population and average demand. All three scenarios, although less likely, are still possible with China's proactive population policy in place and its rapid growth in indirect per capita grain demand.

On balance, the relatively stable changes are more appropriate for the historical trends and current situation of the nine grain demand scenarios in China. China's grain production will be between 709 and 759 Mt during 2020–2050 under the three projections of this study. The results also demonstrate that the three projects of grain production show a large variation when different influencing factors are added. When grain production maintains only the current growth trend, project 1 simulates grain production of 709 Mt in 2050. When further considering a 1–2% increase in grain yields, project 2 predicts a grain production of 738 Mt. If changes in arable land are included, the grain production would further increase to 759 Mt.

This study also shows that there was still a gap between the three scenarios of grain production and the nine scenarios of demand in China, which is becoming a research focus that needs attention at present [65]. Comparing the nine scenarios with project 1, the grain production capacity in 2050 will meet the demand of scenarios 1-LL, 2-LM, 4-ML, and 7-HL, but there is a difference of 117 Mt with scenario 9-HH and 49 Mt with the other three scenario averages. In project 2, the improved agricultural production technology contributes to an increase in total grain production by 29 Mt. The total grain production differs from Scenario 9-HH by 89 Mt in 2050, indicating that it is difficult to supplement the production–demand gap by increased grain production alone. However, this additional grain production will feed more than 40 million Chinese people and is one of the measures to alleviate the contradiction between production and demand for the Chinese government. In project 3, the grain production in 2050 will increase by another 20 Mt, which already exceeds the grain demand of Scenario 6-ML and differs from that of Scenario 8-HM by only 24 Mt. However, although a fundamental production–demand balance was reached, the scenario was the upper limit of food production in China. This study has proven that even if arable land and yields reach a certain level in 2050, there is still a certain gap with the relatively stable demand scenarios 8-HM and 9-HH. This will consume much more arable land resources to support grain production, which will put tremendous pressure on China's agricultural system. In addition, our modeling of production does not consider the reductions due to natural disasters such as floods, droughts, and climate change, which will further aggravate the instability of food production and expand the food gap [66–68].

The study also has some shortages that need to improve in further studies. While stimulating China's overall grain demand and production scenarios, we did not consider intra-China variations in this paper. For example, population age structure determines grain demand changes or urban–rural population disparities that trigger direct and indirect demand differences. These would also be a direction for future refinements in research. In addition, grain supply is subject to multiple uncertainties, with natural disasters directly affecting production and national conflicts limiting grain trade. Due to the lack of sufficient information, the above uncertainties are also not considered by this paper. Considering the complexity of the food security problem, we did not look for a single solution but compared different alternatives under various possible scenarios.

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Article

Social Life Cycle Assessment of Major Staple Grain Crops in China

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Abstract: The agricultural sustainable development for human well-being considers food security and ecological health as well as people's socio-economic conditions. Nowadays, most of the holistic assessments of agricultural sustainability, mainly focus on food production and ecological consequences, relatively lacking analysis from the socio-economic perspective. In this context, this study constructs an agricultural social life cycle assessment model based on the guidelines of UNEP to assess the social and economic impacts on the three major staple grain crops in China, including maize, rice and wheat. The assessment model aims to analyze effects of stakeholders containing farmer, agricultural value chain actors, consumer, rural areas, society, and impact categories including high-quality growth of agriculture, a comfortable life in rural areas, the prosperity of rural people. The data is mainly from national statistical databases and representative industry databases. The impact assessment adopts social risk and social impact as quantitative characterization methods, and Analytical Hierarchical Process to obtain weights. The results show that: among the three major grain crops, farmers are the most important factors for stakeholders, and agricultural industrial development has the greatest potential negative impacts on society; maize has the most positive impacts on agricultural sustainable development in China.

Keywords: social life cycle assessment; food security; social risks; staple grain crops; agricultural socio-economic development

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1. Introduction

The multi-functionality of agriculture, not only meeting the basic food demands of humans, but also playing a role in economy, culture, and other aspects, has gradually become the key link between agricultural modernization and sustainability. Therefore, the three-pillar approach of sustainable development, including People, Planet, and Profit/Prosperity, should be considered when assessing agricultural products and services [1]. Based on this consideration, some assessment methodologies have been developed from the social, economic, or environmental dimensions [2,3]. There are more assessments of agricultural sustainability, which mainly focus on environmental dimensions rather than social and economic dimensions. However, assessing agriculture from a socio-economic perspective is an important method for world sustainable development [4–6]. However, these studies are rare.

The top three grain crops in the world are maize, rice and wheat [7]. They are important foods for humans, main feed sources for agriculture, forestry, animal husbandry and fisheries, as well as indispensable raw materials for food, light industry, chemical and other industries [8–10], showing the multi-functionality of agriculture. China is the representative agricultural country, and thus, the socio-economic impact analysis of the three major grain crops in China could effectively reflect the potential risks existing in current agricultural development.

In recent years, the socio-economic assessments on agriculture have formed a certain foundation. Generally, the related methods include the principal component analysis method [11], data envelopment analysis [12], the entropy-weight-based TOPSIS method [13], energy evaluation [14], life cycle assessment (LCA) [15,16], multidisciplinary and innovative methodologies [17], etc. The relevant methods either mainly focus attention on economic models but are lacking consideration of agricultural characteristics to some extent; or mainly consider agricultural theoretical mechanisms and practical application, but lack socio-economic analysis of the whole agricultural process. Social Life Cycle Assessment (SLCA), proposed by UNEP/SETAC, is an efficient technique aiming to assess the social and the socio-economic impact of products and the potential positive and negative impact in the whole life cycle [18–23]. It puts forward the general framework for a social and socio-economic Life Cycle Impact Assessment following the general guidelines of ISO 14044 (2006), which means a unified consensus from this international expert group.

Summarized from a literature review, the application of SLCA in agriculture is mainly divided into two types. The first type is to compare the different products [24–26]. Du, CY et al. [27] presented a novel multi-criteria decision analysis model for performing robust indicator weighting in LCA and SLCA. The results showed that mechanical harvesting compared to manual harvesting had lower environmental life cycle impacts at the endpoint level and better social impacts for all these convex combinations. Zira, S et al. [28] assessed the risk of negative social impacts, using the SLCA method, for the production and consumption of 1000-kg pork originating from organic and conventional pork production systems. The results showed that the conventional pork system had 42% of the inventory indicators with SR > 0.5 and the organic pork system had 32%. The second type is target tracking to grasp important factors [29–35]. Manik Y et al. [36] investigated the social implications of palm oil biodiesel via a case study using a SLCA framework. The results revealed the critical social hotspots were working conditions and cultural heritage. Prasara-A, J et al. [37] used LCA and SLCA to examine the environmental, socio-economic, and social performances of the various sugarcane-based products. Results showed that cane trash burning, and overuse of chemical fertilizers and agrochemicals were the main causes for both negative environmental performance and negative socioeconomic and social performances. Taken overall, even though unified consensus has been reached from the international expert group, SLCA research is still in the early stage of development and more studies should be conducted, especially for agriculture [38–40]. Besides, the indicators from stakeholder categories to subcategories of SLCA should be more specified when corresponding to agricultural characteristics.

Therefore, the objectives of the study are to: (1) construct an agricultural SLCA model to promote the integration of agriculture and SLCA by refining the SLCA process in detail [41,42], and expanding the theory and method for agricultural assessment in social and economic aspects; (2) apply the agricultural SLCA model to the three major grain crops in China as a case study to verify the feasibility of the model; and (3) provide improvement suggestions and optimization plans for related stakeholders based on the model results.

2. Materials and Methods

The agricultural SLCA model constructed in the paper is undertaken in four main steps [22]: (1) Definition of Goal and Scope: describes the intended use and the goal pursued. It defines the depth of the study and decisions about which unit processes require generic or specific data collection to be made as well; (2) Life Cycle Inventory analysis: is the phase where data are collected, the systems are modeled, and the LCI results are obtained; (3) Life Cycle Impact Assessment: consists of a set of actions to achieve the classification, aggregation and characterization of data according to performance reference points; (4) Life Cycle Interpretation: takes into account all relevant parts of the study for conclusions, recommendations and reporting.

2.1. Definition of Goal and Scope

2.1.1. Goal of the Study

The goal is to assess positive and negative socio-economic impacts of the three major grain crop systems in China, and to put forward suggestions and improvement measures to optimize agricultural development according to quantitative analysis of the life cycle. Results are presented using different levels of aggregation for each stakeholder and impact category. Meanwhile, the paper tests the applicability of the agricultural SLCA model in specific cases.

2.1.2. Functional Unit

Most of the social impacts in SLCA do not depend on, and are not necessarily proportional to, physical flows but reflect the influence of industry behavior with respect to stakeholders [43]. This leads to the problem of linking impacts to a functional unit, which has been overcome to some extent by combining quantitative and semi-quantitative social indicators for SLCA [36,44,45].

Multi-functionality of agriculture means that the life cycle of the agriculture industry is complexity and long periodicity. In order to compare the three major grain crops under the same standard, this paper regards agricultural socio-economic impact itself as a whole. It defines the quantitative inventory indicators as comprehensively as possible to link impacts to a functional unit, instead of the accumulation in each stage of the agricultural life cycle. Therefore, the functional units are defined as the complete life cycle of the maize, rice and wheat industries, respectively in the model.

2.1.3. System Boundary on the Regional Level

The system boundary of the study includes the whole life cycle of the three major grain crops from agricultural planting to product recycling, focusing on the 31 provinces of the Chinese mainland. Related stakeholders in each stage of the three major grain crops' industrial chain are within the assessing scope.

2.1.4. Choice of Stakeholder Categories and Subcategories

In order to construct the agricultural SLCA system, a literature review and bibliometric analysis were conducted. Firstly, the study analyzed the selection relevant articles for a literature portfolio [44,46–49]. Secondly, the Chinese "No. 1 central documents" from 2010 to 2020 were extracted by Python to confirm the key points of agriculture in China. Finally, the assessment indicators system from categories to subcategories was determined based on the above results, combined with SLCA Guidelines and the methodological sheets for subcategories in SLCA proposed by UNEP/SETAC [50]. At the same time, subcategories lacking data or having little or even no impact on Chinese agriculture were excluded. The detailed SLCA indicators from categories to subcategories within the system boundary are specified in Figure 1.

Farmer corresponds to worker in SLCA Guidelines. It is a key component with a wide range of influences on agriculture. Relevant subcategories are as follows.

- Freedom of Association and Collective Bargaining

It aims to verify the compliance of the organization with freedom of association and collective bargaining standards. In particular, whether free to form and join associations and the right to organize unions, to engage in collective bargaining and to strike [51]. Village committees protect farmers and their related rights. Analyzing its coverage rate could reflect the management effectiveness to explain the rural governance ability.

- Fair Salary

It aims to assess whether practices concerning wages are in compliance with established standards and if the wage provided is meeting legal requirements, whether meeting or below industry average and whether it can be considered as a living wage [51]. Regional development differences lead to different income levels in China. And thus, the income gap between urban and rural residents could reflect the relative wealth of rural residents.

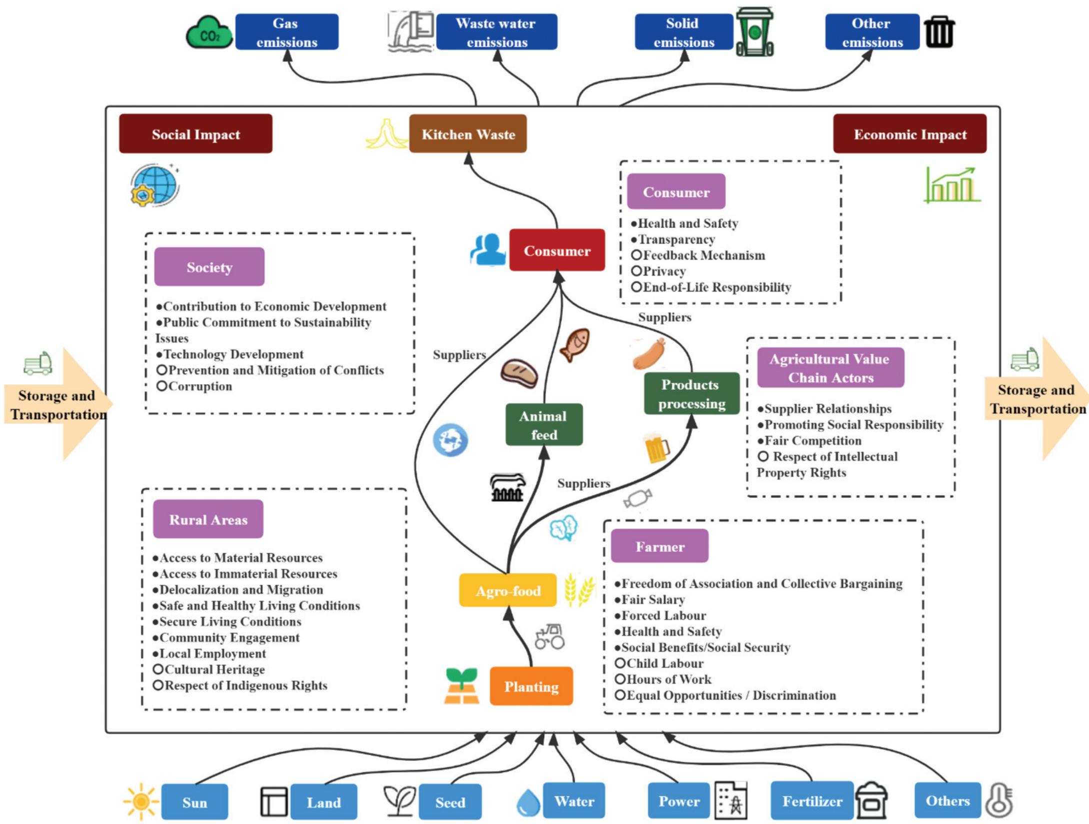

Figure 1. The Agricultural SLCA system from categories to subcategories. ● adopted subcategories from SLCA Guidelines. ○ excluded subcategories from SLCA Guidelines.

- Forced Labor

It aims to verify that there is no use of forced or compulsory labor in the organization [51]. Agricultural mechanization rate reflects the agricultural planting efficiency, showing the degree of reduction in labor intensity.

- Health and Safety

It aims to assess both the rate of incidents and the status of prevention measures and management practices [51]. Working in fields always means a safe working environment. But the rural medical system is relatively imperfect in China nowadays. Coverage rate of rural clinics shows the current rural medical construction, and then explains the soundness of the Chinese health security system and its mechanism.

- Social Benefits/Social Security

It aims to assess whether an organization provides for social benefits and social security of workers and to what extent [51]. Verifying the proportion of rural residents with minimum living security reflects the relative degree of poverty of rural residents, illustrating the mechanism construction of social welfare and security.

Agricultural Value Chain Actors corresponds to value chain actors in SLCA Guidelines. It is an important medium to ensure the industrial chain's stable operation. Relevant subcategories are as follows.

- Supplier Relationships

It aims to assess the potential impacts or unintended consequences of its procurement and purchasing decisions on other organizations and takes due care to avoid or minimize any negative impacts [51]. Analyzing the proportion of animal husbandry structure, which is a representative industry directly related to agricultural supply, could measure the level of regional agricultural modernization, clarifying the stability of supplier relationships.

- Promoting Social Responsibility

It aims to assess whether it promotes social responsibility among its suppliers and through its own actions [51]. Measuring the amount of agricultural chemical fertilizer applied to the cultivated area could reflect protecting situations of locally cultivated land, to prove social responsibilities performance of all parties in the agriculture industry.

- Fair Competition

It aims to assess if the organization's competitive activities are conducted in a fair way and in compliance with legislations preventing anti-competitive behavior, anti-trust, or monopoly practices [51]. Proportion of agricultural related legal entities in China could reflect enterprises' participation in the agricultural market. It explores the potential of economic development in primary industry, along with explaining the current market environment of fair competition.

Consumer corresponds to consumer in SLCA Guidelines. It is the final embodiment of the socio-economic impact of the industrial chain. Relevant subcategories are as follows.

- Health and Safety

It helps to identify the existence and scope of systematic efforts to address consumer health and safety across the organizations involved in the life cycle of a product and/or service [51]. Qualified rate of food quality supervision and random inspection in China shows agricultural products' quality, illustrating efforts of all industrial chain links for consumers' health and safety.

- Transparency

It aims to assess if the organization communicates on all issues regarding its product and social responsibility in a transparent way [51]. The purchasing power of residents is measured by Consumer Price Index for food, which illustrates the influence of transparency.

Rural Areas corresponds to local community in SLCA Guidelines. It is the basic condition guarantee of agricultural operation. Relevant subcategories are as follows.

- Access to Material Resources

It aims to assess the extent to which organizations respect, and work to protect, to provide or to improve community access to local material resources (i.e., water, land, etc.) and infrastructure (i.e., roads, sanitation facilities, etc.) [51]. Water is one of the most representative material resources. Measuring agricultural water use efficiency reflects agricultural planting efficiency, explaining the utilization rate of material resources.

- Access to Immaterial Resources

It aims to assess the extent to which organizations respect, work to protect, to provide or to improve community access to immaterial resources [51]. Rural broadcasting could represent the immaterial resource, especially in rural areas without so much media or information. Analyzing the coverage rate of Rural radio reflects the information dissemination ability, explaining the utilization rate of immaterial resources.

- Delocalization and Migration

It aims to assess whether organizations contribute to delocalization, migration or "involuntary resettlement" within communities and whether populations are treated adequately [51]. The urbanization rate could show rural residents' situations in migration and resettlement, reflecting the process of urban development and the relative wealth of rural residents.

- Safe and Healthy Living Conditions

It aims to assess how organizations impact community safety and health, including the general safety conditions of operations and their public health impacts [51]. The process of rural environmental protection is reflected by the carbon emissions in each stage of agriculture, which shows the degree of the agricultural activities' impacts on safe and healthy living conditions.

- Secure Living Conditions

It aims to assess how organizations impact the security of local communities with respect to the conduct of private security personnel and how the organization interacts with state-led forces [51]. The Engel coefficient could be used to judge rural residents' quality of life. It could reflect the secure living conditions in rural areas, explaining the relative poverty degree of rural residents.

- Community Engagement

It aims to assess whether an organization includes community stakeholders in relevant decision-making processes [51]. The analysis of agricultural budget expenditure's efficiency, representing Chinese government support, reflects the government investment, which explains the influence of community engagement.

- Local Employment

It aims to assess the role of an organization in directly or indirectly affecting local employment [51]. Nowadays, China still promotes employment to the secondary and tertiary industries gradually. Measuring the proportion of employees in primary industry reflects the current situation of local rural employment.

Society corresponds to society in SLCA Guidelines. It is affected as well as the carrier by agriculture. Relevant subcategories are as follows.

- Contribution to Economic Development

It aims to assess to what extent the organization/product or service contributes to the economic development of the country [51]. Measuring the contribution rate of primary industry to reflect the quality of the agricultural output value could explain the role of the agriculture industry's development for Chinese economic growth.

- Public Commitment to Sustainability Issues

It aims to assess to what extent an organization is engaged in reducing its sustainability impacts [51]. Food security is one of the most representative sustainable development goals in China. The analysis of grain production reflects the degree of high-quality agricultural growth, showing the process of Chinese public commitment to sustainable development.

- Technology Development

It aims to assess whether the organization participates in joint research and development for efficient and environmental sound technologies [51]. Measuring the fund investment of agricultural researchers reflects the quality and efficiency degree of agricultural technology development.

2.2. Life Cycle Inventory Analysis

As the three major grain crops are widely distributed in China, this study delimits the regional scope at the province level to restrict data sources. The main steps are (1) collecting the provincial production of the three major grain crops respectively in 2020; (2) selecting provinces whose production rank foremost, and who has an obvious production gap with others. What's more, the sum of the selected provincial production exceeds more than 60% of Chinese total production respectively, as shown in Table 1; (3) taking the proportion of the additive provinces' production as the provincial weights for the following calculation.

Table 1. The regional scope of the three major grain crops (10000 tons).

Ranking of Provincial Production in 2020	Maize		Rice		Wheat	
	Province	Production	Province	Production	Province	Production
1	Heilongjiang	3646.6	Heilongjiang	2896.2	Henan	3753.1
2	Jilin	2973.4	Hunan	2638.9	Shandong	2568.9
3	Inner Mongolia	2742.7	Jiangxi	2051.2	Anhui	1671.7
4	Shandong	2595.4	Jiangsu	1965.7	Hebei	1439.3
5	Henan	2342.4	Hubei	1864.3	Jiangsu	1333.9
6	Hebei	2051.8	Anhui	1560.5	-	-
7	Liaoning	1793.9	Sichuan	1475.3	-	-

According to the connotations of stakeholder categories and their subcategories in this study, the inventory data of the whole country and relevant provinces are collected. The data is mainly from national authoritative statistical databases, such as the China Statistical Yearbook, China Rural Statistical Yearbook [52,53], representative industry databases, such as the Wind database, Carbon emission accounts and datasets (CEADs) [54] and other relative information accumulated by literature and networks. The detailed calculation method and data source of each inventory indicator are shown in Appendix A.

2.3. Life Cycle Impact Assessment

2.3.1. Characterization Method and Model

Social Risk (SR) is a measure of the risk of negative social impacts for each inventory indicator related to the social sustainability issues [28]. SR corresponds to the risk weighting factor Ri representing the risk of negative social impacts in Benoit et al. [55]. In this study, SR is used to calculate the risk value of negative social impacts under the framework of agricultural SLCA. It is used to illustrate the characterization results.

SR, ranging between 0 and 1, is a normalization of the inventory indicator using reference points. A reference point denotes a baseline situation for a certain aspect, and the inventory indicator represents its current condition. SR is 0.5 when the inventory indicator is at the reference point. If for a certain inventory indicator, the situation is worse than the reference point, the value of SR will be between 0.5 and 1. Hence, a low value of SR is preferable, as it means a low risk of negative social impacts. The formulas used to calculate SR are as follows [28]:

$$SR = 1 - \mathrm{EXP}(\mathrm{LN}(0.5) \times \mathrm{IND}/\mathrm{REF}) \tag{1}$$

where a higher value than the reference point reflects a more negative impact.

$$SR = \mathrm{EXP}(\mathrm{LN}(0.5) \times \mathrm{IND}/\mathrm{REF}) \tag{2}$$

where a lower value than the reference point reflects a more negative impact.

Where SR is the social risk value; REF is the reference point value; IND is the inventory indicator value.

The study takes Chinese national average data as the reference point. The sum of related provincial data multiplied by their weights is the inventory indicator value. According to the characterization method, the measurement of SR is to assess the negative social impacts of the three major grain crops relative to the average level of China.

2.3.2. Weighting Method and Model

Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method to help decision-makers facing a complex problem with multiple conflicting and subjective criteria [56]. Due to the different roles of stakeholder categories and subcategories in the agricultural life cycle, this study used AHP to determine factor weights, including four steps:

Problem modelling: divided the general objective into different levels for explaining the subordinate relationship between the factors and the hierarchical structure between the layers, as shown in Figure 2.

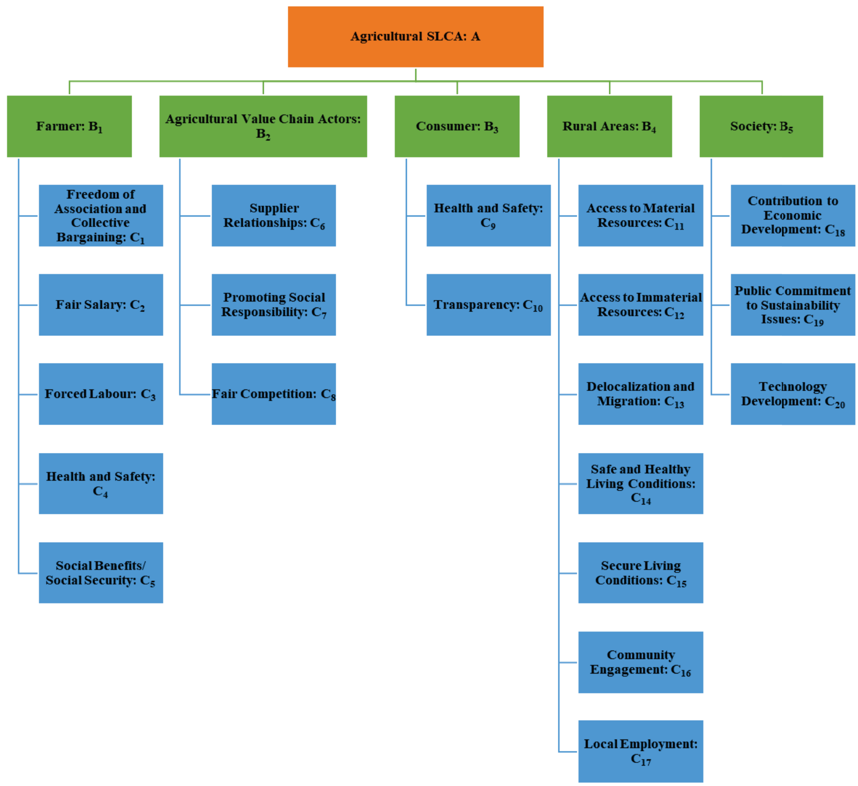

Figure 2. Weighting model of the agricultural SLCA.

Weights valuation: rationalized the importance of each factor by inviting domain experts to score. In order to construct the pairwise comparison relationships of indicators, AHP was conducted through a questionnaire for each stakeholder category and subcategory. The questionnaire shown in Appendix B was collected by email. And the experts were selected by purposive sampling according to their public academic or professional background. Academia, authorities, enterprise staff, etc., in relevant fields were invited to the survey. In total, 35 valid questionnaires were selected in this study. The respondents had work experience in the subject area with an overall average of 12 years, of which the longest was 37 years.

Weights aggregation: carried out standardized processing layer by layer, to obtain the weight value of each factor to the upper layer, as shown in Table 2.

Sensitivity analysis: checked the consistency of the total ranking of layers. The overall results of the study met the consistency test.

Table 2. Priority calculation in AHP.

B \ A	A_1	A_2	A_m	Ranking of Layer B
B_1	b_{11}	b_{12}	b_{1m}	$\sum_{j=1}^{m} a_j b_{1j}$
B_2	b_{21}	b_{22}	b_{2m}	$\sum_{j=1}^{m} a_j b_{2j}$
B_n	b_{n1}	b_{n2}	b_{nm}	$\sum_{j=1}^{m} a_j b_{nj}$

2.3.3. Impact Assessment Method and Model

The impact category corresponds to a model of the social impact pathways to the endpoints of human well-being according to ISO 14044 (2006). To do so, one needs to model from subcategory results to impact categories by aggregating the information at the impact category level [22].

In 2017, there were approximately 0.6 billion people living in Chinese rural areas, accounting for 17.67% of the global rural population [7]. To improve rural development, the Chinese government proposed a new strategy of "Rural Vitalization" in 2017 that aimed to build rural areas with thriving businesses, pleasant living environments, social etiquette and civility, effective governance, and prosperity [57]. In sum, the core objective of the strategy is to systematically establish a coupling pattern of various rural development elements [58], which is corresponding to the three pillar approach of sustainable development, including People, Planet, and Profit/Prosperity.

This study aims to propose improvement plans based on identifying socio-economic impacts of China's three major grain crops. It is consistent with the strategic goal of Rural Vitalization in China. Therefore, the impact categories are divided into three dimensions from the strategic proposal: high-quality growth of agriculture (corresponding to Profit/Prosperity), a comfortable life in rural areas (corresponding to Planet) and the prosperity of rural people (corresponding to People). According to the characteristics of inventory indicators, the impact assessment model is constructed by combining the impact categories with related inventory indicators, as shown in Figure 3.

Social impact (SI) is a measuring method that calculates the accumulated risks of negative social impacts for a given impact category under the agricultural SLCA framework. It multiplies the SR value of each inventory indicator by its weight, and the calculation formula is as follows:

$$\mathrm{SI_i} = \sum_{\mathrm{j=1}}^{\mathrm{J}} \left(\mathrm{SR_{ij}} \times \mathrm{W_{ij}}\right) \tag{3}$$

where j is the inventory indicator (e.g., j= 1...7 for impact category of high-quality growth of agriculture); $\mathrm{SI_i}$ is the social impact value of the impact category i; $\mathrm{SR_{ij}}$ is the social risk for inventory indicator j of category i; $\mathrm{W_{ij}}$ is the weight of inventory indicator j of category i.

2.4. Life Cycle Interpretation

The interpretation step analyzes the calculation results of SR, weights and SI to draw out conclusions on the positive and negative social impacts of the three major grain crops in China. SR shows social risks for different inventory indicators in relation to the reference. Weights illustrate the important degree of each inventory indicator from the socio-economic assessment aspect. SI aggregates negative social impacts from each impact category to make an overall social risk assessment.

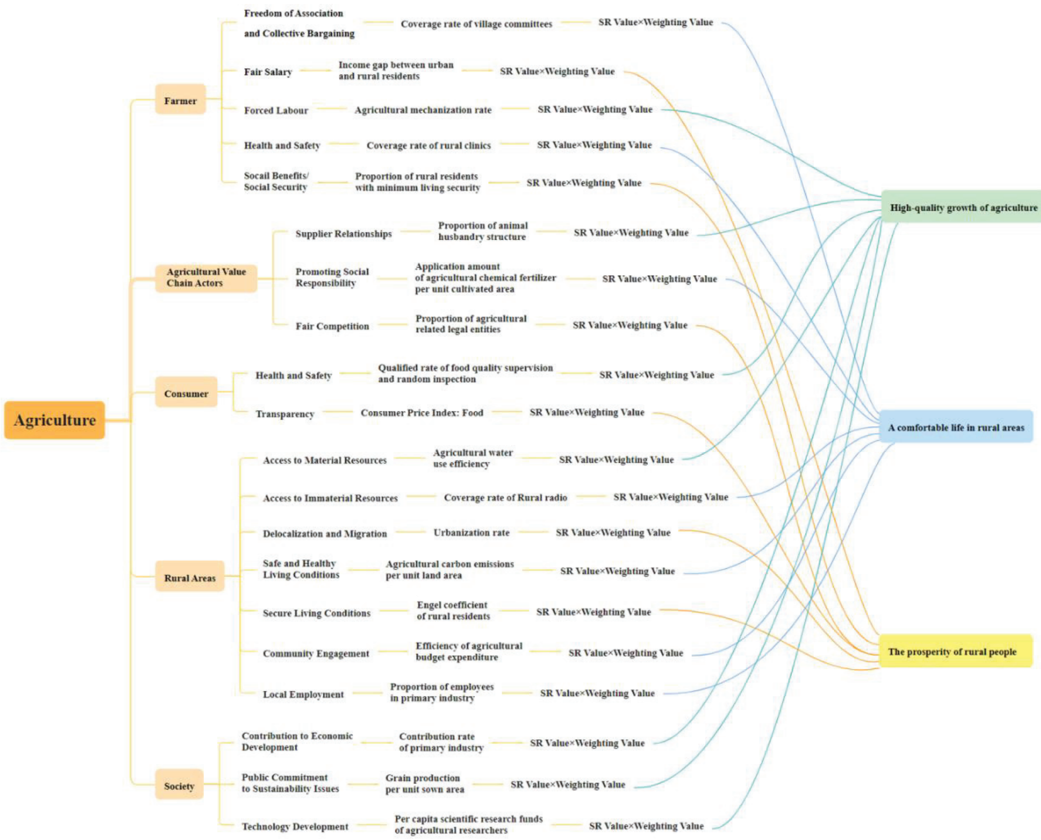

Figure 3. Impact assessment model of the agricultural SLCA.

3. Results

3.1. Social Risk

SR is a value of an inventory indicator in relation to a reference point, measuring the risk of negative social impact, respectively, in all ways. A value higher than 0.5 indicates a worse situation than the reference, which is the average Chinese conditions. Based on the characterization model of the agricultural SLCA, the calculation results are shown in Table 3.

The three major grain crops perform well, social risk coverages are all less than 40%. There are 11 of 20 inventory indicators in wheat, 10 of 20 in maize and 8 of 20 in rice with values of SR < 0.5., a better situation than the national average level, which means the positive socio-economic impacts on related assessing fields. In terms of the impact reach, wheat has the most inventory indicators with SR < 0.5, meaning the widest scope of positive socio-economic impacts. In terms of the impact degree, maize has the most SR values obviously lower than 0.5, of which seven inventory indicators with SR < 0.45, meaning the most outstanding positive socio-economic impacts.

In the field of inventory indicators, SR values of Proportion of agricultural related legal entities are the lowest in maize and rice with 0.31 and 0.37 respectively, and 0.46 in wheat, better than the national average level of 0.5. This result shows that there are enough agricultural related enterprises for the three major grain crops. These enterprises could provide sufficient expansion space for the extension of the industrial chain, thereby promoting economic development and local employment; SR values of Agricultural water use efficiency is the lowest in wheat at 0.37, and is 0.43 in maize which is obviously lower than

0.5. The industrial development of wheat and maize balances the water needs with savings. The agricultural water consumption serves the development of the primary industry reasonably and effectively. SR values of Efficiency of agricultural budget expenditure, Grain production per unit sown area, Engel coefficient of rural residents are all lower than 0.5 among the three major grain crops. Their performance is better than the national average level. The results illustrate the effective development of primary industry by government supporting, the achievement of food safety by stable grain production, and the improvement of residents' quality of life by agricultural industrial advances respectively. Besides, four of five inventory indicators of stakeholder Farmer in maize and wheat have better positive impacts than the national average. Farmers of the maize and wheat industries have better work conditions and basic social guarantees.

Table 3. The characterization model and SR values of the three major grain crops in China.

Stakeholder Categories	Subcategories	Inventory Indicators	REF	Maize		Rice		Wheat	
				IND	SR	IND	SR	IND	SR
Farmer	Freedom of Association and Collective Bargaining	Coverage rate of village committees	9.85	11.9	0.43	8.17	0.56	11.1	0.46
	Fair Salary	Income gap between urban and rural residents	2.56	2.2	0.45	2.26	0.46	2.25	0.46
	Forced Labor	Agricultural mechanization rate	1.53	1.64	0.47	1.46	0.52	1.78	0.45
	Health and Safety	Coverage rate of rural clinics	11.94	13.6	0.45	11.1	0.52	12.4	0.49
	Social Benefits/Social Security	Proportion of rural residents with minimum living security	7.1	7.61	0.52	6.75	0.48	5.37	0.41
Agricultural Value Chain Actors	Supplier Relationships	Proportion of animal husbandry structure	29.22	36.1	0.42	29.9	0.49	27.8	0.52
	Promoting Social Responsibility	Application amount of agricultural chemical fertilizer per unit cultivated area	759.2	777	0.51	618	0.43	851	0.54
	Fair Competition	Proportion of agricultural related legal entities	7.11	12.1	0.31	10.3	0.37	7.86	0.46
Consumer	Health and Safety	Qualified rate of food quality supervision and random inspection	96.85	95.5	0.5	96.3	0.5	96.5	0.5
	Transparency	Consumer Price Index: Food	110.6	109	0.5	111	0.5	111	0.5
Rural Areas	Access to Material Resources	Agricultural water use efficiency	13.38	16.5	0.43	12.7	0.52	19.3	0.37
	Access to Immaterial Resources	Coverage rate of Rural radio	99.17	99.5	0.5	99.5	0.5	99.6	0.5
	Delocalization and Migration	Urbanization rate	63.89	63.7	0.5	62.7	0.51	60.6	0.52
	Safe and Healthy Living Conditions	Agricultural carbon emissions per unit land area	163.2	284	0.7	468	0.86	530	0.89
	Secure Living Conditions	Engel coefficient of rural residents	32.66	30.7	0.48	32.7	0.5	29.7	0.47
Society	Community Engagement	Efficiency of agricultural budget expenditure	3.32	3.76	0.46	3.94	0.44	4.41	0.4
	Local Employment	Proportion of employees in primary industry	23.6	31	0.6	26.3	0.54	23.3	0.49
	Contribution to Economic Development	Contribution rate of primary industry	7.65	13.3	0.7	12	0.66	8.4	0.53
	Public Commitment to Sustainability Issues	Grain production per unit sown area	3997	5038	0.42	4190	0.48	4766	0.44
	Technology Development	Per capita scientific research funds of agricultural researchers	29.86	25.4	0.55	30.8	0.49	28.9	0.51

On the opposite side of SR, there are6 of 20 inventory indicators in both maize and wheat, and 8 of 20 inventory indicators in rice with values of SR > 0.5. These relevant social risks are higher than the national average level, meaning negative socio-economic impacts on related fields. In terms of the impact reach, rice has the most inventory indicators with SR > 0.5, meaning the highest risks.

In the field of inventory indicators, SR values of Agricultural carbon emissions per unit land area, are the highest among all the three major grain crops, of which wheat value is as high as 0.89. The result shows that the carbon emissions of these crops are seriously higher than the national average. It is a prominent problem to be solved urgently. To achieve carbon neutrality by 2060, China needs pay more attention to reducing carbon emissions of the three major grain crops; SR values of Contribution rate of primary industry in maize and rice are 0.7 and 0.66 respectively, which are significantly higher than the national average level. Their limited contributions to economic development for China need to be explored further; The SR value of Proportion of employees in primary industry in maize is higher than the national average. There are more opportunities for strengthening the extension of the secondary and tertiary industries of maize; The SR value of Coverage rate of village committees in rice is slightly higher than the average. It may be caused by the planting area characteristics. But the improvement still needs to be done for a better protection of rural residents' rights and interests.

3.2. Weights

The weights are used to rationalize the importance degree of each indicator. In the aggregation of individual weights, the paper uses the geometric mean of all respondents. Then, we build the judgment matrix at all layers to calculate weights. The consistency ratios at all layers are less than 0.1, which means the consistency tests are passed and the model requirement is met. Finally, the results are sorted to obtain the weighting value of each indicator, being applied to the subsequent system calculation. The weighting results of each stakeholder category and subcategory are shown in Table 4.

Table 4. The AHP results of the weighting model.

Layer C \ Layer B	Farmer 0.363	Agricultural Value Chain Actors 0.229	Consumer 0.164	Rural Areas 0.147	Society 0.098	Ranking of Layer C
Freedom of Association and Collective Bargaining	0.188	-	-	-	-	0.068
Fair Salary	0.332	-	-	-	-	0.121
Forced Labor	0.120	-	-	-	-	0.044
Health and Safety of Farmer	0.196	-	-	-	-	0.071
Social Benefits/Social Security	0.165	-	-	-	-	0.060
Supplier Relationships	-	0.491	-	-	-	0.112
Promoting Social Responsibility	-	0.282	-	-	-	0.065
Fair Competition	-	0.227	-	-	-	0.052
Health and Safety of Consumer	-	-	0.742	-	-	0.122
Transparency	-	-	0.259	-	-	0.042
Access to Material Resources	-	-	-	0.216	-	0.032
Access to Immaterial Resources	-	-	-	0.110	-	0.016
Delocalization and Migration	-	-	-	0.134	-	0.020
Safe and Healthy Living Conditions	-	-	-	0.176	-	0.026
Secure Living Conditions	-	-	-	0.175	-	0.026
Community Engagement	-	-	-	0.090	-	0.013
Local Employment	-	-	-	0.100	-	0.015
Contribution to Economic Development	-	-	-	-	0.515	0.050
Public Commitment to Sustainability Issues	-	-	-	-	0.283	0.028
Technology Development	-	-	-	-	0.202	0.020

Note: According to Figure 2, Layer B corresponds to stakeholder categories, and Layer C corresponds to subcategories.

In the layer of stakeholder categories, the importance order of socio-economic impacts on agriculture from high to low is: Farmer > Agricultural Value Chain Actors > Consumer > Rural Areas > Society; In the layer of subcategories, the top ten socio-economic impacts on agriculture are: Health and Safety of Consumer, Fair Salary, Supplier Relationships, Health and Safety of Farmer, Freedom of Association and Collective Bargaining, Promoting Social Responsibility, Social Benefits/Social Security, Fair Competition, Contribution to Economic Development and Forced Labor. A total of nine out of ten weighting values are higher than 0.05, of which the highest is 0.122 in Health and Safety of Consumer.

Through the statistical analysis of the degree of importance of each indicator, we can see that the importance of micro factors focused on people (e.g., Farmer) are significantly higher than that of macro factors concerned on regions (e.g., Rural Areas). Besides, the top three importance factors affecting agriculture from the socio-economic aspect, are food quality, residents' income level and industry chain stability according to the weighting results. These reflect the hottest topics in the current agricultural field.

3.3. Social Impact

SI measures the accumulated risks of negative social impacts for relevant fields. The result shows that: In the matter of stakeholder categories, the highest SIvalue of all the three major grain crops is Farmer, which is significantly higher than the lowest value in Society. Agricultural value chain actors is the second. The other two stakeholder categories have a similar performance, as shown in Figure 4. From the socio-economic view, workers related agriculture industry, especially farmers have the most improvement requirements in the current three major grain crops, more supporting policies are necessary.

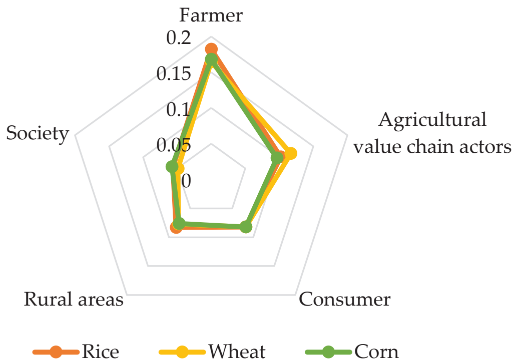

Figure 4. *SI* values of the three major grain crops in stakeholder categories.

In the matter of impact categories, the highest SI value of all the three major grain crops is High-quality growth of agriculture. The development of the agriculture industry is an important reason for the negative socio-economic impacts currently. Balancing the relationship between agricultural development and sustainable development, by improving the quality and efficiency of the three major grain crops, needs to be paid continuous attention. In addition, SI values of A comfortable life in rural areas and The prosperity of rural people are very close, except A comfortable life in rural areas of maize is obviously lower than others. The better performance of maize may be caused by the low risk of carbon emissions and positive impacts of village committees and rural clinics, according to the social risk analysis. Therefore, maize has more positive impacts than wheat or rice on local rural construction. As shown in Figure 5.

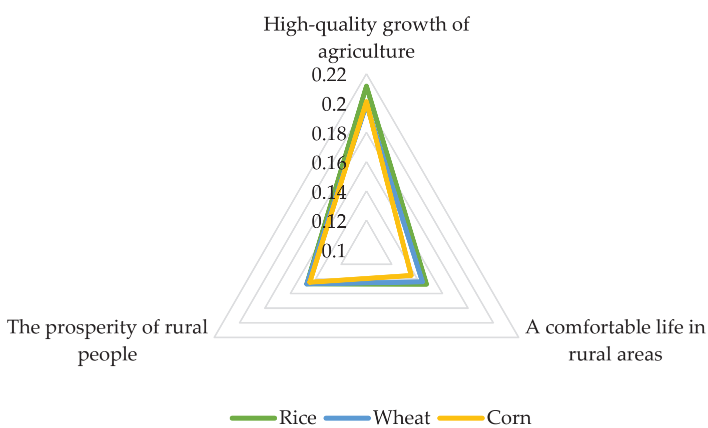

Figure 5. *SI* values of the three major grain crops in impact categories.

The total SI is formed by the sum of each impact category's SI, showing accumulated socio-economic risks of the three major grain crops. The SI of maize, rice and wheat is 0.481, 0.506 and 0.490, respectively. It clarifies that the order of negative socio-economic impacts from high to low is rice > wheat > maize. The result shows that: rice has the worst performance, whose SI is higher than the national average level to 0.5; wheat has more accumulated socio-economic risks than maize according to the SI values, although having the widest scope of positive socio-economic impacts based on the above social risk analysis; maize has the lowest SI values, the most outstanding positive socio-economic impacts and the least inventory indicators with social risks higher than the Chinese average level according to the above social risk analysis. Therefore, maize provides the most positive impacts on the agricultural sustainable development in China.

4. Discussion

4.1. Policy Implications and Recommendations

Based on the above results, this study proposes following suggestions for the sustainable development of the three major grain crops.

Firstly, agricultural enterprises could play a more important role in economy development and employment improvement. The analysis finds that: there are enough agricultural enterprises for the three major grain crops, which has established a good foundation for industrial chain extension in theory. However, according to social risks analysis, the contribution of maize and rice to economic development is limited, and employment in the primary industry of maize is excessive. It means that the three major grain crops in China have not formed a high-quality industrial chain. There is an obvious gap between production and industry. To further promote the main role of enterprises we suggest, enhancing the integration of enterprises into the back-end agricultural industrial construction, attracting employment to the back-end of the industrial chain, and improving the economic contribution of main grain crops.

Secondly, the implementation of ecological environment treatment policy needs to be carried out for a period of time. The analysis finds that: the industrial development of wheat and maize balances the water needs with savings. The agricultural water consumption serves the development of the primary industry reasonably and effectively. However, agricultural water consumption was a prominent social problem in the past several years. China's government proposed many policies for strengthening the construction of farmland water conservancy. Therefore, continuous policy implementation is one of the key factors to consolidate the achievements of environmental protection. Nowadays, the carbon emissions of these crops are serious problems that need to be solved urgently. We suggest establishing a carbon emissions' database of the whole agricultural industry chain, to find a point-to-point way of carbon reduction. Based on the situation, related policies could be proposed and applied for a long period. It would contribute to the realization of China's carbon neutrality goal in 2060 and the world's sustainable development.

Thirdly, more enhanced policies for farmers are needed to be proposed to reduce potential social risks. The analysis finds that: farmers of maize and wheat have better work conditions and basic social guarantee, and the Engel coefficient of rural residents of the three major grain crops are better than the national average, according to the social risk analysis. It shows that the agricultural industrial development provides improvement of residents' lives. In the matter of stakeholder categories, however, the highest accumulated risks of all the three major grain crops are Farmers, followed by Agricultural Value Chain Actors. In addition, the importance of micro factors focused on people are significantly higher than that of macro factors concerned on regions, according to the weights analysis. The results illustrate that the current policy could not really reduce the relevant negative social impacts. We suggest strengthening the policy guarantee for farmers and workers related agriculture industry continuously, to reduce or even eliminate potential socio-economic risks. Improving farmers' and workers' rights and interests are always important policy fields for sustainable development of the three major grain crops.

4.2. Limitations and Further Research

The study has made some innovations in the theoretical research and practical application of agricultural SLCA. There are, however, limitations in theory, method and application, with proposing related suggestions for subsequent research as follows.

In theory, methodological proposal and application cases of SLCA have considerably increased over the years [59]. As the important contents, stakeholder categories, subcategories, inventory indicators and impact categories are guided by, but not the same as, SLCA Guidelines in diverse application cases [47,60–63]. In this context, the following research could explore more relevant assessment systems from stakeholder categories to impact categories on the basis of the standard SLCA framework, so as to build the impact pathway for targeted research fields [64–67].

In method, characterization and weighting methods are key links of the SLCA model construction. Regarding the characterization model, there are SHDB [44,48], PSILCA [68,69], SLCA in Web [70], Life Cycle Working Environment [45], etc., databases utilized in SLCA. Different databases need different data transformation methods with different inventory indicators. These should constantly promote a more stable characterization model construction to adapt various research data [71–74]. Regarding the weighting model, AHP has the characteristic of strong subjectivity based on expert judgments. It still suffers from some theoretical disputes. The rank reversal is surely the most debated problem [56]. Future study may explore more weighting methods for the instrumental SLCA model [75,76].

In application, case studies confirm that the application of SLCA is really important to prove its efficacy and to solidify the technique [49,77–79]. The application scope of the agricultural SLCA model could be expanded further. Based on the agricultural SLCA, analyzing the agricultural socio-economic impacts on dynamic changes by collecting annual data, on regional characteristics by refining regional scope, on industrial trends by specifying agricultural varieties, etc., is attainable. Multi-dimensional and multi-scenario applications are worth the wait [80–82].

5. Conclusions

It is more and more important to analyze agriculture from a socio-economic perspective for agricultural sustainable development. Therefore, applying SLCA in agriculture is of great significance for agricultural socio-economic assessment in theory and practice nowadays.

Based on the theoretical framework of LCA, this study refines the theory of SLCA methods in agriculture, defining the related stakeholder categories, subcategories, inventory indicators and impact categories. The characterization model of quantitative analysis for inventory indicators was built. Additionally, the weighting model for an impact pathway was constructed. This framework could be used for various stakeholders, such as farmers, workers, residents, communities, and society related to the agricultural chain, providing optimized schemes to reduce, or even to avoid, potential social risks.

Grounded on this framework, the socio-economic impacts of the three major grain crops in China are estimated. The results show that: the social impact values of "Farmer" at the stakeholder categories, and "High-quality growth of agriculture" at the impact categories are the highest respectively. It illustrates that farmers are the most important factors for stakeholders in the industry chains, and that high-quality agricultural industrial development has the greatest potential negative socio-economic impacts on society. Additionally, maize has the most outstanding positive socio-economic impacts, the lowest accumulated negative social impact values, and the least inventory indicators with social risks higher than the Chinese average level. Therefore, among the three major grain crops, maize provides the most positive impacts on the agricultural sustainable development in China. Considering the limitations of the study, more work should be done in the future.

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Appendix A

The measurement method of Inventory Indicators is shown in Table A1.

Table A1. Inventory Indicators frameworks of the agricultural SLCA.

Stakeholder Categories	Subcategories	Inventory Indicators	Quantitative Analysis Methods	Unit	Nature
Farmer	Freedom of Association and Collective Bargaining	Coverage rate of village committees	Village committee's quantity [1]/Rural residents' population [1]	Unit/10,000 persons	Positive
	Fair Salary	Income gap between urban and rural residents	Per capita disposable income of urban residents [1]/Per capita disposable income of rural residents [1]	-	Negative
	Forced Labor	Agricultural mechanization rate	Total power of agricultural machinery [2]/Irrigated area of Cultivated land [1]	10,000 KW/1000 hectares	Positive
	Health and Safety	Coverage rate of rural clinics	Rural clinics [1]/Rural residents' population [1]	Unit/10,000 persons	Positive
	Social Benefits/Social Security	Proportion of rural residents with minimum living security	Rural residents entitled to minimum Living allowance [1]/Rural residents' population [1]	-	Negative
Agricultural Value Chain Actors	Supplier Relationships	Proportion of animal husbandry structure	Gross output value of Animal Husbandry [1]/Gross output value of Agriculture, Forestry, Animal Husbandry and Fishery and Related indices [1]	-	Positive
	Promoting Social Responsibility	Application amount of agricultural chemical fertilizer per unit cultivated area	Consumption of Chemical Fertilizers [2]/Irrigated area of Cultivated land [1]	10,000 tons/1000 hectares	Negative
	Fair Competition	Proportion of agricultural related legal entities	Numbers of corporate units in Agriculture, Forestry, Animal Husbandry and Fishery [1]/Total number of corporate units by sector [1]	-	Positive
Consumer	Health and Safety	Qualified rate of food quality supervision and random inspection	Qualification rate of products [1] × (National average food-related qualification rate of examined products [1]/National average qualification rate of products [1])	-	Positive
	Transparency	Consumer Price Index: Food	Consumer Price Index of Food [1]	-	Negative
Rural Areas	Access to Material Resources	Agricultural water use efficiency	Value-added by Primary industry [1]/Agricultural water use [1]	100 million yuan/100 million cu.m	Positive
	Access to Immaterial Resources	Coverage rate of Rural radio	Rural population coverages rate of radio programs [1]	-	Positive
	Delocalization and Migration	Urbanization rate	Proportion of urban population[1]	-	Positive
	Safe and Healthy Living Conditions	Agricultural carbon emissions per unit land area	Carbon emissions of Agriculture, Forestry, Animal Husbandry and Fishery and Related indices [3]/Land areas related agriculture [2]	1000 tons of CO_2/hectare	Negative
	Secure Living Conditions	Engel coefficient of rural residents	Per capital consumption expenditure of rural households in food, tobacco and liquor[1]/per capital consumption expenditure of rural households [1]	-	Negative
	Community Engagement	Efficiency of agricultural budget expenditure	Value-added by Primary industry [1]/Expenditure for Agriculture, forestry and water conservancy [1]	-	Positive
	Local Employment	Proportion of employees in primary industry	Number of employed persons by Primary industry [1]/Number of employed persons by three industries [1]	-	Negative
Society	Contribution to Economic Development	Contribution rate of primary industry	Value-added by Primary industry [1]/Gross regional product [1]	-	Negative
	Public Commitment to Sustainability Issues	Grain production per unit sown area	Output of grain products [1]/Swon areas of farm crops [1]	ton/1000 hectares	Positive
	Technology Development	Per capita scientific research funds of agricultural researchers	Scientific research funds in agricultural related universities and institutes [4]/Number of researchers in related agricultural universities and institutes [4]	10,000 yuan/person	Positive

Sources: [1] is from China Statistical Yearbook-2021; [2] is from China Rural Statistical Yearbook-2021; [3] is from CEADs; and [4] is from public website of related universities and research institutions.

Appendix B

Questionnaire on the Agricultural Social Life Cycle Assessment

Dear expert:

Thank you for taking the time to fill out the questionnaire.

We are constructing an agricultural social life cycle assessment (SLCA) model based on the guidelines of UNEP/ SETAC to assess the social and economic impacts on the three major staple grain crops in China. To assess the relative importance from stakeholder categories to subcategories of the agricultural SLCA, this survey is carried out by analytic hierarchy process method. It includes two parts: Part 1 is the relative importance from stakeholder categories to subcategories of the agricultural SLCA, and Part 2 is basic personal information. All data collected in the questionnaire are only used for academic research. The personal information would be strictly confidential.

Please fill in the questionnaire based on your professional knowledge and experience. Your answer is of great significance to the development of the agricultural SLCA. Thanks again for your support and academic help!

College of Agronomy and Biotechnology
China Agricultural University
January 2022

[Instruction]

According to the standard theoretical framework of LCA, and combined with China's national conditions, the assessment system identified the key process and elements to define the agricultural industrial stakeholder categories including five items: Farmer, Agricultural Value Chain Actors, Consumer, Rural Areas and Society. And the system determined 20 subcategories of stakeholders. Among them, the subcategories of Farmer included 5 items: Freedom of Association and Collective Bargaining, Fair Salary, Forced Labor, Health and Safety, Social Benefits/Social Security. The subcategories of Agricultural Value Chain Actors included three items: Supplier Relationships, Promoting Social Responsibility and Fair Competition. The subcategories of Consumer included two items: Health and Safety, Transparency. The subcategories of Rural Areas included seven items: Access to Material Resources, Access to Immaterial Resources, Delocalization and Migration, Safe and Healthy Living Conditions, Secure Living Conditions, Community Engagement, Local Employment. The subcategories of Society included three items: Contribution to Economic Development, Public Commitment to Sustainability Issues, Technology Development, as shown in Table A2.

Table A2. Agricultural social life cycle assessment indicators.

Stakeholder Categories	Subcategories	Inventory Indicators
Farmer	Freedom of Association and Collective Bargaining	Coverage rate of village committees
	Fair Salary	Income gap between urban and rural residents
	Forced Labor	Agricultural mechanization rate
	Health and Safety	Coverage rate of rural clinics
	Social Benefits/Social Security	Proportion of rural residents with minimum living security
Agricultural Value Chain Actors	Supplier Relationships	Proportion of animal husbandry structure
	Promoting Social Responsibility	Application amount of agricultural chemical fertilizer per unit cultivated area
	Fair Competition	Proportion of agricultural related legal entities
Consumer	Health and Safety	Qualified rate of food quality supervision and random inspection
	Transparency	Consumer Price Index: Food
Rural Areas	Access to Material Resources	Agricultural water use efficiency
	Access to Immaterial Resources	Coverage rate of Rural radio
	Delocalization and Migration	Urbanization rate
	Safe and Healthy Living Conditions	Agricultural carbon emissions per unit land area
	Secure Living Conditions	Engel coefficient of rural residents
	Community Engagement	Efficiency of agricultural budget expenditure
	Local Employment	Proportion of employees in primary industry
Society	Contribution to Economic Development	Contribution rate of primary industry
	Public Commitment to Sustainability Issues	Grain production per unit sown area
	Technology Development	Per capita scientific research funds of agricultural researchers

This study uses an analytic hierarchy process to assess the relative importance from stakeholder categories to subcategories of the agricultural SLCA. Please compare the relative importance of A with B in the comparison table, by selecting the more important factor corresponding to the number, as shown in Table A3.

Table A3. Assessment principle and assignment of relative importance between factors at the same layer.

Scale (a_{ij} Assignment)	Meaning (i Relative to j)
9	Extremely important
7	Strongly important
5	Obviously important
3	Slightly important
1	Equally important
1/3	Slightly unimportant
1/5	Obviously unimportant
1/7	Strongly unimportant
1/9	Extremely unimportant
2, 4, 6, 8, 1/2, 1/4, 1/6, 1/8	The intermediate value of the above two adjacent judgments

[Part 1]

Research on the relative importance from stakeholder categories to subcategories of the agricultural SLCA.

1. Stakeholder category layer

Please assess the relative importance of stakeholders in Table A4.

Table A4. The assessment of the relative importance of stakeholders.

Comparative Stakeholder Category		Relative Importance Scale									
A	**B**	**1/9**	**1/7**	**1/5**	**1/3**	**1**	**3**	**5**	**7**	**9**	**Others**
Farmer	Agricultural Value Chain Actors										
Farmer	Consumer										
Farmer	Rural Areas										
Farmer	Society										
Agricultural Value Chain Actors	Consumer										
Agricultural Value Chain Actors	Rural Areas										
Agricultural Value Chain Actors	Society										
Consumer	Rural Areas										
Consumer	Society										
Rural Areas	Society										

Note: If selecting "others", please fill in the relative importance value in the form.

2. Subcategories layer

2.1. Farmer

Please assess the relative importance of subcategories "Farmer" in Table A5.

Table A5. The assessment of the relative importance of subcategories "Farmer".

Comparative Subcategories		Relative Importance Scale									
A	**B**	**1/9**	**1/7**	**1/5**	**1/3**	**1**	**3**	**5**	**7**	**9**	**Others**
Freedom of Association and Collective Bargaining	Fair Salary										
Freedom of Association and Collective Bargaining	Forced Labor										
Freedom of Association and Collective Bargaining	Health and Safety										
Freedom of Association and Collective Bargaining	Social Benefits/Social Security										
Fair Salary	Forced Labor										
Fair Salary	Health and Safety										
Fair Salary	Social Benefits/Social Security										
Forced Labor	Health and Safety										
Forced Labor	Social Benefits/Social Security										
Health and Safety	Social Benefits/Social Security										

Note: If selecting "others", please fill in the relative importance value in the form.

2.2. Agricultural Value Chain Actors

Please assess the relative importance of subcategories "Agricultural value chain actors" in Table A6.

Table A6. The assessment of the relative importance of subcategories "Agricultural value chain actors".

Comparative Subcategories		Relative Importance Scale									
A	**B**	**1/9**	**1/7**	**1/5**	**1/3**	**1**	**3**	**5**	**7**	**9**	**Others**
Supplier Relationships	Promoting Social Responsibility										
Supplier Relationships	Fair Competition										
Promoting Social Responsibility	Fair Competition										

Note: If selecting "others", please fill in the relative importance value in the form.

2.3. Consumer
Please assess the relative importance of subcategories "Consumer" in Table A7.

Table A7. The assessment of the relative importance of subcategories "Consumer".

Comparative Subcategories		Relative Importance Scale									
A	**B**	**1/9**	**1/7**	**1/5**	**1/3**	**1**	**3**	**5**	**7**	**9**	**Others**
Health and Safety	Transparency										

Note: If selecting "others", please fill in the relative importance value in the form.

2.4. Rural Areas
Please assess the relative importance of subcategories "Rural areas" in Table A8.

Table A8. The assessment of the relative importance of subcategories "Rural areas".

Comparative Subcategories		Relative Importance Scale									
A	**B**	**1/9**	**1/7**	**1/5**	**1/3**	**1**	**3**	**5**	**7**	**9**	**Others**
Access to Material Resources	Access to Immaterial Resources										
Access to Material Resources	Delocalization and Migration										
Access to Material Resources	Safe and Healthy Living Conditions										
Access to Material Resources	Secure Living Conditions										
Access to Material Resources	Community Engagement										
Access to Material Resources	Local Employment										
Access to Immaterial Resources	Delocalization and Migration										
Access to Immaterial Resources	Safe and Healthy Living Conditions										
Access to Immaterial Resources	Secure Living Conditions										
Access to Immaterial Resources	Community Engagement										
Access to Immaterial Resources	Local Employment										
Delocalization and Migration	Safe and Healthy Living Conditions										
Delocalization and Migration	Secure Living Conditions										
Delocalization and Migration	Community Engagement										
Delocalization and Migration	Local Employment										
Safe and Healthy Living Conditions	Secure Living Conditions										
Safe and Healthy Living Conditions	Community Engagement										
Safe and Healthy Living Conditions	Local Employment										
Secure Living Conditions	Community Engagement										
Secure Living Conditions	Local Employment										
Community Engagement	Local Employment										

Note: If selecting "others", please fill in the relative importance value in the form.

2.5. Society
Please assess the relative importance of subcategories "Society" in Table A9.

Table A9. The assessment of the relative importance of subcategories "Society".

Comparative Subcategories		Relative Importance Scale									
A	**B**	**1/9**	**1/7**	**1/5**	**1/3**	**1**	**3**	**5**	**7**	**9**	**Others**
Contribution to Economic Development	Public Commitment to Sustainability Issues										
Contribution to Economic Development	Technology Development										
Public Commitment to Sustainability Issues	Technology Development										

Note: If selecting "others", please fill in the relative importance value in the form.

[Part 2]
Basic personal information
1. How long have you been worked or researched in agricultural related fields?
years
2. Professional title:
○ Professor ○ Associate Professor ○ Lecturer ○ Others (   )

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Article

The Effect of Plate and Decoration Color on Consumer Food Waste in Restaurants: A Case of Four Chinese Cities

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Abstract: Food waste hampers global food security, rational use of global resources and environmental sustainability. Food waste is becoming a global problem, especially on restaurants, and it is particularly important to explore more effective measures to reduce food waste. Color psychology studies show that color can influence human behavior, but how colors may affect consumer food waste behavior has not been thoroughly investigated to date. In this study, we aim to investigate whether food plate colors or restaurant decorations affect food waste behavior using a large-scale field survey in four Chinese cities (2160 samples across Beijing, Shanghai, Chengdu, and Lhasa). Our results show that the per capita food waste of all consumers in the surveyed restaurants was 80.21 g per meal, whereas the per capita food waste of those with warm-color plates was 61.83 g per meal. The results suggest that warm plate colors are associated with reduced restaurant consumer food waste. We also show that the restaurant decoration color was found to correlate significantly with the reduced amount of food ordered per capita per meal (both warm and cool colors). Cool colors for plates and decoration have a negative effect on the weight of per capita per meal food eaten. Additionally, other characteristics of consumers, such as their age, education, and income levels, and other factors, such as for the purposes of meals, were found to affect food waste behavior. Our case study suggests that further investigation into the role of color psychology may be warranted to help mitigate consumer food waste.

Keywords: consumer food waste; color psychology; plate color; decoration color; restaurant

1. Introduction

Food waste has sparked widespread attention globally in recent years. The Food and Agriculture Organization of the United Nations estimated that roughly one third of the world's food (approximately 1.3 billion tons) is wasted from farm to fork every year [1]. There has been a growing body of literature on food waste in different countries such as the United States [2,3], the United Kingdom [4,5], Sweden [6,7] and China [8,9]. Food waste is a threat not only to global food security but also to global resources and environmental sustainability [10,11]. FAO reports that the global annual food waste cost arable land loss, blue water loss, economic cost [12], and lead to carbon dioxide emissions [13]. Research shows 27% of the food produced for human consumption in China is lost or wasted annually [14]. Consumption segment is an important part of food waste [15]. Catering companies generate tremendous amounts of waste [16]. As such, study on food waste in the catering industry is particularly important in recent years.

The effect of color on the human body has been recorded in early civilization such as in ancient Chinese medical texts including *HuangdiNeijing* (literally *The Yellow Emperor's Classic of Medicine*). Health-related theories of "color therapy" believe that color has an effect on the human body, and the choice of color can affect the health of the body. The book Color Psychology and Color Therapy mentions a description of the historical aspects of color as they relate to superstition, the story of mystics, charms, and color healers [17]. Different colors can evoke distinct feelings and emotions [18,19]. Colors are conveyed to the human brain through the senses and then result in human behavior [20].

Therefore, we hypothesize that the plate color and decoration color will have an effect on consumer food waste behavior. In this study, we study on the influence of plate color and decoration color on consumer food waste behavior in restaurants. The restaurant was chosen as a case study because of its relatively large contribution to total food waste [21], particularly in China [22,23], as well as because of increased frequency of dining out. In the country with the world's largest emerging economy, the restaurant sector in China showed that food wasted is about 11 to 17% of that ordered (by weight) [24]. China promulgated the anti-food-waste law in 2021, and the specific implementation details need to be further studied. Because changing plate and decoration color would be a relatively low-cost measure, our results, if positive, can be potentially implemented as an important strategy for restaurant food waste reduction.

2. Literature Review

Food waste at the consumer segment is affected by factors such as economic development, demographic characteristics, and consumer awareness [15]. Food waste per-capita increases with an increase in per-capita GDP [25]. Reducing consumer food waste requires a good understanding of its causes and the role played by consumers. From the perspective of consumers, the factors affecting food waste can be summarized in three areas: (i) consumer behaviors [26], such as a lack of shopping planning, impulse buying [27], and excessive purchasing [28]; (ii) consumer perception [29], including attitudes [30], dietary knowledge [31], and habits and emotions [32]; and (iii) socioeconomic factors [33], such as income and education [34].

Consumers' food waste is also influenced by other factors, such as the reason for eating [34], restaurant categories and purposes of meals [22]. Diet culture is closely related to food waste, and differences in consumption patterns leads to differences in food waste [35]. In recent years, researchers began to explore whether intervention information had an impact on food waste. Researchers have developed different intervention experiments [36], such as written message interventions [37] and social media interventions [38], to study how intervention information might directly affect consumer food waste behavior. Intervention measures will have a positive impact on consumers, and the intervention effect is affected by the intervention design [39]. The impact of plate color and decoration color in a dining environment on consumer food waste, however, has not been investigated.

The food service sector is responsible for more food waste than households in China. According to the field survey conducted by the Institute of Geographic Sciences and Natural Resources Research of Chinese Academy of Sciences, the total amount of food waste in China's urban catering industry is about 17–18 million tons in 2015, equivalent to 3% of the national grain output [40]. The food waste per capita per meal in China's catering industry is 79.52 g [34], which is higher than that urban households of 5.54 g per capita per meal [29] and rural households of 8.74 g per capita per meal [41].

More recently in psychology, there is an increasing focus on the influence of color on human behavior. Psychologists have observed that different colors can evoke distinct feelings and that human physical and mental health and work performances can be affected positively by colors in varying degrees [42,43]. Experiments show that participants are found to overestimate the diameter of food portions by 1.5% and the visual area of food portions by 3% on plates with rim coloring compared with plates with no coloring [44].

The influence of color on human behavior and cognition provides an important basis for potential consumer behavior interventions [45]. For example, studies show that indoor color affects consumer sentiment and cognitive performance, and wall colors can therefore be an effective interior design factor to positively influence the customers' store selection and product purchases [46,47]. Violet and blue interiors produced higher levels of positive affective tone and increased purchase intentions when compared with red and orange interiors [48]. It was also found that people feel differently toward warm colors and cool colors [49], such that different colors associated with food may exert distinct effects on appetite [20].

3. Material and Methods

3.1. Questionnaire Design

The questionnaire was designed by the Food Waste Research Group of the Institute of Geographic Sciences and Natural Resources Research of Chinese Academy of Sciences. Before the formal survey, we conducted a pre-survey on restaurants in June 2015. Based on the pre-survey results and consumer feedback, we adjusted the final questionnaire. The food waste survey comprised three questionnaires: restaurant questionnaire, consumer table questionnaire, and weighing questionnaire. Restaurant questionnaire of each restaurant was filled in by restaurant manager to understand the restaurant's consumer flow, turnover, business philosophy, and other information. Consumer questionnaire of each table was filled in by the surveyed consumer who ordered the food or paid the bill to gain information about consumer, such as education level, gender, age, income and dining reason. Weighing questionnaire of each table was filled in by investigators, aimed at identifying the amount and composition of food waste on the table.

3.2. Definition and Sample Selection

Food waste occurs in the food supply chain at all stages. We mainly focus on food waste on the dining table of restaurants in this study. Food waste in this study refers to the weight of the edible, nonliquid portion of the food leftover on all plates on the table after the dining process. Inedible parts such as excipients, bones, or liquid parts in the food surplus, as well as any packed food leftover in dog bags, were excluded.

Food waste data were obtained from a large-scale survey of restaurant food waste in four Chinese cities, namely Beijing (China's capital), Shanghai (China's economic center), Chengdu (famous food resort in western China), and Lhasa (a tourism city on the Tibetan plateau), between June and August 2015. Different areas in each city were selected to sample the food waste behavior of consumers in both the central and more remote areas of the city (Figure 1).

The food waste data are taken primarily from the consumer questionnaire and the weighing questionnaire. Only when both questionnaires were collected and filled out at the same time can a complete questionnaire be considered. Thus, the final sample size chosen for analysis in this work is slightly smaller than that in our previous research [22] because of a stricter screening of removing vacant values related to data processing and analysis. Specifically, a total of 2160 reliable samples from 161 restaurants (542 samples from 46 restaurants in Beijing, 546 samples from 39 restaurants in Shanghai, 798 samples from 50 restaurants in Chengdu, and 274 samples from 26 restaurants in Lhasa) were included in this study.

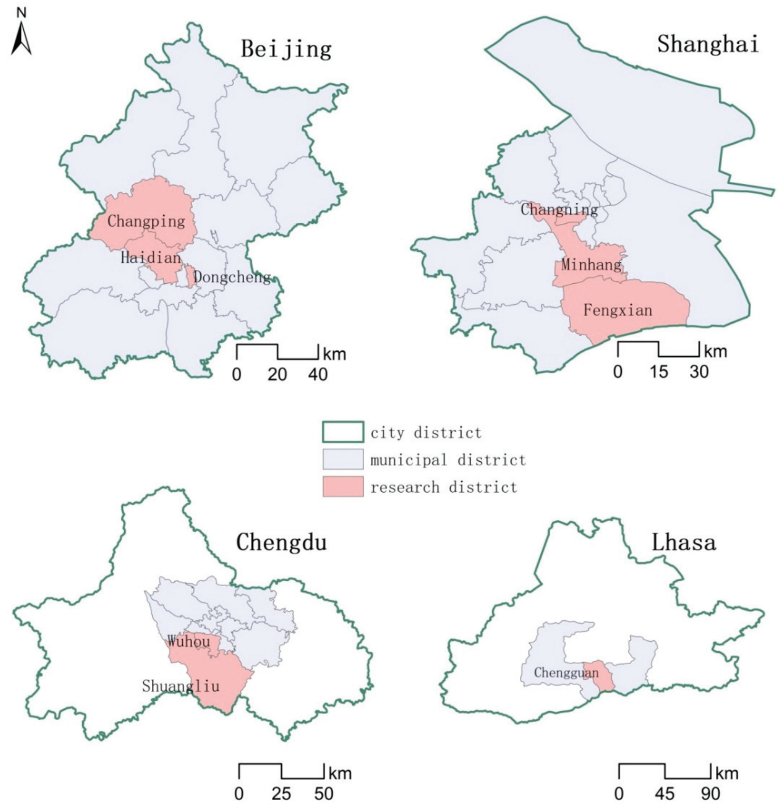

Figure 1. Survey area in four case Chinese cities.

3.3. Field Survey and Direct Weighing

Briefly, stratified random sampling was used, and the number of restaurants surveyed in each city was determined according to the scale and type of restaurants in each city. Sampled restaurants were drawn on the basis of the proportion of different types of restaurants in each city to the total number of restaurants. Relatively large samples were obtained from different cities. Stratified random sampling and field survey were used to obtain specific research samples from the entire catering industry, so the samples are representative. Details on the survey design and sample description can be found in our previous work [22].

The survey covered both lunch and dinner over a full week from Monday to Sunday. We recruited local college students and trained them in research training. Students as investigators who were qualified in the research and training then performed the field surveys of food waste. One dining table was used as a sample for food waste quantification. After the consumer left the restaurant, the restaurant waiter was responsible for sending the plate to the research table where food waste was weighed, and the investigators recruited by the research team calculated food waste using electronic loading balances between 1 g and 5 kg. The food waste weighing location was arranged by the restaurant manager and located out of sight of the consumers.

In the survey process, we also weighed the plate and each dish served at the table before and after it was served to the customer. From this, the weight of food consumed per table was calculated. The remaining edible part was weighed to obtain food waste data. Direct weighing method was used to identify food waste, which is accurate in data identification. During field research, we measured the residue of each dish in each table according to the type of raw materials.

3.4. Variables Description

According to psychological feelings, colors were divided into warm colors (such as red, orange, yellow, and brown), cool colors (such as green, cyan, blue, and purple), and neutral colors (such as black, gray, and white). In our study, the plate/decoration warm/cool color is used as a binary variable with a value of 1 if the plate/decoration contains warm/cool colors, and 0 if the plate/decoration does not contain cool/warm colors.

The key variables in this study, as summarized and detailed in Table 1, include the plate color (whether the plate color contains warm, cool, or neutral colors), decoration color (whether the decoration color in restaurants contains warm, cool, or neutral colors), and the per capita per meal food waste (per capita per meal food waste, i.e., the amount of total food waste measured by direct weighing divided by the number of people on sample tables). The per capita per meal food ordered was recorded both in terms of the number of dishes and the physical weight. The per capita per meal food eaten was the weight of the food that was eaten by consumers, and the per capita per meal eaten ratio was measured by per capita per meal food eaten divided by per capita per meal food ordered by weight.

Table 1. Definition and description of major variables used in this analysis.

Variable Name	Variable Description	Units of Measurement	Variable Value
Per capita per meal food waste	The per capita per meal food waste of all food ofthe sample tables	gram	The per capita per meal food waste weight of the sample tables
Per capita per meal food ordered by amount	The per capita per meal amount of food ordered measured by number of dishes	number	Per capita per meal number of dishes ordered on sample tables
Per capita per meal food ordered by weight	Theper capita per meal weight of food ordered measured by physical weight	gram	Per capita per meal weightof food ordered on the sample tables
Per capita per meal food eaten by weight	The per capita per meal food eaten by consumers of the sample tables	gram	Per capita per meal weightof the sum of the initial weight of the dishes minus the remaining weight of the dishes ordered on sample tables
Per capita per meal eaten ratio	The ratio of per capita per meal food eaten to per capita food ordered	percentage	Per capita per meal food eaten divided by per capita per meal food ordered by weight
Warm color for plate	Whether the plate color contains warm colors		Binary value; if the plate color contains warm colors the value is 1; otherwise, the value is 0.
Cool color for plate	Whether the plate color contains cool colors		Binary value; if the plate color contains cool colors the value is 1; otherwise, the value is 0.
Warm color for decoration	Whether therestaurant decoration color contains warm colors		Binary value; if the decoration color contains warm colors the value is 1; otherwise, the value is 0.
Cool color for decoration	Whether the restaurant decoration color contains cool colors		Binary value; if the decoration color contains cool colors the value is 1; otherwise, the value is 0.

Table 1. *Cont.*

Variable Name	Variable Description	Units of Measurement	Variable Value
Cities	Case cities		
Beijing	Whether the case city is Beijing		The value is 1 if the case city is Beijing and is otherwise 0.
Shanghai	Whether the case city is Shanghai		The value is 1 if the case city is Shanghai and is otherwise 0.
Chengdu	Whether the case city is Chengdu		The value is 1 if the case city is Chengdu and is otherwise 0.
Lhasa	Whether the case city is Lhasa		The value is 1 if the case city is Lhasa and is otherwise 0.
Price	The restaurant's comprehensive price level, to a certain extent, reflects the restaurant's level	yuan	The price variable refers to the average price per gram of food in the restaurants, which is calculated from the total price of all meals and the total net of serving dish weight.
Time	Mealtime		Binary value; the value is 1 if it is dinner; otherwise, the value is 0.
Age	The age of the respondent		The value varies between 1 and 6, as defined below: 1 (under 20 years old); 2 (21–30 years old); 3 (31–40 years old); 4 (41–50 years old); 5 (51–60 years old); and 6 (over 60 years old)
Tourist	Whether the consumersare tourists		Binary value; if the consumers are tourists, the value of 1; otherwise, the value is 0.
Frequency	The eatingout frequency of consumers in this restaurant		The range of values is 1–5, and the higher the value, the less frequently they eat out in this restaurant
Gender	The gender of the respondent		Binary value;the value is 1 for male and 0 for female.
Frugality	The frugal consciousness of the respondent compared with most people		The range of values is 1–5, and the higher the value, the greater the frugal consciousness.
Income	The monthly income level of the respondent		The range of values is 1–6, with definition as follows: 1 (under 2000 RMB); 2 (2001–4000 RMB); 3 (4001–6000 RMB); 4 (6001–8000 RMB); 5 (8001–10,000 RMB); 6 (10,001–12,000 RMB); 7 (12,001–14,000 RMB); 8 and (above 14,000 RMB)
Edu	The level of education of the respondent		The range of values is 1–6, with definition as follows: 1 (primary school or below); 2 (junior high school); 3 (high school); 4 (university); 5 (masters); and 6 (doctorate)
Farming experience	Whether the respondent has farming experience		If there is farming experience, the value of 1; otherwise, the value is 0.

Table 1. *Cont.*

Variable Name	Variable Description	Units of Measurement	Variable Value
Ordering	Whether the respondentis the one who has ordered food		If the respondent is the one who has ordered food, the value is 1; otherwise, the value is 0.
Dining reason	The reasons for dining		
Business/official	Whether the reason for dining is business/official		It has a value of 1 for business/official; otherwise, it has a value of 0.
Family gathering	Whether the reason for dining is family gathering		It has a value of 1 for family gathering; otherwise, it has a value of 0.
Friend gathering	Whether the reason for dining is friend gathering		It has a value of 1 for friend gathering; otherwise, it has a value of 0.
Working meal	Whether the reason for dining is working meal		It has a value of 1 for working meal; otherwise, it has a value of 0 (reference group).
Not specific	Whether the reason for dining is not specifically mentioned		It has a value of 1 for not specified purpose; otherwise, it has a value of 0.
Others	Whether the reason for dining is other		It has a value of 1 for other purposes; otherwise, it has a value of 0.
Elderly	Whether the respondent has family members above 50 years oldin their household		Thevalue is 1 if there are family members above 50 years old; otherwise, the value is 0.

4. Results

4.1. Effect of Plate and Decoration Color on Food Waste, Food Ordered, and Food Eaten

We collected a total of 2160 samples, including 752 samples with zero food waste reported. This means that not all consumers have food waste behavior. The data showed that consumers of 65.19% of the investigated tables have food waste behavior, and the remaining consumers do not have food waste behavior. There may be measures for consumers to reduce food waste. The per capita food waste of consumers was found to be 80.21 g/capita/meal. Table 2 shows the descriptive statistics of the main variables used in this analysis.

We used per capita per meal food waste as an explanatory variable to establish a model to empirically analyze the food waste behavior of consumers under the influence of different plate and decoration colors. Because the amount of per capita per meal food waste is not less than 0, the Tobit model was adopted to overcome the data interception of the explanatory variables.

Our empirical results as shown in Table 3 confirm that consumer food waste behavior is affected by plate color. When the plate color contains warm colors, the consumer food waste per capita per meal is significantly reduced, and their food waste behavior is positively affected. When the plate color contains cold colors, no statistically significant effect on the food waste behavior of consumers was found. In this context, we speculate that warm colors give consumers a positive feeling that may help reduce food waste.

Table 2. Descriptive statistics of main variables used in this analysis.

Variable Name	Mean	Std. Dev.
Per capita per meal food waste	80.210	117.430
Per capita per meal food ordered by amount	2.188	2.078
Per capita per meal food ordered by weight	1114.556	1768.839
Per capita per meal food eaten	1034.620	1760.131
Per capita per meal eaten ratio	0.917	0.116
Warm color for plate	0.124	0.329
Cool color for plate	0.054	0.225
Warm color for decoration	0.699	0.459
Cool color for decoration	0.106	0.307
Cities		
Beijing	0.251	0.434
Shanghai	0.253	0.435
Chengdu	0.369	0.483
Lhasa	0.127	0.333
Price	0.063	0.122
Time	0.369	0.483
Age	2.477	1.000
Tourist	0.252	0.434
Frequency	3.957	1.380
Gender	0.496	0.500
Frugality	3.783	1.096
Income	3.156	1.963
Edu	3.775	0.880
Farming experience	0.325	0.468
Ordering	0.743	0.437
Dining reason		
Business/official	0.032	0.177
Family gathering	0.193	0.394
Friend gathering	0.277	0.448
Working meal	0.172	0.378
Not specific	0.305	0.460
Others	0.021	0.143
Elderly	0.627	0.484

Note: The sample size is 2160. (N = 2160).

Table 3. Effect of plate and decoration color on per capita per meal food waste.

Variable Name	Coef.	Std. Err.	t	Marginal Effect
Warm color for plate	−26.588 **	11.689	−2.27	−15.914
Cool color for plate	1.762	17.119	0.10	1.055
Warm color for decoration	−6.668	10.631	−0.63	−3.991
Cool color for decoration	−1.907	14.333	−0.13	−1.141
Control variables	Controlled			
_cons	−94.030 ***	46.270	−2.03	

Note: **, *** indicates statistical significance at the 0.05, 0.01 levels, respectively (N = 2160).

The decoration color, however, was found to have no statistical effect on food waste per capita per meal generation. This applies to both warm decoration colors and cool decoration colors. This means that changing the decoration color is unlikely to affect food waste per capita per meal generation by consumers.

Food waste is the product of a consumer's choice of the amount to order as well as to eat. To find a better way to reduce food waste in restaurants from the perspective of color, we attempted to explore the effect of colors on consumer food ordered and food eaten, separately. It is worth noting that consumers cannot see the plate when they are ordering the food, so decoration color can only be used to analyze any effect on food ordered. In China, some restaurants will provide pictures of the dishes at the point of ordering, but because this picture is a schematic diagram, it differs from the actual dishes and the plates that are served. Although these restaurants may offer menus that include pictures of plates, the plates in the pictures have little resemblance to the actual plates.

The effect of decoration color on consumer food ordered was analyzed from two aspects: Table 4 shows the effect of decoration color on per capita per meal food ordered by amount, and Table 5 shows the effect of decoration color on per capita per meal food ordered by weight. The control variables in Tables 4 and 5 are the same as those in Table 3. Table 4 shows that both warm and cool decoration colors have a significant negative effect on per capita per meal food ordered by amount. Table 5 shows that both warm and cool decoration colors have no effect on per capita per meal food ordered by weight.

Table 4. Effect of decoration color on per capita per meal food ordered by amount.

Variable Name	Coef.	Std. Err.	t	P > |t|
Warm color for decoration	−0.335 ***	0.130	−2.58	0.010
Cool color for decoration	−0.515 ***	0.176	−2.93	0.003
Control variables		Controlled		
_cons	0.926 *	0.550	1.68	0.093

Note: * and *** indicate statistical significance at the 0.10 and 0.01 level, respectively (N = 2160).

Table 5. Effect of decoration color on per capita per meal food ordered by weight.

Variable Name	Coef.	Std. Err.	t	P > |t|
Warm color for decoration	−45.046	110.871	−0.41	0.685
Cool color for decoration	−224.078	150.287	−1.49	0.136
Control variables		Controlled		
_cons	588.343	469.904	1.25	0.211

Note: N = 2160.

We can find the effect of plate and decoration colors on the weight of food eaten per capita per meal in Table 6. The control variables in Table 6 are the same as those in Table 3. Interestingly, cool colors for plates and decoration have a negative effect on the weight of per capita per meal food eaten. It is also interesting that both warm colors for plates and warm colors for decoration have no statistically significant effect on the weight of per capita per meal food eaten. Because consumers eating as much as possible will reduce food waste, these negative effects are necessarily desirable from the perspective of waste.

Table 6. Effect of plate and decoration colors on per capita per meal food eaten by weight.

Variable Name	Coef.	Std. Err.	t	P > |t|
Warm color for plate	−192.817	118.288	−1.63	0.103
Cool color for plate	−325.351 *	176.044	−1.85	0.065
Warm color for decoration	−31.136	110.993	−0.28	0.779
Cool color for decoration	−248.510 *	149.915	−1.66	0.098
Control variables		Controlled		
_cons	677.364	466.685	1.42	0.155

Note: * indicates statistical significance at the 0.10 level. (N = 2160).

Because the eating weight cannot be greater than the ordering weight, the effect of decoration color on eating weight is derived from the effect of decoration color on ordering weight. We therefore researched the effect of the plate and decoration colors on the eating ratio. No significant effect was found for both warm and cool colors of plate or decoration colors (Table 7). It is worth mentioned that warm color for a plate has a positive effect on eating ratio, which is very close to significant.

Table 7. Effect of plate color on per capita per meal eaten ratio.

Variable Name	Coef.	Std. Err.	t	Marginal Effect
Warm color for plate	0.012	0.008	1.62	0.012
Cool color for plate	−0.006	0.011	−0.54	−0.006
Warm color for decoration	0.000	0.007	0.07	0.000
Cool color for decoration	−0.013	0.010	−1.37	−0.013
Control variables		Controlled		
_cons	0.932 ***	0.031	30.48	

Note: *** indicates statistical significance at the 0.01 levels (N = 2160).

4.2. Effect of Other Variables on Food Waste

Our regression analysis reveals that other socioeconomic parameters have statistically significant impacts on food waste (Table 8). It should be noted that, although our previous research [22] reported similar variations of per capita per meal food waste generation among different consumer groups, because of the use of the Tobit and OLS based regression analysis in this study, we were able to control the impact of other factors on food waste when analyzing a specific factor. This enables more robust conclusions over the effect of other socioeconomic variables on food waste generation. These are summarized below.

- The meal time period exerted a significant effect on consumer food waste behavior. Consumers waste more food during dinner, which takes practically more time than at lunch.
- The personal characteristics of consumers significantly affected their food waste behaviors as well. In our study, we find the food waste increases first and then decreases with age, in an “inverted U shape”. The education level has a similar impact on food waste as an “inverted U shape”. Regarding household income, it was found that the higher the income level, the more food waste was generated.
- The frugal consciousness of consumers had a significant effect on food waste behavior. The more consumers self-report frugal consciousness, the less food waste they generate.
- Food waste behaviors between tourists and nontourists were significantly different. Results suggest that tourists waste more food than nontourists per capita per meal.
- The frequency of consumers dining out in restaurants significantly affects consumer food waste behavior. The less frequently the consumers go to restaurants, the more food waste they generate. This may be because consumers who dine out more frequently are more aware of the quantity, type, and taste of the food in the destination restaurants.
- Meal purposes were found to have a significant impact on consumer food waste behaviors. Consumers who were dining out for a friend gathering wasted more food. This is mainly related to the special *mianzi* culture and hospitality conventions in China.

Table 8. Effect of other variables on per capita per meal food waste.

Variable Name	Coef.	Std. Err.	t	Marginal Effect
Cities				
Beijing	8.000	13.810	0.58	4.882
Shanghai	−7.734	13.929	−0.56	−4.569
Chengdu	−2.185	13.417	−0.16	−1.306
Price	−0.919	28.185	−0.03	−0.550
Time	20.523 ***	7.620	2.69	12.283
Age	40.337 **	15.927	2.53	24.143
Age_sq	−6.754 ***	2.559	−2.64	−4.042
Tourist	35.295 ***	8.307	4.25	21.125
Frequency	6.740 **	2.811	2.40	4.034
Gender	−4.252	7.394	−0.58	−2.545
Frugality	−6.990 **	3.285	−2.13	−4.184

Table 8. *Cont.*

Variable Name	Coef.	Std. Err.	t	Marginal Effect
Income	3.104	2.192	1.42	1.858
Edu	64.441 ***	19.676	3.28	38.570
Edu_sq	−11.014 ***	2.812	−3.92	−6.592
Farming experience	−4.086	8.178	−0.50	−2.445
Ordering dishes	−26.930 ***	8.292	−3.25	−16.118
Dining reason				
Business/official	26.512	21.981	1.21	16.211
Family gathering	15.355	12.607	1.22	9.179
Friend gathering	43.816 ***	11.709	3.74	27.702
Not specific	−24.410 **	11.483	−2.13	−13.370
Others	−26.661	27.723	−0.96	−14.526
Elderly	1.987	7.533	0.26	1.189

Note: **, *** indicates statistical significance at the 0.05, 0.01 levels, respectively (N = 2160).

5. Discussion

There are inconsistencies in the definitions and calculation methods used to measure food waste in the previous papers [50], and some literature is based on secondary data on food waste [25]. We used statistical analysis and quantitative regression to provide more robust results as well as first-hand direct-weighing-based consumer food waste data, which can be more reliable than secondary data based on literature or modeling for the analysis. Therefore, we suggest to conduct more surveys on food waste and obtain first-hand data for research.

According to our results, plate color has different effects on per capita per meal food waste, food ordered, and food eaten. Warm colors may have a positive effect in reducing consumer food waste in restaurants. These results are consistent with the previous research on color psychology: color does affect the mind of consumers and their behavior, and consumers have different feelings and behaviors in response to distinct colors [38]. For example, it was previously claimed that plate color plays an important role in people's perception of food [51]. Because changing the plate color is a relatively low-cost intervention, it may be an impactful way to reduce consumer food waste and one that has not been often discussed in the food waste literature.

The personal characteristics of consumers affected their food waste behaviors, such as age [52,53], education [31,54], and income [55,56], which is consistent with previous research results. It has been previously found that the more aware youths are concerning food waste, the more likely they are to reduce leftovers [26]. Building consumer awareness [54] and perception [29] about food waste is an important measure for reducing food waste. Tourists wasted more food than local residents on a per capita level, which is consistent with previous research [57]. More quantitative research will help to inform policy making and to increase public awareness of the problem in China [58].

Multiple food supply chain actors should take action to measure and reduce food waste [50,59]. There are simple but effective food waste minimization strategies that can lead to a drastic decrease in global food waste generation, such as provide consumers with menu by petite nature [60]. We anticipate that our case study on China can enable more scientific analyses on these effects and promote discussion for efforts and interventions to mitigate against food waste. We believe our case studies and results can contribute usefully in furthering our understanding of the effect of color on consumer food consumption and waste. Food waste behavior of consumers may be affected by COVID-19, and there may be some changes in purchasing and consumption behavior. These need further study.

6. Conclusions and Limitation

6.1. Conclusions

Our results show that the per capita per meal food waste of all consumers in the surveyed restaurants was 80.21 g, whereas the per capita per meal food waste of those with warm-color plates was 61.83 g. This indicates that warm plate colors may have a positive effect in reducing restaurant consumer food waste. We have also shown that although the restaurant decoration color does not have a statistically significant effect on consumer food waste, it does show a negative effect on per capita per meal food ordered by amount (both warm and cool colors). Cool colors for plates and decoration have a negative effect on the weight of per capita per meal food eaten. This means decorating the restaurant environment with cool colors may help to reduce the weight of food eaten and the possibility of increase food waste, which merits further research.

Additionally, the personal characteristics of consumers, such as age, education, and income levels, and other factors such as for the purposes of meals, were found to affect food waste behavior. Our case study confirms that color psychology may be important in reducing food waste, and it suggests that more research in this area may be valuable for the purposes of mitigating consumer food waste.

6.2. Limitation

Because of methodology and data limitations, our analysis has some unavoidable limitations. First, we have only recorded information on plate color and decoration color in our survey, without specifying different components of the dining environment (e.g., table cloth, wall, and floor) or different shades of the same color (e.g., dark red versus light red). Second, only the one who ordered the food or paid the bill has filled in the questionnaire on individual consumer characteristics such as age, occupation, education, and income, which may not be representative of all consumers on the sample table. Third, other potentially important factors related to consumer food waste behavior, such as the mental state of consumers and the external intervention, are not included and require further analysis. Additionally, meals can vary in size if eaten on weekdays versus on weekends. Last but not least, despite our best efforts, the sample representativeness may still be limited, and wider coverage may be useful for future study.

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Article

A Research on the Evaluation of China's Food Security under the Perspective of Sustainable Development—Based on an Entropy Weight TOPSIS Model

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Abstract: Food safety is an important basis for promoting economic development, ensuring social stability and maintaining national security. Research on the evaluation of food security is the basis by which to accurately grasp the food security situation and to establish national food security policies in a scientific manner. Based on China's agricultural economic data from 2001 to 2020, this research uses an entropy weight TOPSIS model to start from the new connotations and goals of food security in the new development stage, takes quantity security, structural security, ecological security of resources, economic security and policy security as the breakthrough points, builds a food security evaluation system containing 25 indicators, and aims to conduct evaluation and research on the evolution and current situation of China's food security. The results show that China's food security level drops first and then rises, that China attaches increasing importance to the ecological security and policy security of food resources, and that China's food security level is restricted by such factors as resources, modes of production, circulation, storage, transportation, trade and structure. This article puts forward some policies and suggestions in terms of resources, technology and foreign trade to safeguard China's food security.

Keywords: food security; sustainable development; indicator system; evaluation; entropy weight TOPSIS model

1. Introduction

Food safety is an issue of overall national strategy and an important basis to promote economic development, safeguard social stability and maintain national security, and it has been a concern in all walks of life for a long time [1,2]. China has always attached great importance to food safety, and has introduced a series of policies such as "taking grain as the key link and ensuring an all-round development", "ensuring basic self-sufficiency of grain and absolute security of staple food" and "establishing 'great food security concept'", which fully reflects the degree of importance attached by China to food security in the long term [3]. In recent years, China has had a succession of good harvests in terms of grain production, and its grain circulation capacity has greatly improved, so that the 1.3 billion Chinese people have no need to worry about the problem of food, but at the same time, several new conditions and problems arose, presenting a formidable challenge to food security work. From the perspective of production links: first, the environmental constraints of resources such as arable land and freshwater resources are aggravated, and the constraints of sustainable development of food are increasing; second, production becomes divorced from marketing, and the supply of some varieties can become seriously excessive in stages; third, the cost of grain planting rises, high yield co-exists with low efficiency, farmers' incomes can hardly be increased, and the financial burden on farmers becomes heavy [4,5]. From the perspective of demand: first, with the changes in the childbearing policy and the acceleration of the urbanization process, the food demand increases rapidly, and this trend will not change; second, with the increase in residents' income level, the grain consumption increase is accelerated, and the contradictions in varieties and quality structures become prominent [6]. Moreover, such factors as globalization, climatic variation, ecological degradation, COVID-19 pandemic, regional conflicts and carbon peaking and carbon neutrality goals also present significant challenges to China's food security [7–9].

Food security is a relative and dynamic concept. The state of food security (or insecurity) can be reflected through a certain number of indicators, to answer the questions such as "what's food security" and "how to evaluate the development level of food security" [10]. The evaluation and research on food security is not only the basis to grasp the situation of food security, but also the basis for a state to formulate food security policies [11,12]. No.1 Central Document for 2022 clearly points out that China should fully implement "equal accountability of Party and government organizations" in terms of food security, strictly carry out the examination of the food security responsibility system, vigorously carry out green actions with high quality and high efficiency, deeply implement high-quality food projects, and fully improve the level of food security. Against this background, the scientific design of the food security evaluation indicator system and the objective measurement of China's food security level are major issues in determining the development direction of China's food security, reducing China's food security risks and building a sustainable agriculture and food system [13,14].

The Food and Agriculture Organization of the United Nations (FAO) has defined food security three times, and these definitions of food security are widely accepted by the international community. The essence of food security is to enable everyone to enjoy sufficient food at any time and to meet the living needs of people. On this basis, many experts, scholars and related agencies in China and abroad adopted multiple methods to conduct quantitative evaluation of food security [15–17]. In 2013, the Food and Agriculture Organization (FAO) released the "2013 Report on the State of Food Insecurity in the World: Multiple Dimensions of Food Security", in which they selected 30 indicators from four dimensions, i.e., food availability, food stability, food access and food utilization, built a food security evaluation indicator system, and conducted the evaluation of the state of food security in 157 countries and regions in the world [18]. After that, there were many foreign researchers who established food security evaluation systems from the aforementioned four dimensions to conduct evaluation of the state of food security in their countries or regions [19–24]. Moreover, there were many foreign researchers who started from the macroscopic angle and adopted the questionnaire method to conduct comprehensive evaluation of the state of food security in countries or regions from the microscopic angle [25–30].

Chinese scholars mostly adopt multi-indicator comprehensive measurement methods to conduct evaluations of food security. The research thought is as follows: building a multi-stage indicator system first, conducting dimensionless standardized processing of indicators, calculating the development levels of indicators one by one, and finally calculating comprehensive indexes on the basis of different weights. For example, Wang Guomin et al. (2013) [31] adopted the Delphi method and the AHP method to establish a food security evaluation system containing nine indicators, and measured China's food security level. Yao Chengsheng et al. (2015) [32] built China's food security evaluation indicator system from four levels, i.e., grain production resources, food availability and stability, food access and food utilization, and conducted quantitative evaluation of the state of food security in China. Mao Xuefeng et al. (2015) [33] evaluated the state of food security in China from the perspectives of food structure, food circulation and trade links. Gao Yanlei et al. (2019) [34] started from major grain producing areas, and adopted the entropy weight TOPSIS model to evaluate the state of food security in China from four dimensions, i.e., availability, access, stability and sustainability. Furthermore, Cui Mingming et al. (2019) [35], Li Xiuxiang et al. (2020) [36], and Qi Yue et al. (2020) [37] applied different methods of evaluating food security through building different indicator systems.

Generally speaking, there are rich research results regarding food security, which can reflect some of the characteristics of food security. However, there are some shortcomings in the research process, such as limited sample selection, single or crossed indicator selection, and strong subjectivity, so that the research can hardly reflect the actual development level of food security in a comprehensive, systematic and accurate manner. As China steps into a new development stage and the environment of food security both at home and abroad changes fundamentally, the connotation of food security is steadily enriched and the goals of ensuring food safety are constantly boosted [1]. The previous research studies on the food security indicator system are more focused on quantity security, but less focused on structural security, ecological security of resources, economic security and policy security, so that they cannot meet the needs of evaluation of food security level under the current development strategy. On the basis of previous research, both at home and abroad and in combination with the new connotation and goals of the food security concept in the new era, this article establishes a food security evaluation system from five levels, i.e., quantity security, structural security, ecological security of resources, economic security and policy security, and adopts the entropy weight TOPSIS model to conduct quantitative evaluation of China's food security. Moreover, it reviews the historical evolution of China's food security on the basis of evaluation results, analyzes the shortcomings and potential risks existing in China's food security, and puts forward corresponding policy suggestions.

Compared with the existing literature, this article may have the following marginal contributions: (1) the food security evaluation indicator system built in the research is more comprehensive and systematic, and when considering quantity security, the system is more focused on such important aspects as structural security, ecological security of resources, economic security and policy security; (2) the entropy weight TOPSIS model used in the research can avoid subjective bias effectively and improve the accuracy of judgment about the actual development level of food security; (3) in the research reviews the development and evolution of food security on the basis of the evaluation results, determines the root cause of food security issues, and provide specific recommendations for China to solve food security issues.

The structure arrangement of the remainder of this article is as follows: Part 2 is concerned with the construction and research design of the food security evaluation indicator system, including data sources, modeling principles and modeling steps; Part 3 presents empirical research, focused on the analysis of model results; Part 4 mainly discusses the evolution of the development level of food security, the existing problems, the shortcomings of the research, and the next research direction; Part 5 sets forth conclusions and policy suggestions.

2. Methods and Data

2.1. Construction of Evaluation Indicator System

2.1.1. Design Principles for Indicator System

Food security issues involve multiple factors. All these factors are interrelated and interact with each other, and constitute an organic whole. Due to the systematic nature and complexity of food security influencing factors, the food security evaluation indicator system should be a well-bedded and well-organized complex. Thus, the setting of the food security evaluation indicators should conform to the following principles:

(1) Systematic Principle. The food security evaluation indicator system is a system concept, consisting of the subsystems at different layers, such as target layer, criterion layer and indicator layer. All system layers are interrelated, depend on each other, influence each other and restrict each other. When building the food security evaluation indicator system, one is required to adopt systematic thinking, i.e., regarding the evaluation indicator system as an effective, inclusive and open system that is characterized by the natures of dynamics and complexity. Furthermore, it is a requirement to apply system-related theories to carrying out the overall layout of the evaluation indicator system and realize the

optimization and upgrading of the organic whole through interaction and transformation of the factors inside and outside the system [38,39].

(2) Scientific Principle. The design of the food security evaluation indicator system must stick closely to the stage goals, contemporary connotation and features of food security and carry out evaluation from the aspects such as economic benefits, social benefits and ecological benefits. The evaluation indicators should be able to reflect the actual development level of food security in the current stage as well as the future development direction and development potential of food security. It is a requirement to define the category and weight of each indicator in the evaluation system in a scientific and reasonable manner, and select and use scientific calculation methods and models to carry out quantification and evaluation [40].

(3) Guiding Principle. The design of the food security evaluation indicator system should fully reflect the emphasis and key points of the construction of food security in countries or regions, and it is the breakthrough and point of strength to improve the food security level at present and in the short run. Through the construction and use of the food security evaluation indicator system, directional guidance should be provided for countries or regions to improve their food security levels, enabling academic circles and related government decision-making departments to clearly understand the focus and direction of future research [30,38].

(4) Operability Principle. The design of the food security evaluation indicator system should be in line with the development goals set forth in relevant policy documents such as No.1 Central Document formulated by the Party and the state as well as Outline of the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and Vision 2035 of the People's Republic of China, to ensure that the evaluation indicator system highlights major points and has a clear logic and a reasonable framework. Each designed indicator should be simple, clear and measurable, and all involved data should be of strong availability, to facilitate future calculation and evaluation [37,38,41].

(5) Harmonization Principle. The design of the food security evaluation indicator system shall harmonize the comprehensiveness and representativeness of evaluation indicators. The evaluation indicator system should reflect the development state of food security as fully and comprehensively as possible, and cover the essence of the connotation of food security in the current stage. However, the food security evaluation indicator system is unlikely to cover every aspect, and can only involve important areas and representative areas; thus, it is a requirement to find the point of equilibrium between full coverage and representativeness. Moreover, the design of the evaluation indicator system requires coordinating the relationship among the past, the present and the future, and it does not only need to meet the current needs and consider the future condition, but also need to adopt the existing evaluation indicator system [38,42].

2.1.2. Construction of Indicator System

In the construction process of the food security (A) evaluation system, the research regards "sustainable development" as the main line, sticks closely to the contemporary connotation of food security, and follows the systematic principle, the scientific principle, the guiding principle, the operability principle and the harmonization principle. On the basis of related research results both at home and abroad, corresponding indicators can be selected to build a food security evaluation system from 5 aspects, i.e., quantity security (A1), structural security (A2), ecological security of resources (A3), economic security (A4) and policy security (A5). The system sets 25 indicators in total, including volatility of grain yield, grain sowing area and grain yield per unit area (Table 1). Evaluation indicators consist of positive indicators and negative indicators. Positive indicators are positively correlated with the level of food security.

Table 1. Food Security Evaluation Indicator System.

1st Grade Indicator	2nd Grade Indicator	Unit	Properties
Quantity Security (A1)	Volatility of Grain Yield (A11)	%	Negative
	Grain Sown Area (A12)	1000 ha.	Positive
	Grain Yield per Unit Area (A13)	kg/ha.	Positive
	Per Capita Grain Possession (A14)	kg/person	Positive
Structural Security (A2)	Degree of Dependence on Grain Foreign Trade (A21)	%	Positive
	Proportion of Feed Grain Sowing Area in Grain Sowing Area (A22)	%	Positive
	Proportion of Soybean Imports in Grain Imports (A23)	%	Negative
	Stock-to-Use Ratio (A24)	%	Positive
Ecological Security of Resources (A3)	Pesticide Consumption per Unit Sown Area (A31)	kg/ha.	Negative
	Consumption of Chemical Fertilizers per Unit Sown Area (A32)	kg/ha.	Negative
	Proportion of Effective Irrigation Area (A33)	%	Positive
	Multiple Cropping Index (A34)	%	Positive
	Per Capita Water Resources (A35)	m^3/person	Positive
	Arable Land Per Capita (A36)	m^2/person	Positive
	Proportion of Disaster-affected Area (A37)	%	Negative
Economic Security (A4)	Food Price Volatility (A41)	%	Negative
	Net Profit of Grain Planting (A42)	RMB/ha.	Positive
	Engel's Coefficient of Rural Residents (A43)	%	Negative
	Agricultural Labor Productivity (A44)	10,000 RMB/Person	Positive
	Agricultural Land Productivity (A45)	10,000 RMB/ha.	Positive
Policy Security (A5)	Transportation Route Intensity (A51)	km/km^2	Positive
	Agricultural Mechanization Level (A52)	kW/ha.	Positive
	Contribution Rate of Agricultural Scientific and Technological Progress (A53)	%	Positive
	Educational Level of Agricultural Labor Force (A54)	%	Positive
	Financial Expenditure for Grain Production (A55)	100 million RMB	Positive

2.1.3. Indicator Calculation and Description

(1) Quantity Security. Quantity security embodies the grain amount that is maintained to ensure food supply capacity and meet people's grain demand. The first indicator designed is volatility of grain yield. This indicator is an important indicator that reflects the stability of grain supply. The computational formula is: $R_t = \left(Y_t - Y_t^{'}\right)/Y_t^{'}$, among which, Y_t represents the grain yield of the year t and $Y_t^{'}$ represents the trend yield, which is expressed as the moving average of five years in this research [32,35]. The second indicator is grain sown area. The grain sown area is the basis of food quantity security. The higher the value, the higher the guaranteed level of food quantity security [36]. The third indicator is grain yield per unit area. This indicator r mainly reflects the degree of development of food technology and efficiency. The higher the value, the higher the guaranteed level of food quantity security [43,44]. The fourth indicator is per capita grain possession. This indicator starts from the microcosmic angle of view and can reflect both the stability of total grain output and the changes in grain supply capacity with the increase in population [45,46].

(2) Structural Security. The food structure in the research contains supply structure, plantation structure and import structure. The first indicator designed is the degree of dependence on grain foreign trade, which is expressed as the ratio of grain import volume to grain yield (in the research, food/grain mainly refers to cereals). This indicator mainly considers the impact of the international grain market on national food security and reflects the degree of structural security of the food supply [47]. The second indicator is the proportion of feed grain sowing area in the grain sowing area. In the research, feed grain mainly refers to corn and soybeans [36]. As people's demand for animal products such as meat, eggs and milk increases, the feed grain consumption will rise accordingly. This indicator is designed to evaluate the state of China's grain planting structure and further reflect the degree of security of the grain planting structure. The third indicator is the proportion of soybean imports in grain imports. The design of this indicator is mainly

based on China's large soybean imports and high degree of dependence upon foreign trade, and this indicator is used to evaluate the degree of structural security of grain import. In this indicator, grain mainly refers to rice, wheat, corn and soybeans. The fourth indicator is stock-to-use ratio [48]. This indicator mainly embodies the food supply capacity of the state in responding to major natural disasters, wars and other serious sudden events. The calculation formula is $\beta = (S_t/C_{t+1}) * 100\%$, among which, β represents stock-to-use ratio, S_t represents the carry-over stock of the year t, and C_{t+1} represents the grain consumption of the year t + 1.

(3) Ecological Security of Resources. The indicator system mainly reflects the connotation and characteristics of the sustainability of food security and has received extensive attention. The two indicators designed refer to pesticide consumption per unit sown area and consumption of chemical fertilizers per unit sown area, which are, respectively expressed as the ratio of pesticide consumption and the ratio of chemical fertilizer consumption to sown area of farm crops. The excessive use of chemical fertilizers and pesticides would lead to serious agricultural non-point source pollution, has a big impact on arable land and water resources, and further restricts the sustainability of grain production [49,50]. The two indicators, i.e., proportion of effective irrigation area [51] and multiple cropping index [52], are designed to evaluate the sustainability of grain production from the perspective of resource utilization efficiency. The proportion of effective irrigation area is expressed as the ratio of effective irrigation area to sown area of farm crops. This multiple cropping index reflects the degree of reutilization of arable resources within one year, and it is expressed as the ratio of sown area of farm crops to arable area. The two indicators, i.e., per capita water resources and arable land per capita, are designed to evaluate the supply status of the main resources required by grain production from the microscopic perspective, and they are, respectively, expressed as the ratio of water resource quantity to population and the ratio of arable area to population [53]. Plant diseases, insect pests and natural disasters are the results of the interaction among the species in the farmland ecosystem and the interaction between crops and climatic conditions, and constitute an important indicator used to evaluate the ecological environment security of grain. The research adopts the proportion of disaster-affected area to reflect the indicator [54]. The calculation formula is $R_d = S_d/S * 100\%$, among which, R_d represents the proportion of disaster-affected area, S_d represents the disaster-affected area, and S represents the total sown area.

(4) Economic Security. This indicator system focuses primarily on consumption, effectiveness and efficiency. The first indicator designed is food price volatility. Food price fluctuation is the result of interaction between various factors, and can reflect the overall risk faced by food security in a comprehensive manner [31]. In order to eliminate the impact of inflation on food price volatility, the calculation formula of the indicator used in the research is $\varnothing = (GPI/CPI - 1) * 100\%$, among which, ∅ represents food price volatility, GPI represents grain price index, and CPI represents consumer price index. The second indicator is net profit of grain planting [55]. The profit of grain planting directly affects the direct income of farmers and influences the enthusiasm of farmers for grain planting. The higher the profit of grain planting and the enthusiasm of farmers for grain planting, the higher the guaranteed extent of food security. The research adopts the net profit of grain production per hectare to evaluate the profit of grain planting of farmers, which mainly refers to the net profit of staple food grain planting. Considering the urban–rural income gap and the availability of statistical data, Engel's coefficient of rural residents is regarded as one of the evaluation indicators [47]. Engel's coefficient reflects the proportion of residents' food expenses in their living expenses. It is negatively correlated to the food security level and it is an indicator designed to measure the fairness in food security. Agricultural labor productivity and agricultural land productivity are designed to evaluate the effectiveness and efficiency of grain output and then evaluate the economic sustainability of food security [47,55]. Agricultural labor productivity is expressed as the ratio of gross agricultural output value to the number of employed persons of the primary

industry; agricultural land productivity is expressed as the ratio of gross agricultural output value to the sown area of farm crops.

(5) Policy Security. This indicator system focuses primarily on all kinds of policies and safeguards supporting food security, e.g., financial expenditure, infrastructures, technological development and talent cultivation. The first indicator is transportation route intensity [32]. Road traffic is closely related to grain production, allocation and transportation, and it is the basic condition for equilibrium in the supply of grain. This indicator is mainly used to measure the availability of grain and is expressed as the length of transportation route per unit area. The second indicator is agricultural mechanization level [56]. This indicator reflects the degree of mechanization of grain production, and it is used to measure the production sustainability and efficiency of food security and is expressed as the ratio of total power of agricultural machinery to sown area of farm crops. The third indicator is contribution rate of agricultural scientific and technological progress [47]. The sustainable development of food security must be supported by modern agricultural science and technology as well as advanced materials and equipment. On the condition that technical conditions remain unchanged, scientific and technological progress is an important driver to promote the improvement of grain input–output level, so that the evaluation indicator is set. The fourth indicator is the educational level of the agricultural labor force [57]. The agricultural labor force is the main body of grain production. The quality of the agricultural labor force directly determines the level of production of grain, and thus influences the development level of national food security. In the research, this indicator is expressed as the number of technical secondary school or college graduates or above in every 100 rural workers. The fourth indicator is financial expenditure for grain production [35]. The support and regulation of the government for food security is reflected in multiple links such as production, allocation and storage, and the measures adopted are varied, including grants, subsidies and technical support, and can hardly be measured in a comprehensive manner. Considering that the strength of support and regulation is generally reflected in financial input, the research adopts financial expenditure for grain production as an evaluation indicator. The calculation thought of this indicator is to reduce the state financial expenditure on agriculture, forestry and water affairs according to the proportion of grain sown area to total sown area. The calculation formula is $B_f = F \times S_f / S$, among which, B_f represents financial expenditure for grain production, F represents financial expenditure for agriculture, forestry and water, S_f represents grain sown area, and S represents total sown area of farm crops.

2.2. Data Sources

Subject to the data release condition and the availability of indicator data, the research adopts national grain production, consumption, prices, resource environment and other factors for the period from 2001 to 2020 as its objects, and aims to conduct evaluation and research of the development level of China's food security on this basis. The data used by various food security evaluation indicators of the research are, respectively, sourced from the statistical yearbooks, such as *China Statistical Yearbook*, *China Rural Statistical Yearbook*, *National Agricultural Products Cost–benefit Data Collection*, *China Grain Yearbook*, *China Yearbook of Agricultural Price Survey* and *China Statistical Yearbook on Environment*, as well as the statistical information published by the website of Ministry of Agriculture and Rural Affairs, the website of National Bureau of Statistics and the website of General Administration of Customs. Moreover, some indicator values are calculated according to relevant data of the BRIC Agricultural DataBase (Table 2).

2.3. Entropy Weight TOPSIS Model

2.3.1. Model Introduction

The TOPSIS method is a multi-attribute decision-making method with finite alternatives, which is an extremely important method in multi-objective decision analysis, also called the "Technique for Order Preference by Similarity to Ideal Solution". This method was first put forward by Hwang CL and Yoon K in 1981 [58]. The essence of the entropy weight TOPSIS model is the improvement of the traditional TOPSIS method. This method is mainly utilized by determining the weights of all evaluation indicators on the basis of the entropy weight method, effectively eliminating the deviations in evaluation indicator weights caused by subjective factors, and further making use of the technique for similarity to the ideal solution to determine the sort order of evaluation objects [38].

Table 2. Data Sources.

1st Grade Indicator	2nd Grade Indicator	Data Sources
A1	A11	Calculated according to the relevant data of "*China Statistical Yearbook*"
	A12	*China Statistical Yearbook*
	A13	National Bureau of Statistics
	A14	National Bureau of Statistics
A2	A21	Calculated according to relevant data of BRIC Agricultural DataBase
	A22	Calculated according to the relevant data of "*China Statistical Yearbook*"
	A23	Calculated according to the relevant data on the website of the General Administration of Customs
	A24	Calculated according to relevant data of BRIC Agricultural DataBase
A3	A31	Calculated according to the relevant data of " *China Rural Statistical Yearbook* "
	A32	Calculated according to the relevant data of " *China Rural Statistical Yearbook* "
	A33	Calculated according to the relevant data of the National Bureau of Statistics
	A34	Calculated according to the relevant data of the National Bureau of Statistics
	A35	*China Yearbook of Agricultural Price Survey* and *China Statistical Yearbook on Environment*
	A36	National Bureau of Statistics
	A37	Calculated according to the relevant data of the National Bureau of Statistics
A4	A41	*China Grain Yearbook* and *China Yearbook of Agricultural Price Survey*
	A42	*National Agricultural Products Cost–benefit Data Collection*
	A43	National Bureau of Statistics
	A44	Calculated according to the relevant data of the National Bureau of Statistics
	A45	Calculated according to the relevant data of the National Bureau of Statistics
A5	A51	Calculated according to the relevant data of "*China Statistical Yearbook*"
	A52	Calculated according to the relevant data of the National Bureau of Statistics
	A53	The website of Ministry of Agriculture and Rural Affairs
	A54	*China Rural Statistical Yearbook*
	A55	Calculatd according to the relevant data of the National Bureau of Statistics

The basic thought behind this method is as follows: first, determine the ideal solution (the negative ideal solution), that is to say, each attribute value has reached the optimal/worst value in the alternative; then, make a judgment by measuring the relative distance between each evaluation object and the optimal/worst solution, and if the evaluation object is closest to the optimal solution and the farthest from the worst solution, the solution is optimal; otherwise, it is non-optimal [59]. The entropy weight TOPSIS model can make full use of original data and reflect the gaps between different alternatives. This model has no special requirements on sample size and is not disturbed by reference sequence selection, and it has such advantages as intuitive geometric significance, reduced loss of information and flexible operation [34,60].

2.3.2. Modeling Process

Suppose there are m evaluation objects and n evaluation indicators and x_{ij} is the original data of the jth indicator in the ith evaluation object, the original evaluation indicator matrix X:

$$X = \begin{vmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{vmatrix} \tag{1}$$

(1) Standardized Processing of Data. As each indicator has a different dimension, it is a requirement to carry out standardized processing of the data of each indicator first. With regard to positive indicators, Equation (2) shall apply; with regard to negative indicators, Equation (3) shall apply.

$$y_{ij} = \frac{x_{ij} - minx_{ij}}{maxx_{ij} - minx_{ij}} \tag{2}$$

$$y_{ij} = \frac{maxx_{ij} - x_{ij}}{maxx_{ij} - minx_{ij}} \tag{3}$$

In the formulas, y_{ij} is the standardized value of the *j*th indicator in the *i*th evaluation object, and the standardized matrix Y is worked out after processing:

$$Y = \begin{vmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{vmatrix} \tag{4}$$

(2) Calculate the characteristic proportion (contribution degree) of the *i*th> evaluation object (r_{ij}) under the *j*th indicator according to Equation (5).

$$r_{ij} = y_{ij} \Big/ \sum_{i=1}^{m} y_{ij} \tag{5}$$

The characteristic proportion matrix R is obtained through the calculation above:

$$R = \begin{vmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{vmatrix} \tag{6}$$

(3) Calculate the information entropy of each indicator (e_j) according to Equation (7).

$$e_j = -K \sum_{i=1}^{m} r_{ij} ln r_{ij}\ ,\ K = 1/lnm \tag{7}$$

(4) Calculate the weight of each indicator (w_j) according to Equation (8).

$$w_j = \left(1 - e_j\right) \Big/ \sum_{j=1}^{n} \left(1 - e_j\right) \tag{8}$$

(5) Adopt vector normalization method to work out normalization matrix G.

$$G = \begin{vmatrix} g_{11} & g_{12} & \cdots & g_{1n} \\ g_{21} & g_{22} & \cdots & g_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ g_{m1} & g_{m2} & \cdots & g_{mn} \end{vmatrix} \tag{9}$$

$$g_{ij} = y_{ij} \Big/ \sqrt{\sum_{i=1}^{m} {y_{ij}}^2} \tag{10}$$

(6) Build weighted and normalized decision-making matrix Z.

$$z_{ij} = w_j * g_{ij} \tag{11}$$

$$Z = \begin{vmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1} & z_{m2} & \cdots & z_{mn} \end{vmatrix} = \begin{vmatrix} w_1 g_{11} & w_2 g_{12} & \cdots & w_n g_{1n} \\ w_1 g_{21} & w_2 g_{22} & \cdots & w_n g_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_1 g_{m1} & w_2 g_{m2} & \cdots & w_n g_{mn} \end{vmatrix} \tag{12}$$

(7) Determine the positive ideal solution and negative ideal solution of each indicator.

Suppose z_j^+ and z_j^- are, respectively maximum and minimum values of the jth indicator in the matrix Z:

The positive ideal solution is:

$$Z_j^+ = \left[z_1^+,\ z_2^+,\ \cdots,\ z_n^+\right]\ (j = 1,\ 2,\ \cdots,\ n) \tag{13}$$

The negative ideal solution is:

$$Z_j^- = \left[z_1^-,\ z_2^-,\ \cdots,\ z_n^-\right]\ (j = 1,\ 2,\ \cdots,\ n) \tag{14}$$

(8) Calculate the Euclidean distance from each evaluation object to positive ideal solution and negative ideal solution (degree of separation).

$$d_i^+ = \sqrt{\sum_{j=1}^n \left(z_{ij} - z_j^+\right)^2}\ (1 \le i \le m,\ 1 \le j \le n) \tag{15}$$

$$d_i^- = \sqrt{\sum_{j=1}^n \left(z_{ij} - z_j^-\right)^2}\ (1 \le i \le m,\ 1 \le j \le n) \tag{16}$$

(9) Calculate the degree of similarity (S_i) between each evaluation object and positive ideal solution.

S_i represents the closeness of the food security level of the ith evaluation object to the optimal level, generally called "degree of similarity". The value range is (0, 1). The greater S_i, the higher the food security level [61,62]. The calculation formula is as below:

$$S_i = \frac{d_i^-}{d_i^+ + d_i^-}\ (1 \le i \le m) \tag{17}$$

3. Results

3.1. Determination of Weights of Indicators

The weight of each evaluation indicator is worked out according to Equations (1)–(8). See Table 2 for details. From Table 3, it can be seen that the weights of quantity security, structural security, ecological security of resources, economic security and policy security among food security indexes are, respectively, 14.62%, 16.71%, 28.52%, 19.03% and 21.12%. Among them, the weights of ecological security and policy security of food resources are the greatest, which indicates that China attaches great importance to the environmental security and policy security of good resources and also objectively reflects the state of China's food security for quite a long time in the past. Figure 1 refers to the histogram of weights of indicators. From Figure 1, it can be seen that Volatility of Grain Yield (A11), Degree of Dependence on Grain Foreign Trade (A21), Pesticide Consumption per Unit Sown Area (A31), Consumption of Chemical Fertilizers per Unit Sown Area (A32), Agricultural Labor Productivity (A44) and Educational Level of Agricultural Labor Force (A54) are important factors that influence the development level of China's food security.

Table 3. Information entropies and weights of all evaluation indicators of food security.

1st Grade Indicator	Weight of 1st Grade Indicator	2nd Grade Indicator	Information Entropy	Weight of 2nd Grade Indicator
A1	14.62%	A11	0.9622	5.42%
		A12	0.9556	2.80%
		A13	0.9580	3.29%
		A14	0.9309	3.11%
A2	16.71%	A21	0.9554	5.12%
		A22	0.9342	3.30%
		A23	0.9481	3.42%
		A24	0.9451	4.87%
A3	28.52%	A31	0.9709	5.88%
		A32	0.9396	5.53%
		A33	0.9621	3.84%
		A34	0.9250	4.07%
		A35	0.9380	2.16%
		A36	0.9395	4.47%
		A37	0.9618	2.58%
A4	19.03%	A41	0.9581	1.81%
		A42	0.9168	2.80%
		A43	0.9388	4.27%
		A44	0.9269	5.56%
		A45	0.9538	4.59%
A5	21.12%	A51	0.9206	4.48%
		A52	0.9254	2.83%
		A53	0.9652	3.11%
		A54	0.9756	6.16%
		A55	0.9423	4.54%

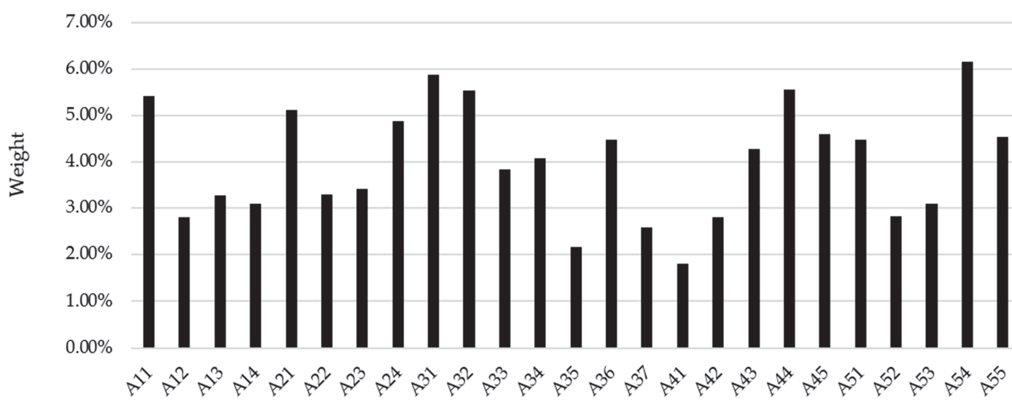

Figure 1. Histogram of Weights of Food Security Indicators.

3.2. China's Food Security Index

China's food security index and indexes of five second grade indicators for 2001–2020 are calculated on the basis of the abovementioned food security evaluation indicator system and the weights of all indicators (Equations (9)–(17)). The results are shown in Figure 2. Seen from general food security index according to Equation (17), from 2001 to 2007, the state of China's food security had been declining, and after 2007, the state of China's food security began to improve gradually. In terms of the specific ranking of the overall food security index by year, the lowest index level for food security was 0.23 in 2007, after which it began to increase, reaching a maximum value of 0.74 in 2020, as shown in Table 4.

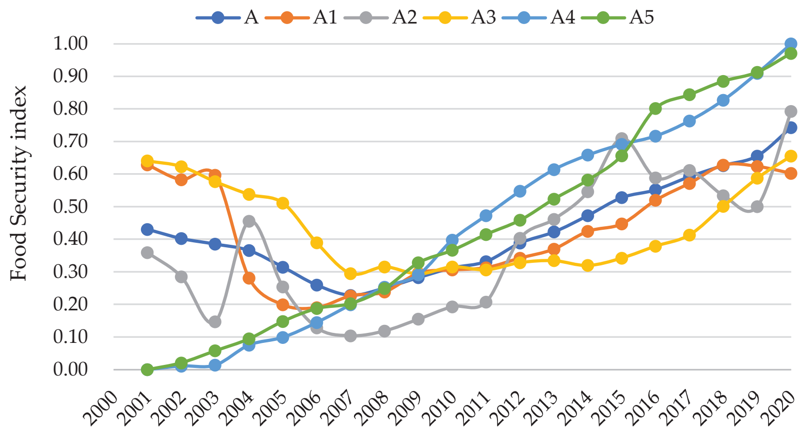

Figure 2. Changes in China's Food Security Index from 2001 to 2020.

Table 4. Overall food security index and its ranking, 2001–2020.

Year	Similarity	Rank	Year	Similarity	Rank
2001	0.43	8	2011	0.33	14
2002	0.40	10	2012	0.39	11
2003	0.39	12	2013	0.42	9
2004	0.37	13	2014	0.47	7
2005	0.31	15	2015	0.53	6
2006	0.26	18	2016	0.55	5
2007	0.23	20	2017	0.59	4
2008	0.25	19	2018	0.63	3
2009	0.28	17	2019	0.66	2
2010	0.31	16	2020	0.74	1

As seen from the quantity security index, China's food quantity security showed a trend of growth in fluctuation, i.e., declining firstly and then rising; from 2001 to 2006, the state of China's food security was on the decline, and later, it began to rise gradually. In recent years, the food quantity security index was lower than the general food security index, but the variation trend of the food quantity security index was close to that of the general food security index. This provides support for the general food security index. Seen from the food structure security index, China's food structure security showed a trend of growth in fluctuation on the whole, i.e., declining firstly and then rising, and in some years, the fluctuation range is relatively large, which indicates that there are big risks in China's food structure security.

Seen from the ecological security index of food resources, the variation trend of this index is basically the same as that of the general food security index. From 2007 to 2014, the index rose slightly, and in recent years, it rose rapidly. This is identical to the national food security policy that is focused on greenness, high quality and high efficiency. Seen from economic security index and policy security index, from 2001, both of the indexes were on the rise, and their variation trends of were basically identical. This indicates that the income, living standards and production efficiency of China's rural residents are constantly rising, and reflects the increasing emphasis in China on the technology, policy and fund inputs in terms of agriculture, rural areas and farmers.

3.3. Changes in China's Food Security Trend

By developing a radar chart of food quantity security index, structural security index, ecological security index of resources, economic security index and policy security index

(Figure 3), we can analyze the development process of China's food security from 2001 to 2020, which can be generally divided into three stages.

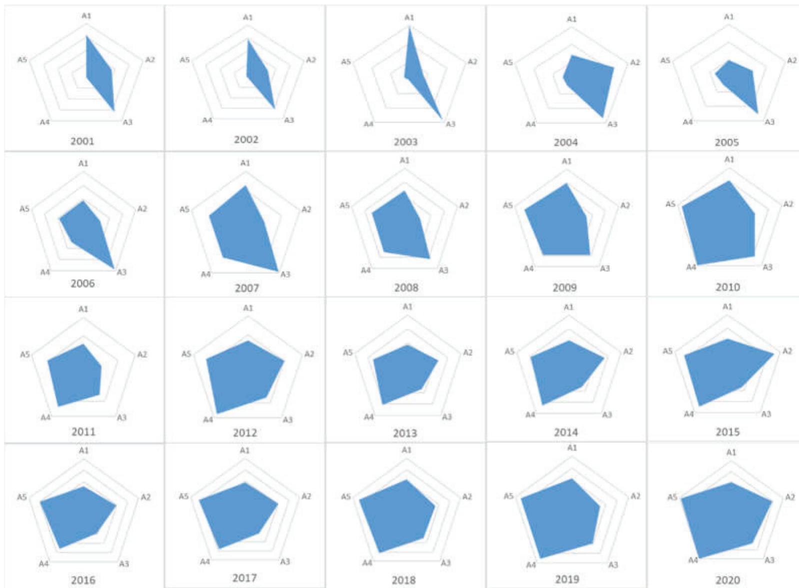

Figure 3. Chart of Changes in the Connotation of China's Food Security from 2001 to 2020.

From 2001 to 2006 was a rapid development stage. Food quantity security and ecological security of food resources were at a relatively high level, but economic security and policy security were at a relatively low level. In this stage, China introduced a lot of polies supporting agriculture and benefiting farmers, collection and storage policies and technology policies, and improved the input levels and output levels of factors continuously. The use level of pesticides and chemical fertilizers per unit of sown area was improved continuously, but the overall level was relatively low, the fluctuation range of grain yield was large, and the grain self-sufficiency rate was constantly declining; in the same way, the labor productivity and the agricultural land productivity were rising constantly, but their levels were not high, and so their abilities to support structural security and economic security of food resources were poor.

From 2007 to 2013 was an uneven development stage. Economic security and policy security of food resources were relatively prominent, and structural security of food and ecological security of resources were poor. In this stage, the consumption of pesticides and chemical fertilizers per unit sown area hit a record high, and high inputs in production factors ensured the quantity security of food, but due to the resulting non-point source pollution, the ecological environment security level of food resources continued to decline, grain production seemed to only focus on quantity but not focus on tendency of resource ecology, and the issues relating to agriculture, rural areas and farmer became increasingly prominent. Furthermore, food imports kept growing, but the dependence of soybeans on foreign trade increased year by year, bringing serious hidden troubles to the structural security of food.

From 2014 to 2020 was an even development stage. Food security developed in a balanced manner, and economic security, policy security and ecological security of resources showed a stable and positive trend, but structure security showed a fluctuating downward trend. In this stage, the consumption of pesticides and chemical fertilizers per unit of sown area showed a downward trend, and the ecological security of food resources showed a positive trend. The food structure security situation showed a fluctuating downward trend and should cause great concern. The main reason might be the increasing demand of residents for animal products, which leads to a sharp increase in the demand for feed grain, but the supply quantity of main feed grains such as corns and soybeans in China is insufficient, and the dependence on importing such feed grains goes up year by year. Moreover, the benefits of grain planting of farmers are low, the land transfer is complex and difficult, and the increase in food inventory aggravates the financial burden, which also brings certain risks to the level of food security.

Generally speaking, all indicators of national food security show a balanced development trend; with the adjustment of national food security strategy and the deepening of food policy reform, the economic security of food will inevitably be improved.

4. Discussion

4.1. Lack of Arable Land and Fresh Water Resources, Unsustainable Mode of Production

Lack of arable land and freshwater resources is a serious constraint for China's food security [63]. With the acceleration of urbanization and industrialization, China's arable area shows a downward trend. In 2020, China's per capita arable area was only 0.09 hectares per person, 0.17 hectares per person less than the world's per capita arable area (0.26 hectares per person). Meanwhile, the sustained sharp increase in the prices of means of production such as chemical fertilizers leads to the constant rise in the cost of grain production, which is considerably higher than the increase in food prices, and the benefits of grain planting decreased year by year. In 2016, the net profit of grain planting of farmers was −1204.2 RMB/hectare. This was the first time that China suffered a loss in grain planting of farmers. In the three subsequent years, the grain planting of farmers had been at a loss, the enthusiasm of famers for grain planting declined, the phenomenon of non-agricultural circulation of farmland became prominent, and the phenomenon of abandonment of arable land was serious. "Who is going to plant grain in the future" will become a major hidden trouble for China's food security [64]. The freshwater resources are the lifeblood of agricultural production. In 2020, the per capita freshwater quantity in China was 2239.8 m^3, only 1/4 of the world average. In terms of the utilization efficiency of water resources, to produce the same amount of food, China needs to use an amount of water equivalent to twice the water consumption in the US. Lack of freshwater resources and inefficient utilization of water resources cannot guarantee stable food supply [35].

The ecological resource environment will directly impact the sustainable supply of food and the sustainable development of agriculture in China. The mode of agricultural production in China involving high investments guarantees the quantity security of food to some extent, but poses a threat to the ecological security and green high quality development of food resources [65]. China is the world's largest country of production and consumption of chemical fertilizers and pesticides. Reasonable use of chemical fertilizers can increase the current grain yield per unit area, but heavy or excessive use of chemical fertilizers would make the ecological environment of the soil and water even worse and make the land productivity decline, accordingly posing a threat to the ecological security of food resources. Excessive use of pesticides would lead to the increase in the level of pesticide residues in crops and the accumulation of pesticide residues in the food chain, thereby reducing the food quality. Since 2015, China has begun to carry out zero growth action in the consumption of chemical fertilizers and pesticides. After the implementation in recent years, the consumption of chemical fertilizers and pesticides decreased significantly, and the utilization rate of chemical fertilizers and pesticides is greatly improved, but the consumption of chemical fertilizers and pesticides per unit area in China is still 3.7 times the world average, which is a significant setback to the sustainable development of China's food resources [1].

4.2. High Food Inventory Cost and Excessive Financial Burden

China's high food inventory and big policy-related grain reserves aggravate the financial burden. Take rough rice as an example, if stored for 1 year, the central financial subsidy is RMB 260 per ton, and for the second year, the central government needs to pay RMB 210 as the storage fee and the interest subsidy. Where a ton of rough rice is stored for 2 years on average, on the basis of the current inventory of rough rice which is more than 100 million tons, the financial expenditure nationwide would exceed RMB 47 billion and cause a huge financial burden. Moreover, under the current grain collection and storage system, the minimum grain purchase price plus the huge grain storage fee makes the grain cost higher [66]. Due to the restriction of the high grain cost, China's grain loses its pricing advantages on the market and cannot effectively use the international market to reach a balance in the throughput, so that it is more difficult to reduce food inventory. Thus, the government can hardly continue to use huge funds to adjust grain supply. Moreover, the high grain cost would cause a lot of foreign grain to pour into the domestic market. According to the import and export trade data released by General Administration of Customs, in 2021, China's annual grain imports reached 166.94 million tons, China became the largest grain importing country, and China's imports of crops such as soybeans, wheat and corns ranked among the world's highest. The increase in the grain cost leads to a sharp increase in the grain imports, thereby forming a vicious circle of high grain yield, high imports and high inventory [67].

4.3. Grain Planting Structure Does Not Match Consumption Structure

In the new development stage, the main contradiction faced by Chinese society has turned into the contradiction between unbalanced and inadequate development and the people's ever-growing needs for a better life. As income rises, the grain consumption structure of residents is continuously upgraded, and people are no longer satisfied by "enough to eat", but "being well fed" and "healthy eating", and people's demand for safe, green, environmentally friendly and nutritious food keeps growing. However, at present, the green high-quality agricultural products in China are in short supply, and the problem faced by food security has turned into the structural contradiction under resource constraints from insufficient quantity [68]. Seen from the angle of supply, China's food supply is at risk of becoming greater than demand on the whole and less than demand in some areas. In terms of the grain ration, China's grain ration is absolutely safe at present. According to the data released in the China Agricultural Outlook Report (2022–2031), in 2021, China's grain consumption was 31,617 million tons, the actual grain yield was 66.234 million tons, and the grain ration guarantee degree was 197%. In terms of the structure, the main grain crops such as rice, wheat and corns are oversupplied in some stages, and the inventory is high. High-quality wheat products (e.g., plain flour and strong flour), minor grain crops and high-quality rice are undersupplied and need to be imported from foreign countries.

In terms of feed grain, with the development of urbanization, the consumption structure of Chinese people has turned into the consumption of animal food such as meat, eggs, milk and aquatic products from the consumption of staple food grain, and the gap in protein feed grain is big. On the whole, there are great differences among various grain varieties in China in terms of self-sufficiency rate. Some varieties are oversupplied, some varieties are undersupplied, and the structural contradiction between grain production and supply and consumer demand creates great risks for the future food security [69]. Furthermore, due to the impact of decentralization of producers, the grain production structure in China is mainly manifested as follows: (i). structural assimilation in variety, in the centralized producing area of wheat, rough rice, corns and soybeans, the grain yield of the same variety is high; and (ii). structural assimilation in quality, the producers lack of the ability to produce grain food according to requirements. To some extent, assimilation in grain production means homogenization and is manifested as low level in China's food structure security.

Moreover, the prominent grain loss and wastage problem in China, plus the factors such as unreasonable consumption structure, further increase the pressure in terms of food security. On one hand, loss and wastage results in the big gap between the demand and the share of grain; on the other hand, unreasonable dietary structure is also an important factor that threatens China's food security [1]. Restricted by the availability of data, this article does not consider grain loss and wastage and food consumption structure. The researcher plans to seek the evaluation indicators that can reflect the two factors in the subsequent research process and conduct empirical research on them. In addition, this study used the entropy weighting method to derive the weights of each evaluation index, and no comparative analysis was conducted with the results obtained from other weighting calculation methods. In the subsequent study, it is planned to use hierarchical analysis, principal component analysis, and other methods to calculate the weights of each index separately and conduct comparative analysis to arrive at the most scientific and reasonable index weights.

5. Conclusions

Food security is the foundation and prerequisite for social stability and economic development. The evaluation of food security status and the analysis of food security situation can provide basis for the scientific selection of the food security strategy in the new development stage and the promotion of sustainable development of agriculture. This article starts from quantity security, structural security, ecological security of resources, economic security and policy security and conducts empirical research on the state of China's food security from 2001 to 2020. The results show that: (1) from 2001 to 2020, China's food security level shows a trend of declining firstly and then rising; (2) China attaches increasing importance to the ecological security and policy security of food resources; (3) the promotion of China's food security level is restricted by such factors as resources, mode of production, circulation, storage and transportation, trade and structure. Accordingly, this article puts forward relevant policy suggestions as follows:

Implement the strategy of storing grain in land, stick to the red line in terms of the quantity and quality of arable land, and safeguard the grain production capacity. Firstly, the Chinese government should strictly observe the red line of 1.8 billion mu of arable land, attach importance to increasing land consolidation and reclamation, implement the replenishment of arable land, avoid the extensive use or abandonment of arable land, and prevent arable land from becoming non-agricultural or non-grain agricultural areas. Meanwhile, it is also crucial to increase investment in agricultural infrastructure and improve field irrigation and ecological protection projects, and build about 1 billion mu of high-standard farmland with the focus on major grain-producing areas. Thirdly, it also needs to promote green agricultural production activities, such as reduced application of chemical fertilizers and pesticides, soil testing and formula fertilization techniques, and conservation tillage techniques to steadily improve the quality of cultivated land. Finally, China should strengthen the construction of systems for monitoring basic farmland area and soil quality, and improve China's monitoring and early warning capacity for the area and quality of cultivated land.

Implement the strategy of storing grain in technology, increase the content of agricultural science and technology, and improve the comprehensive competitiveness of agriculture. Increase inputs in agricultural science and technology and carry out a revolution of production technologies to realize "storing grain in technology", to promote the advances in and the popularization of agricultural technology. Strengthen the transformation and application of scientific and technological achievements of seed-breeding techniques, production techniques, mechanical techniques and information techniques. Coordinate the relationship between the grain production and the ecological environment, conduct R and D activities to popularize the technique of returning straw to field and the biological pesticide technique, reduce the agricultural non-point source pollution, and enhance the capacity for the sustainable development of agriculture. Improve the level of information technology in the grain industry and rely on big data and advanced technologies in the internet of things to promote the transformation and upgrading of the whole industry chain covering grain production, processing, circulation and storage. Strengthen the construction of the innovation system for grain science and technology, integrate scientific and technological resources, adjust the regional layout, clarify the division of labor and cooperation, optimize the innovation environment, and enhance the innovation capacity of grain science and technology.

Coordinate and utilize two resources (i.e., international and domestic resources) and two markets (i.e., international and domestic markets), and strengthen deep cooperation with foreign countries On the basis of adhering to absolute food security and basic self-sufficiency in cereals, China should expand trade channels through diversified import sources to maintain the stability of imports for soybeans and coarse grains that do not have comparative advantages in production. Use international markets and resources to stimulate domestic production potential, optimize the layout of productive forces, concentrate advantageous resource conditions, and strengthen the construction of advantageous industrial zones, highlighting major grain varieties such as rice and wheat. Actively participate in the international governance system of grain trade and the grain acquisition and distribution chain in developing countries to improve the discourse and China's international position in the global grain market.

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Article

Spatial Evolution, Driving Mechanism, and Patch Prediction of Grain-Producing Cultivated Land in China

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Abstract: China has implemented strict policies for protecting cultivated land, and the Chinese government has focused on the non-grain production (NGP) of cultivated land. This study aimed to analyze the spatial evolution law of grain-producing cultivated land (GPCL) in China between 2000 and 2018, explore the mechanism of GPCL, and simulate the spatial characteristics of GPCL in 2036. We used the Geographic Information System (GIS) and a patch-generating land-use simulation model, a new model that proposes a land expansion analysis strategy by improving previous rule-mining methods. China's grain production rate (GPrate) shows a gradual upward trend between 2000 (36.98%) and 2018 (47.18%). The mutual conversion of GPCL and non-grain-producing cultivated land (NGPCL) are the primary transfer types. The evolution of GPCL is driven by climatic, economic, and social factors, of which population density is the most important factor. GPCL expansion patches are distributed in densely populated, economically developed, and warm and humid plain areas. Further, the simulation results showed that the GPrate in 2036 is estimated to be 41.39%, with GPCL transfer-in significantly exceeding the amount transferred out. Our results further cultivated land evolution-associated research and provide a basis for formulating scientific land-use policies for cultivated land protection for other countries.

Keywords: China; cultivated land; grain production; spatial evolution; driving mechanism

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1. Introduction

As a large agricultural country, China uses less than 9% of the world's arable land to feed 20% of the world's population [1]. Cultivated land is the primary driver of food production, and China has always implemented a strict policy of cultivated land protection [2]. Recently, China has experienced rapid urbanization, thereby exhausting a large amount of cultivated land resources and converting them to construction land [3]. Simultaneously, the internal utilization mode of cultivated land has also undergone changes, and non-grain production (NGP) is attracting significant attention from the Chinese government [4].

Grain-producing cultivated land (GPCL) is transformed into non-grain-producing cultivated land (NGPCL), exempting cultivated land from food production and thereby posing great challenges to China's food security [5]. Previous studies on the evolution of cultivated land have primarily studied the (1) extraction, spatiotemporal evolution, and driving mechanism of cultivated land based on remote sensing and GIS [6–8]; (2) relationship between cultivated land change and food production, urbanization, population, and terrain slope based on statistical and econometric models [9–11]; and (3) quality of cultivated land and its influencing factors, as well as the impact of long-term farming methods on the ecological environment and soil, based on experimental science [12,13]. However, most related studies have discussed the transformation process of cultivated land and its reasons as a whole, while ignoring the internal differences impacting the transformation of cultivated land. There are still gaps in the knowledge concerning the transformation of the internal utilization mode of cultivated land and its driving mechanism, especially the evolution of cultivated land for different crops. By studying the evolution process and mechanism of GPCL, the internal reasons for the evolution and differentiation of cultivated land at a larger scale will be better understood.

Currently, several models for predicting land-use changes exist, such as cellular automata (CA), a framework for simulating land-use transitions and their impacts, and future land-use simulation (FLUS) models [14–17]. However, existing studies lack a flexible mechanism for dealing with multi-type land use patch changes to simulate fine-scale land-use changes, which restricts their application in practical planning and land policy formulation. In this study, our technical implementation of land-use change prediction is based on a new model, the Patch-generating land-use simulation (PLUS) model. Unlike other models, this model proposes a new land expansion analysis strategy by improving previous rule mining methods, such as transfer analysis strategy or pattern analysis strategy. In addition, the PLUS model retains the advantages of existing models, avoiding the need to analyze transformation types that grow exponentially with the number of categories, and the ability to analyze land-use change mechanisms over a certain period of time. The PLUS model has been shown to be a more efficient model that provides more accurate simulation results [18].

Thus, we aimed to (1) map and analyze the evolution of GPCL in China, (2) explore the driving mechanism of the evolution of GPCL, and (3) evaluate the future GPCL based on the PLUS model. We comprehensively analyzed the evolution of NGPCL and GPCL in China and enriched scientific knowledge of cultivated land evolution to provide a basis for making rational policies for cultivated land use while demonstrating the idea of cultivated land protection for other countries at the same stage of development.

2. Materials and Methods

2.1. Patch-Generating Land-Use Simulation (PLUS) Model and Simulation Process

PLUS is a patch generation land-use change simulation model based on raster data. This model: (1) enables better excavation of the inducements of various land-use changes by applying a new analysis strategy; (2) contains a novel multi-class seed growth mechanism that can better simulate multi-class land use patch-level changes; and (3) coupled with multi-objective optimization algorithms, provides simulation results that can better support planning policies to achieve sustainable development.

The PLUS model comprises a (1) land expansion analysis strategy that extracts the various types of land use expansion part between two phases of land-use change; then, sampling from the increased part, the random forest algorithm is used to mine the factors of various types of land use expansion and driving forces one by one. The development probability and the contribution of driving factors to the expansion of various types of land use during this period can thus be obtained. This avoids conversion types that grow exponentially with the number of analyzed categories and retains the model for a certain period of time and the ability to analyze mechanisms of land-use change with better interpretability; (2) cellular automata (CA) model: combined with random seed generation and a threshold-decreasing mechanism, the PLUS model can dynamically simulate the automatic generation of patches in space and time under the constraint of a development probability [15,18].

In this study, we extracted data on the expansion of various types of land between 2000 and 2018 and used the random forest algorithm to obtain their development probabilities. We then used the CA model based on multi-type random patch seeds to predict the future landscape. First, according to the actual situation and the availability of data, 11 driving factors from three categories (natural factors, socio-economic factors, and accessibility) were selected. After rasterization, they were unified into the same projected coordinate system and spaced as the land cover data resolution. Secondly, the development probability of each land use type was obtained using the Land Use Expansion Analysis Strategy (LEAS) module. Finally, combined with relevant parameters, such as the number of target pixels of various types of land in the future, transfer cost matrix, probability of random patch seeds, and neighborhood factors, the CA model based on multiple types of random patch seeds simulated land-use change in 2036. In this study, the Markov model was used to forecast the demand for future landscape types. Based on the existing data, the trial-and-error method was used to repeatedly debug each parameter, and the Kappa coefficient and figure of merit (FOM) coefficient were selected to evaluate the accuracy of the simulation results. The Kappa coefficient and FOM coefficient were 0.812 and 0.152, respectively, indicating that the simulation results of the PLUS model were accurate.

2.2. Variable Description

2.2.1. Measurement of GPrate

According to the official document of the Chinese government, "Opinions on preventing the non-grain production of cultivated land and stabilizing grain production", which includes the grain crops rice, wheat, and corn, the GPrate is calculated as follows:

$$\mathrm{GPrate} = \mathrm{L}/(\mathrm{C} \times \mathrm{I}) \times 100\% \tag{1}$$

where L is the sum of the area of wheat, corn, and rice, C is the cultivated land area, and I is the multiple cropping index.

2.2.2. Drive Factor Determination

The change in cultivated land use is very complex and has non-linear characteristics. Different study areas and periods have different degrees of influence on driving factors, and the selection of driving factors affects the accuracy of spatial simulation models to a certain extent. Therefore, their selection should be based on the principles of comprehensiveness, data availability, and quantification. We comprehensively considered driving factors selected by previous researchers [19–22] and selected 11 factors in 3 categories (Table 1): climate and environmental factors, socioeconomic factors, and accessibility factors. Climate and environmental factors include elevation, slope, annual average temperature, annual precipitation, and potential evaporation; socioeconomic factors include population density and gross domestic product (GDP); accessibility factors include distance from expressways, railways, urban roads, and water systems. A few drivers for each category have been discussed below:

1. Slope: The gentler the slope, the greater the tendency to experience land-use change, regardless of the type of change. The transition of land use from agricultural land to urban and vice versa is more likely to occur on land with lower slopes [23,24].
2. Elevation: The difference in altitude distribution will affect the growth and environment of crops. The effect of elevation on land-use change is particularly obvious in areas with rough terrain and peaked altitude differences [25,26].
3. Population density: Labor productivity is the driving force for urban construction and development. In the process of urbanization, a large portion of the rural population drift to cities, and high population-density areas are often areas where construction land is rapidly expanding. Therefore, high population density becomes an increasingly attractive factor for the further development of a city [27,28].
4. Distance from various traffic arteries: Accessibility is an important factor affecting land use. It can be expressed as the ease in displacing from a starting point to a specified destination and is usually expressed by indicators such as the distance between the starting point and destination, travel cost, and time [29–31]. Advanced accessibility conditions are the driving force for investing, accelerating the construction of urban infrastructure, and attracting agricultural and industrial enterprises. Land use transits quickly to urban, alongside major transportation arteries, forming linear towns, thereby connecting urban areas.

Table 1. Driver Indicators.

Code	Variable	Data Type	Spatial Resolution
	Climatic and environmental factors		
PET	Potential Evaporation	Raster	1 km
PREL	Annual Precipitation	Raster	1 km
SLOP	Slope	Raster	30 m
TEM	Annual Mean Temperature	Raster	1 km
DEM	Elevation	Raster	30 m
	Accessibility factors		
HWD	distance to highway	Raster	1 km
RWD	distance to railway	Raster	1 km
WD	distance to city road	Raster	1 km
RVD	distance to river	Raster	1 km
	Socioeconomic factors		
POP	Population	Raster	1 km
GDP	GDP	Raster	1 km

2.3. Data Source

Data on land use, population density, GDP, elevation, aspect, and slope were obtained from the Chinese Academy of Sciences Resource and Environment Science Data Center (https://www.resdc.cn/, accessed on 16 March 2022). Annual precipitation and average temperature spatial interpolation datasets were obtained from the National Earth System Science Data Center (http://www.geodata.cn/, accessed on 16 March 2022). Road traffic data was obtained from the National Geographic Information Resource Directory Service System (https://www.webmap.cn/main.do?method=index, accessed on 16 March 2022).

The 2000–2018 annual spatial distribution data of China's three major crops, wheat, rice, and corn, with a resolution of 1 km, was obtained from the study by Luo et al. [32]; the data is shared at https://data.mendeley.com/datasets/jbs44b2hrk/2 (accessed on 16 March 2022). The multiple cropping index data was obtained from a study by Liu et al. [33]; the data is shared at https://doi.org/10.6084/m9.figshare.14099402 (accessed on 16 March 2022). This dataset released the global, 250-m resolution annual multi-cropping index distribution map. All data were unified at a resolution of 1 km $\times$ 1 km.

3. Results

3.1. Spatial Evolution

The distribution map revealed that GPCL is mainly distributed in eastern China (Table 2, Figure 1). From 2000 to 2018, GPCL gradually spatially expanded to the northeast, and this spatial distribution was relatively stable.

Table 2. GP_{rate} for nine agricultural sub-regions.

Agricultural Zoning	2000	2005	2010	2015	2018
Northeast Plain	29.10	32.65	45.98	54.32	59.26
Northern arid and semi-arid	18.65	19.77	24.21	29.31	27.15
Huanghuaihai Plain	44.36	42.50	44.55	46.61	52.72
Loess Plateau Region	24.23	23.86	28.04	30.51	27.91
Qinghai-Tibet Plateau	16.80	10.65	11.54	11.76	10.02
Middle and lower reaches of the Yangtze River	53.36	54.93	58.90	62.55	63.46
Sichuan Basin and surrounding areas	33.40	32.31	32.82	32.77	31.62
Yunnan-Guizhou Plateau	38.96	39.98	40.10	51.58	47.28
Southern Region	50.13	45.90	43.07	64.95	49.93
Nationwide	36.98	37.35	41.60	46.93	47.18

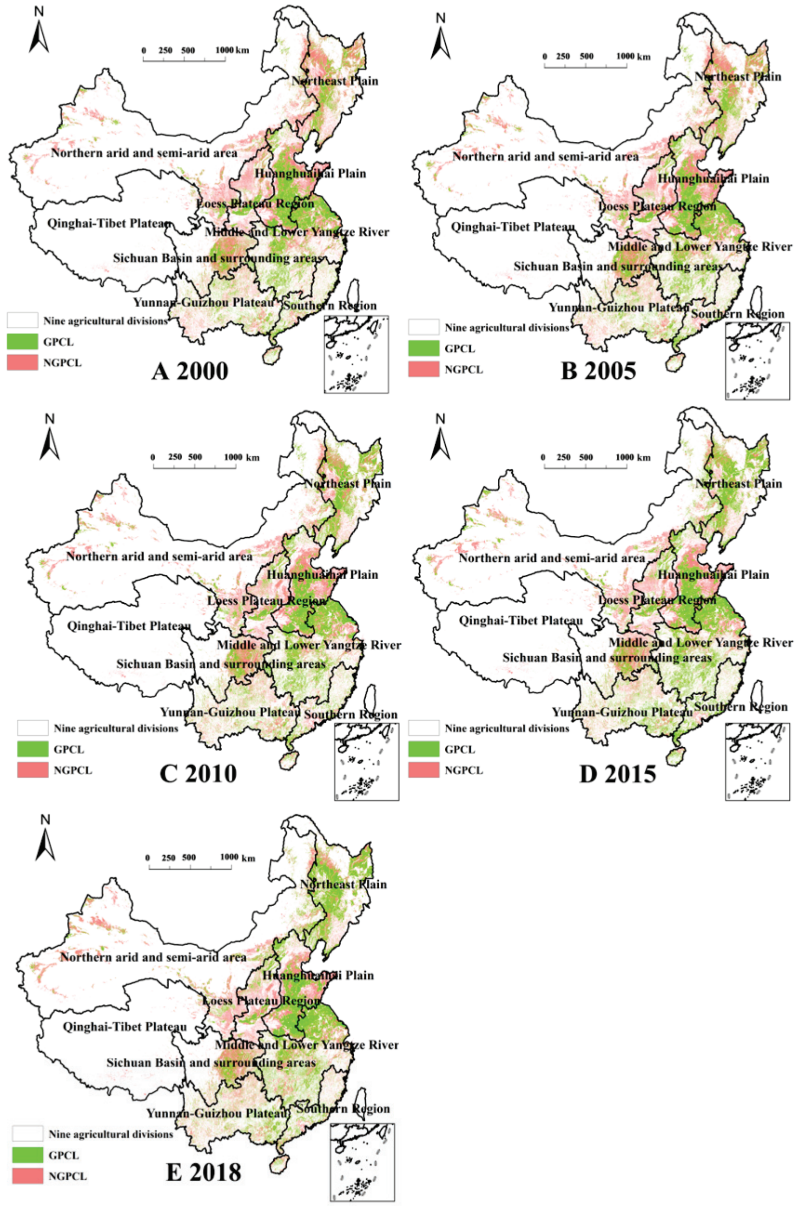

Figure 1. Spatiotemporal distribution of grain-producing cultivated land (GPCL) and non-grain-producing cultivated land (NGPCL) in China from 2000 to 2018.

Moreover, China's GPrate demonstrates a gradually increasing trend from 36.98% in 2000 to 47.18% in 2018. Apart from the Qinghai-Tibet Plateau, which experienced a drastic drop in GPrate from 16.80% to 10.02%, the Sichuan Basin and its surrounding areas experienced a slight drop in GPrate from 33.40% to 31.62%, and the Southern Region remained basically stable (from 50.13% to 49.93%). The GPrate of the other regions increased in varying degrees. Among them, the Northeast Plain increased the most, from 29.10% to 59.26%.

In the metastatic map of GPCL from 2000 to 2018 (Figure 2), the spatial variation of GPCL is more intense. The GPCL that has remained unchanged for 18 years spans 2.71×10^7 ha and is mainly distributed in Huanghuaihai Plain. The transferred GPCL was 3.91×10^7 ha in the middle and lower reaches of the Yangtze River, Sichuan Basin and surrounding areas, and the Southern Region. The transferred GPCL was 5.65×10^7 ha, with the largest distribution in the Northeast Plain and the rest of the eastern regions. Thus, in the past 18 years, the inflow of GPCL is greater than its outflow, showing an increase of 1.74×10^7 ha. From the perspective of the type of transfer, we primarily observed the internal transformation of cultivated land, which is the mutual transformation of GPCL and NGPCL. In the past 18 years, 65.48% of the total transfer volume of GPCL was transferred to NGPCL, accounting for 51.23% of the increased area of NGPCL. Among the transfer types of GPCL, 52.33% of the transfers are attributed to NGPCL.

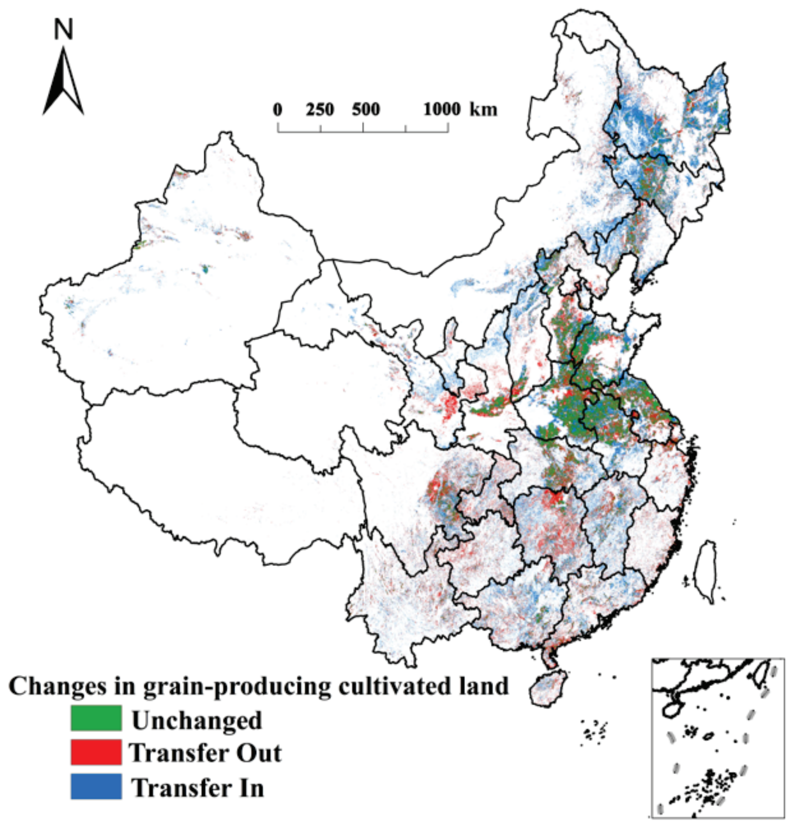

Figure 2. Grain-producing cultivated land (GPCL) changes from 2000 to 2018.

3.2. *Driving Mechanism*

From 2000 to 2018, the factors driving the changes in China's GPCL can be attributed to socio-economic factors, such as population (POP), GDP, and accessibility, as well as natural environmental factors, such as slope, elevation, precipitation, and temperature. As demonstrated in Figure 3, the main drivers of GPCL expansion are POP, elevation (DEM), GDP, annual mean temperature (TEM), and annual precipitation (PREL).

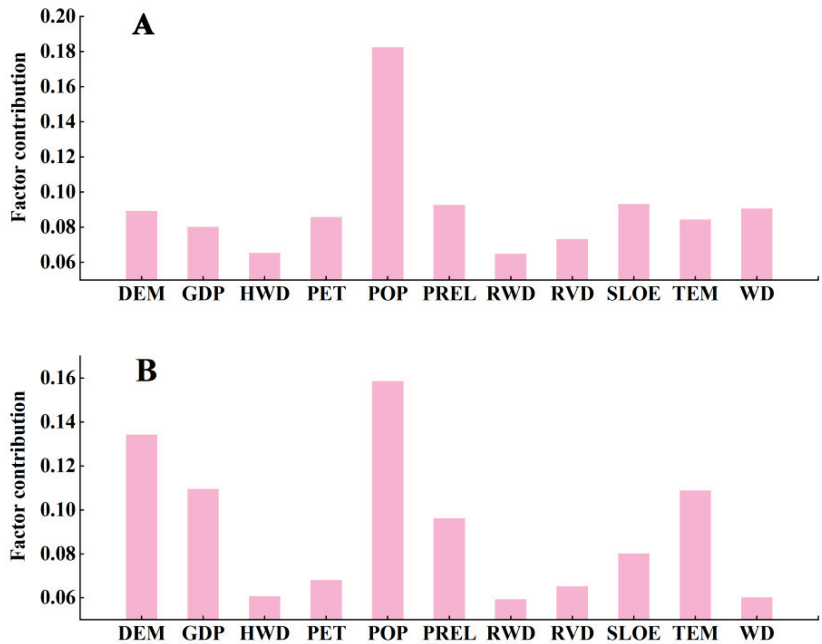

Figure 3. Expansion contribution factors of (**A**) non-grain producing cultivated land (NGPCL) and (**B**) grain-producing cultivated land (GPCL).

On studying the GPCL expansion area and the five driving factors (Figure 4), we found that GPCL expansion patches are distributed in densely populated, economically developed, warm and humid plain areas. From the analysis of the individual factors influencing NGPCL, the top five driving factors were found to be population (POP), slope (SLOP), annual precipitation (PREL), distance to city road (WD), and DEM. We found that POP was the main factor affecting their expansion regardless of GPCL or NGPCL. China's rapid urbanization has led to a large-scale population shift from rural to urban areas, with far-reaching impacts on China's food production. To a certain extent, the evolution of the spatial pattern of GPCL and NGPCL is a result of China's urbanization and continuous adaptation to the natural environment.

3.3. Patch Prediction

The patch simulation results showed that the spatial distribution of cultivated land predicted in 2036 is more consistent than that in 2018, and the GPrate in 2036 is predicted to be 41.39%. Analysis of the GPCL transfer map from 2018 to 2036 (Figure 5) revealed that the amount of transfer-in (9.72×10^6 ha) is significantly greater than the amount of transfer out (1.78×10^6 ha), with the unchanged and newly added GPCL being 8.18×10^7 ha and 7.94×10^6 ha concentrated in the Northeast Plain and Huanghuaihai Plain, respectively. From the perspective of transfer types, transfer can be primarily attributed to the mutual conversion of GPCL and NGPCL. The transferred GPCL primarily changed to NGPCL, accounting for 88.77%, and the transferred GPCL from NGPCL accounted for 75.55%.

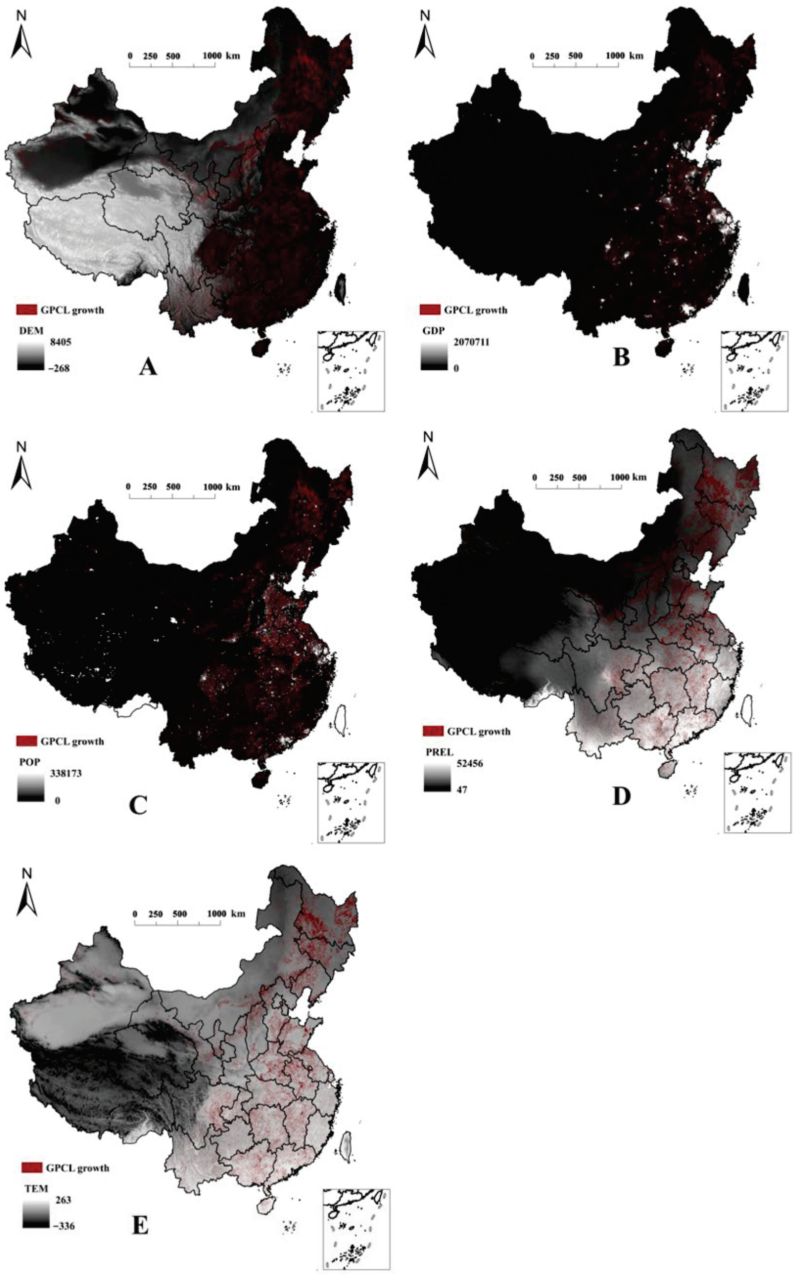

Figure 4. Superposition of grain-producing cultivated land (GPCL) expanding plaques and major contributors. (**A**) Superposition of grain-producing cultivated land (GPCL) expanding plaques and DEM. (**B**) Superposition of grain-producing cultivated land (GPCL) expanding plaques and GDP. (**C**) Superposition of grain-producing cultivated land (GPCL) expanding plaques and population (POP). (**D**) Superposition of grain-producing cultivated land (GPCL) expanding plaques and annual precipitation (PREL). (**E**) Superposition of grain-producing cultivated land (GPCL) expanding plaques and annual mean temperature (TEM).

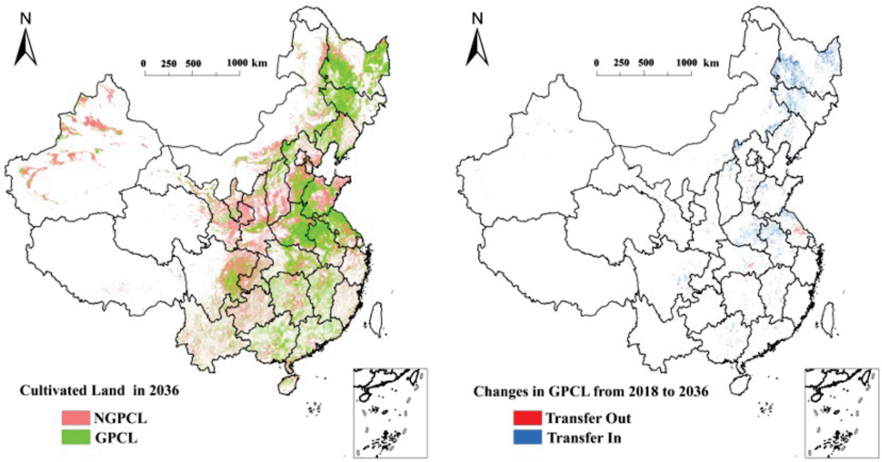

Figure 5. Estimated grain-producing cultivated land (GPCL) distribution and changes in 2036.

4. Discussion and Policy Implications

4.1. Bottom Line of GPrate as a Deciding Factor in the Production Use of Cultivated Land

Guaranteeing the production of food rations, especially the three major staple crops, is the bottom line for the development of a country with a large population, such as China [34]. The Chinese government attaches great importance to food security and emphasizes the implementation of the strictest farmland protection policies. Studying how much food should be grown on arable land in order to ensure food security is of prime importance [3,35]. Our study reveals that from 2000 to 2018, China's GPrate gradually increased from 36.98% to 47.18%, and the predicted value in 2036 was 41.39%, indicating that approximately 50% of the GPrate meet the needs of food production, and it is clear that cultivated land must be used to produce the three major crops. The remaining 50% of the cultivated land can be developed for multi-purpose functions and engaged in the development of other industries, such as cash crops or forest fruits [36].

4.2. Evolution Process of GPCL as a Result of the Natural Adaptation of China's Agricultural Production Layout and as a Response to China's Urbanization Development

For two decades, China's economy and society have developed rapidly, and China's grain production pattern has also undergone rapid changes. We demonstrated that the evolution of GPCL is driven by natural, economic, and social factors, of which population density was the most important factor, consistent with the conclusions of other studies [21,22,37]. China's urbanization rate is increasing rapidly, with a large number of the rural population drifting to cities. The per capita arable land area in different regions has also changed significantly, and the transformation of GPCL and NGPCL is more obvious. The evolution process of GPCL is the natural adaptation result of China's agricultural production layout and is also a response to China's urbanization. One can predict that the spatial pattern of GPCL is relatively stable, and there will be no major changes in the pattern in the future.

4.3. Large Reserve of GPCL Backup Resources of China from NGPCL Allows Planning and Issue of Land Use Policies in the Future

The current NGP has aroused great concern in the government, especially regarding the "zero tolerance" attitude towards the conversion of GPCL to NGPCL [38]. Our study revealed that a large number of NGPCL is expected to get converted to GPCL in the future owing to a large number of NGPCL transforming into GPCL under strict restrictions in the future. At the same time, some researchers have demonstrated that in the future, as a large number of rural homesteads will be withdrawn into cultivated land [39], China's GPCL may further increase. This requires the government to further strengthen planning, introduce reasonable land-use policies, conduct scientific research and judgment on the evolution of GPCL, and ensure China's food security [40].

4.4. Policy Implications

1. Implementation of the action plan for the mapping of arable land: in the entire county, comprehensive mapping and investigation should be conducted to determine the type, area, and distribution of NGPCL, accurately determine the distribution of GPCL in space, and accurately analyze the spatial position.
2. Construction of NGPCL withdrawal account: The management platform for the withdrawal of NGPCL and data information has been set up in the entire province to strengthen on-the-spot verification, grasp the actual situation, and ensure the validity and accuracy of the survey data.
3. Formulating regional implementation plans for cultivated land: According to the comprising factors and the difficulty of withdrawal of NGPCL, the zoning plan of NGPCL shall be drawn up, and according to the plan, the withdrawal plan and timetable shall be drawn up to provide specific guidance for the withdrawal of NGPCL.

4.5. Limitation

This study was conducted on a national scale. It is worth noting that land use decisions are usually finer than the 1-km grid applied here, and the results will need to be described in more detail in the future by further taking small areas as research scales. It should be pointed out that, due to the scale and length of the study, the model assumes that temperature and precipitation are constant in the simulation of future evolution. With the complex changes in the global climate in the future, more complex models can be used in the future, with more variable models considered for further research.

5. Conclusions

We analyzed the spatial evolution law of GPCL in China from 2000 to 2018, then explored the driving mechanisms of GPCL, and finally simulated the spatial characteristics of GPCL in 2036. The following conclusions were drawn:

1. China's GPrate has shown a gradually increasing trend, rising from 36.98% in 2000 to 47.18% in 2018. The transfer map of GPCL revealed that a GPCL of 2.71×10^7 ha has remained unchanged for 18 years, and the amount of transfer-in is greater than that of transfer-out, with an increase of 1.74×10^7 ha. The main transfer observed was the mutual conversion of GPCL and NGPCL. Concerning the transfer volume, 65.48% of GPCL were transferred to NGPCL, and among the transfer types of GPCL, NGPCL accounted for 52.33%.
2. The evolution of GPCL is driven by natural (such as climate), economic, and social factors, of which population density is the most important factor. The main drivers of GPCL expansion are POP, DEM, GDP, TEM, and PREL. GPCL expansion patches are distributed in densely populated, economically developed, warm, and humid plain areas.
3. The simulation results showed that the GPrate in 2036 is estimated to be 41.39%. From 2018 to 2036, the amount of GPCL transfer-in is significantly greater than the amount transferred out. The unchanged GPCL was 8.18×10^7 ha, the transfer-out was 1.78×10^6 ha, the transfer-in was 9.72×10^6 ha, and the newly added GPCL was 7.94×10^6 ha, mainly from the conversion of NGPCL.

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