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Special Issue Reprint

Challenging the Status Quo to Shape Food Systems Transformation from a Nutritional and Food Security Perspective

Second Edition

Edited by
António Raposo, Renata Puppin Zandonadi and Raquel Braz Assunção Botelho

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Preface to "Challenging the Status Quo to Shape Food Systems Transformation from a Nutritional and Food Security Perspective: Second Edition"

For decades, food security and nutrition have been prominent elements of the international development agenda. Over time, however, development priorities and challenges have oscillated, and the investment required has not been sustained. A wider consensus has appeared, specifically one that guarantees food security and, in all its aspects, reduces hunger and malnutrition to promote strong economies, human and planetary health, and sustainable development. Our moral imperative is to positively change food systems to ensure that the food we produce is accessible, sustainable, safe, healthy, and equitable for everyone.

Taking into account these premises, and since the topicality of the subject has emerged and attracted great demand and interest, as demonstrated in the first edition of this reprint, we decided to launch a second edition that aims to present original research articles and reviews on the most emergent topics in food security and nutrition.

This reprint involves authors from 12 different countries, including Australia, Bangladesh, Brazil, China, Colombia, Greece, Italy, Portugal, Spain, Qatar, United Arab Emirates, and the USA, reinforcing that attitudes and knowledge of health, food, and nutrition are key factors that face food insecurity in several countries. The editors are grateful to their families, friends, and colleagues for the support provided. We thank the Brazilian National Council for Scientific and Technological Development (CNPq) for the scientific support of professors Raquel Botelho and Renata Zandonadi. We would also like to thank and congratulate all the authors and the entire MDPI team who allowed the construction of this reprint to become a reality.

António Raposo, Renata Puppin Zandonadi, and Raquel Braz Assunção Botelho

Editors

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Editorial

Challenging the Status Quo to Shape Food Systems Transformation from a Nutritional and Food Security Perspective: Second Edition

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Access to and choices of food are doubtless beyond the realms of biological and nutritional needs. This does not mean that limitations to individuals' access to the social, cultural, economic, and psychological aspects should also be overlooked. Access to safe, nutritious, pleasant, sustainable, and healthy food for all individuals should be the focus of food producers, industries, services and policymakers [1–4]. In this sense, food security and nutrition (FSN) have been in the spotlight of the international development agenda for decades, with development priorities and challenges oscillating over the years. FSN plays a central role in global policy as one of the world's targets most urgently in need of achieving, particularly in the current COVID-19 pandemic era, and has become a mission-critical goal [5]. In addition to the pandemic period, a conflict between two agricultural powers, Russia and Ukraine, has induced several negative socioeconomic impacts on global FSN since the war is producing direct and indirect cascading effects on food production [6]. In many countries, the FSN level represents the level of self-sufficiency and population well-being [5]. In the broader analysis, policies that guarantee food security (in all aspects) and reduce hunger and malnutrition work to promote strong economies, human and planetary health, and sustainable development. Therefore, it is imperative that we positively change food systems in order to ensure universal access to sustainable, safe, and healthy food. Overall, FSN is a complicated and multi-faceted issue that cannot be restricted to a single variable, necessitating the deeper integration of various multi-disciplinary interventions [5].

Considering these premises and the continuous demand for, interest in, and topicality of the subject, as demonstrated in the Special Issue first edition [7], we promoted this second edition in order to promote discussions of food access (affordability, allocation, and preference of food); food availability (the production, distribution, and exchange of food); circularity in food systems at local, regional, or global levels; development, impact, and ethics of novel and data-driven technologies in food systems; and food security and policy, governance, institutions, and trade. These are the factors influencing food consumption and demand considering the food environment; the stability and dynamics of food security aspects; sustainable food systems and agro-ecological food production; and the utilization of the nutritional value, social value, and safety of food.

Healthy and sustainable food systems are essential in the efforts to meet increasing food security, nutrition and health demands [8]. Despite the demand for healthy and sustainable food products, the priority food system components of food purchase and food service require transformation in order to protect the population and planetary health [8]. The ongoing environmental disruptions will increase the demands to develop healthy food products in order to be resilient to changing environmental circumstances and to have a low environmental footprint [8]. Interaction among food producers, food industry, food services and policymakers is imperative to the achievement of sustainable FSN [5,8].

The FSN drivers and policies should be used by policymakers to improve food security, contributing to sustainable food production and food policies for different income groups in order to promote a sustainable food system transformation [5,9].

There is great concern about animal products consumption and the impact of the practice on health and the environment. In this sense, the food industry and consumers are searching for alternatives to reduce animal product consumption globally. However, the use of plant-based foods as substitutes for animal products is challenging from technological, sensory, nutritional, consumer acceptance and sustainable points of view [10,11]. Further studies on animal product substitutes' effect on environmental pollution reduction, safety, and ethical risk perception are required to construct an effective animal-product substitute regulatory system [10].

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Systematic Review

Innovation in Healthy and Sustainable Food Product Development for Health and Aged Care: A Scoping Review

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Abstract: Population ageing and climate change are issues of global concern. Subsequently, the need for healthy and sustainable food systems to meet the increasing demands for health and aged care is evident. This review aimed to systematically identify studies reporting new or innovative foods, drinks and snack products in health and aged care, and describe health and environmental sustainability considerations where reported. Methods were guided by the Joanna Briggs Institute guidelines for scoping reviews and reported against the PRISMA-ScR guidelines. Eligible studies were conducted in an inpatient healthcare setting or aged care facility where a new or innovative food, drink or snack product was evaluated with outcomes of product use, acceptability, cost, appropriateness for the population, and clinical or environmental sustainability outcomes in the last decade. Three databases were searched using a replicable strategy, with five publications of four studies included in the final library. Product innovations were led at the facility level and included testing dewaxed brown rice, talbinah, and an apple/pear juice fibre solution. Results suggest that food industry suppliers are operating in parallel with foodservices within hospital and aged care. Future intersection would be transformative for both industry sectors.

Keywords: innovation; food; aged care; healthcare; sustainability

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1. Introduction

Each year, an estimated 265 million meals are served to hospitalised patients (n = 190,000 per day) [1] and people living in residential aged care settings (n = 537,000 per day) [2] in Australia. Global food production and delivery in these settings is magnified at scale. According to the Australian and New Zealand Standard Industrial Classification (ANZSIC), the food and beverage sector is in the top three industries that provide agricultural product inputs into the aged care sector, accounting for 18% of all intermediate inputs [3]. The health sector food system that supports the production, procurement, transportation and foodservice to ensure that each meal is delivered is layered with complexity. In addition to reliance on a supply chain which has been shown to be increasingly unstable throughout the COVID pandemic [4], there is an extended array of health conditions to be considered, many of which require therapeutic diets. In hospitals these will vary across the spectrum of disease states, whilst in aged care, dietary needs are focused on reducing nutritional decline. Health and aged care have been identified as sectors where the food system is in particular need of transformation in order to be healthier and more sustainable [5,6].

In this respect, the information and material flow related to food supply is an important component of the health and aged care sector. It entails a complex supply chain made up of multiple stakeholders and operations. Policy commitments to support transforming these components to promote healthy and sustainable food systems in hospital and aged care have been made at state [7] and global [8] levels of governance, however innovation to the food supply and manufacture within this sector has not previously been described. In line with global imperatives to improve food systems to protect human and planetary health [9], the integration of healthy and sustainable food system into health services and aged care is becoming increasingly apparent. Policy statements released by authoritative bodies [9,10] highlight the challenges of influencing planetary health, the health sector and aged care sector, and the globalised food system. However, there is very little information and research on the foods and processing methods required to meet these demands.

An important step in facilitating this food system transition is to examine the interface between the food sector and the aged care sector, identify research needed to meet the challenges faced at the food sector-health/aged care sector intersection, and explore issues such as how to improve the collaboration and coordination, and what partnerships could be fostered and strengthened to facilitate change. Previous authors have already established that innovation is a means to developing healthy and sustainable foods [11]. Accessing appropriate food products is an identified challenge for health service food retailers [12], highlighting the importance of understanding the current and potential food supply of healthy and sustainable food products that are safe and flavoursome.

To address this research gap, this review aimed to systematically (1) identify studies reporting new or innovative foods, drinks and snack products in health and aged care, and (2) describe health and environmental sustainability considerations where these were reported.

2. Materials and Methods

A scoping review was undertaken guided by the Joanna Briggs Institute Manual for Evidence Synthesis (Chapter 11 Scoping Reviews) [13,14] and reported against the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews checklist (PRISMA-ScR) [15]. This design was selected due to the broad scope of the research question, whilst still providing a replicable and transparent process. The review protocol was not prospectively registered.

The inclusion criteria are outlined in Table 1. Studies were eligible if they were conducted in an inpatient healthcare setting including hospitals or an aged care facility. The concept of interest was the trial or evaluation of a new or innovative food, drink or snack product with outcomes of product use, acceptability, cost, appropriateness for the population, and any relevant clinical or environmental sustainability outcomes. To identify relevant new and or innovative products, research publication dates were restricted to the last 10 years (from 1 January 2012). Exclusion criteria included literature that reported a change in the foodservice menu design, food size, composition, or texture changes, fortification of current items with no whole foods added, the product of interest being a pill, tablet, nutraceutical or medication, and the provision of additional oral nutrition support supplements to patients. Peer reviewed papers in any language and study design were eligible. Papers were ineligible if they were letters to the editor, conference abstracts, theses or grey literature.

Table 1. Inclusion criteria.

Criteria	Description
Participants	Health care inpatients and aged care residents
Concept	New or innovative nutrition product for patient consumption including food, drink or snack being trialled/tested, implemented or evaluated; Product acceptability, cost, appropriateness for the population, any relevant clinical or sustainability outcomes
Context	Health service: including hospital (public or private), medical centre, aged care facility (nursing home, retirement home, assisted living facility) that provides food for patients/residents through a foodservice model
Study design	Primary peer reviewed research with any observational or experimental study design including studies using quantitative, qualitative or mixed method data collection, pilot or evaluation study

The following databases were searched on 5 August 2022 via EBSCOHost using a search strategy designed in conjunction with a subject librarian: MEDLINE Complete, Global Health and CINAHL Complete (Table S1: Database search strategies). The search terms utilised three fields relating to hospital and aged care settings, new and innovative products, and food. All keyword search terms were repeated across the three databases and subject headings were customised to suit each individual database selections in line with the themes of the search fields, remaining as similar as possible. All results were downloaded into EndNote (version X9, Clarivate Analytics, Philadelphia) [16] and duplicates were removed before being uploaded to Covidence where additional duplicates were removed by the software (Veritas Health Innovation, Melbourne) [17]. Title and abstract screening was completed independently and in duplicate for 10% of the identified papers with 98% agreement, as such the remainder of the title and abstract screening was completed by one reviewer. The full text screening was completed independently and in duplicate by the same two reviewers where consensus and agreement were reached on any discrepancies that arose. Additionally, the reference lists of the included papers were hand searched for possible eligible papers.

A customised table designed for this review was used to extract data from the included papers. Data were extracted on the following study characteristics: author, year, setting, foodservice type, location, study aim, study design and method, the new or innovative nutrition product used (e.g., food, drink, snack) and its preparation, how this product was implemented in the foodservice delivery, the end user, and any acceptability, clinical or sustainability outcomes reported during the introduction of the product to the foodservice. Data were synthesised narratively. Guided by the JBI Guidance for scoping reviews [13,14] and the PRISMA-ScR guidelines, [15] a quality assessment of included studies was not completed.

3. Results

From the database searches a total of 15,084 articles were located. After removal of duplicates 7898 articles were imported into Covidence [17] for title and abstract screening, documented in Figure 1. Four articles were identified as eligible for inclusion [18–21]. From the hand searching of included paper reference lists a related article from a previously identified study was eligible [22]. A list of excluded studies and reasons for exclusion are provided in Table S2: Excluded full text references.

Included studies were conducted in Malaysia [18], Japan [20], the United States [21], and Denmark [19,22]. There were two reports contributing to one study, whereby one tested food in the nursing home setting [22] and the other evaluated the sustainability of the items [19]. Three studies were completed in homes for the aged [18,20,22], an academic orthopaedic specialty hospital [21] and to meet the Danish Ministry of Food institution-diet recommendations for elderly populations with poor appetite and dysphagia in nursing homes [19]. The four studies [18,20–22] which implemented food product innovations delivered them to depressed older adults, 60 years or older (GDS-R >3) [18], adults 65 years or older [20], dysphagic older adults, over 70 years [22] and postoperative spine fusion patients with an expected length of stay at least three days [21]. Research designs included two randomised trials [18,21], two non-randomised interventional studies [20,22] and one cross sectional study [19].

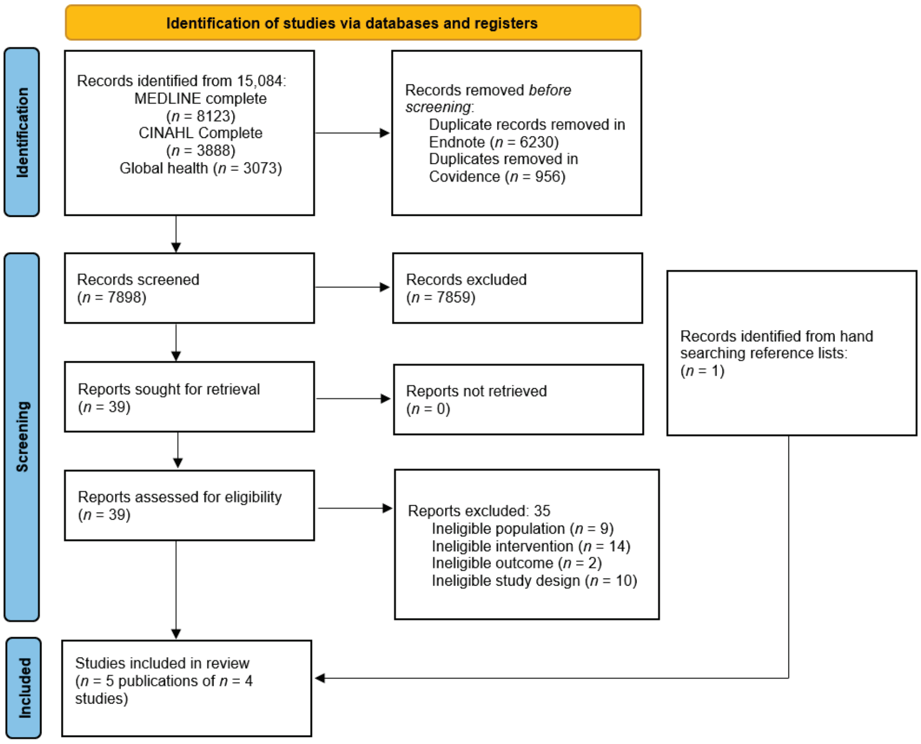

Figure 1. PRISMA flow diagram of included studies for the systematic review of new or innovative nutrition products used in hospital and aged care foodservices.

All studies prepared their new or innovative food, drink or snack products on site at the aged care facility [18,20,22] or hospital [21] with no food industry involvement. A detailed description of the food, preparation method and reasons for implementation are presented in Table 2. The continued use of the innovative or new food were not reported in any study. The foods, drinks and snacks were trialled and then either recommended [18–20,22], not recommended [21], or to be further studied for potential use in the future.

Different innovative foods were described by three studies including: dewaxed brown rice (DBR) to improve cognitive function [20], talbinah to decrease depression [18], and an apple and pear juice drink to promote bowel movements [21] (Table 2). Two of the studies [19,22] were based on 20 snack recipes developed to increase the energy and protein intake in elderly Denmark nursing home residents through product innovations such as apple porridge with vanilla cream, tuna mousse and prune trifle.

Clinical outcomes were reported in three of the studies, measuring their outcomes of interest using previously developed patient questionnaires before [18,20], during [18,20] or after [18,20,21] the delivery of their interventions (Table 3).

The dewaxed brown rice study [20] used the Revised Hasegawa's Dementia Scale to measure age associated dementia. Participants were allocated into a low cognitive or high cognitive function group. There were no significant differences between the consumption of dewaxed brown rice and the control (white rice) at the end of the intervention, however, in the low cognitive function group there were significant increases in their HDS-R scores when the consumption of dewaxed brown rice was compared to white rice. Additionally, compared to their baseline HDS-R scores the low cognitive function group had more improved scores, and less decreased or no changes in scores, when comparing their ingestion of white rice to dewaxed brown rice.

To measure depression, the talbinah (porridge made from barley flour) study [18] used the Geriatric Depression Scale; the total mood disturbances scale; and the depression anxiety and stress scale 21-item questionnaire including the subcategories of depression, stress and anxiety. Mood improvements were identified across the majority of measures.

The apple and pear juice fibre solution study [21] measured participants' bowel function index and constipation assessment scale scores, time to first bowel motion post-surgery and number of bowel movements between surgery and up to day three post-surgery. There were no significant differences between any of the outcomes measured in this study.

The sustainability profiles of the new or innovative foods, drinks or snacks were reported by one study [19]. The sustainability of the 20 snack foods were measured using a consequential life cycle assessment technique (that identifies the environmental consequences of a decision or a proposed change in the system under study) to describe their environmental impact moving from soil-to-table using 16 impact categories (Table 3) and three functional units, the weight of the foods and their energy (kJ) and protein content. The sustainability of items was reported in total global warming impact measured in kgCO2-eq and the overall monetised environmental impact (EUR) generated through the 16 impact categories where the three most important categories (respiratory inorganics, nature occupation, global warming) were reported separately compared to the sum of the remaining 13 categories. For snacks, both global warming impact and monetised environmental impact were reported. The ten snacks which had lower kgCO2-eq and monetary value (EUR) on average had a 40% less sustainability impact compared to those ranked 11–20 regardless of functional unit chosen. However, when the functional unit changed (energy, protein, weight) the order of the 10 lowest kgCO2-eq producing and monetised environmental impact snacks from the total 20 included reformed to represent different snacks.

Acceptability of the new or innovative food was only reported in one study [22]. Of the 20 food products tasted by residents, vanilla ice cream, strawberry parfait and panna cotta were the most preferred between meals. Foods with added garnishes or layered foods were not significantly preferred over foods without these accompaniments.

Table 2. Study characteristics of innovative food and drinks implemented in health and aged care.

Author, Year	Population, Setting, Foodservice Type, Location	Study Aim	Study Design; Method	New or Innovative Food, Drink, Snack; Preparation
Baradari et al. 2013 [18]	*n* = 30 depressed (GDS-R > 3) older adults (>60 yrs old), long term care facility, not stated, Malaysia	Measure the effect of talbinah on depression, stress, anxiety and mood	Crossover randomised clinical trial; two groups, one serving of talbinah/day at morning tea vs. control (habitual diet) for 7 wks–3 wk intervention, 1 wk washout, 3 wk intervention where depression (GDS-R, DASS-D), stress (DASS-S), anxiety (DASS-A) and mood (POMS, TMD) were measured at 0, 3, 4 and 7 wks	Talbinah is a traditional Arab food which is ground roasted barley with milk and honey; 25 g ready-made market bought talbinah mixed in 100 mL warm water
Saxe et al. 2017 [19]	Older adults with poor appetite and dysphagia, nursing homes, not stated, Denmark	Measure the environmental impact and sustainability of 20 common snacks developed to meet the Danish institution-diet recommendations for elderly populations with dysphagia and poor appetite and identify which ingredients are responsible for higher environmental impacts	Descriptive cross sectional; Consequential life cycle assessment (cLCA) of each snack recipe including ingredients, cooking, baking, cooling and freezing. The cLCA measured 16 environmental impact categories: the three most important impact categories are presented separately in this study (respiratory inorganics, nature occupation, global warming) and the rest were presented as a sum (human carcinogenic and non-carcinogenic toxicity, ionizing radiation, ozone layer depletion, aquatic and terrestrial ecotoxicity, acidification, aquatic and terrestrial eutrophication, respiratory organics, photochemical ozone effects on vegetation, non-renewable energy and mineral extraction). Snacks were split into two groups, the 10 best and 10 worst as defined by their global warming and monetised environmental impact.	Snacks were: apple porridge with vanilla cream, cauliflower soup, chocolate mousse, lemon mousse, mashed roots with butter, milkshake, protein drink, panna cotta, prune trifle, raspberry jelly with vanilla cream, rice porridge with cinnamon sugar, rum mousse, ryaa high-energy vanilla ice cream, rye bread soup and whipped cream, soup of asparagus with chicken, strawberry parfait, strawberry porridge and vanilla cream, tuna mousse, vegetable soup, yoghurt/strawberry drink. Although some of these foods were fortified using traditional approaches (e.g., cream) many were fortified with fruits, and other core foods to increase their appeal. All snacks have at least 6 g of protein, and 400 kj, and all weighed 100 g; preparation not stated.
Uenobe et al. 2019 [20]	*n* = 31 elderly (>65 yrs old), nursing home, not stated, Japan	Measure the effect of continuous ingestion of DBR on cognitive function improvement	Controlled crossover trial; two groups (low or high cognitive function) ate DBR or WR 3 x/day for approximately 6 mths and then the other rice type for the same period, HDSR-R scores measured at 0, 6 & 12 mths.	DBR is brown rice with only the outermost wax bran layer removed, DBR has 0.81 ng vs. WR 0.04 ng lipopolysaccharides; the WR and DBR were prepared in rice cookers as rice meal or rice porridge. DBR rice meal was prepared with 2–3 parts water added to one-part DBR (g) and rice porridge was cooked using five parts water added to one-part DBR.

Table 2. *Cont.*

Author, Year	Population, Setting, Foodservice Type, Location	Study Aim	Study Design; Method	New or Innovative Food, Drink, Snack; Preparation
Wittig-Wells et al. 2019 [21]	*n* = 46 postoperative orthopaedic patients between 36–82 yrs old, orthopaedic specialty hospital, not stated, United States	Measure the effect of a prune juice and apple juice fibre solution to prevent constipation	Post-test control group randomised control trial; two groups, control and one where patients consumed the dietary fibre solution orally twice a day at 9 am and 9 pm for 3 days post operation, participant constipation was measured using the BFI and CAS on the third night, the total number of bowel movements in the 3 days post operation and time (hrs) to first bowel movement post operation were recorded. Stool softeners and laxatives could be requested by patients.	These juices were chosen due to their recommendation for the prevention and treatment of constipation. The fibre solution comprised 118 mL prune juice and 118 mL apple juice and was heated for 10 s in a microwave; consumption followed 237 mL room temperature water.
Okkels et al. 2018 [22]	*n* = 30 dysphagic elderly (>70 yrs old) from 3 nursing homes; Denmark	Identify the most liked between meal items based on flavour, describe the sensory properties of these items and identify the equality of flavour and appearance-based preferences	Non-randomised interventional study. 20 most popular between meals were chosen from a combination of two hospital and one municipal kitchen menus. 15 min interviews partnered with a 3-point Likert scale questionnaire (bad, neither bad or good, good) asked participants about appetite, appearance and flavour of the items they tasted. Participants tasted 5 items per day across 4 days. Each tasting was separated by a spoon of water.	Between meals were: pumpkin soup, carrot soup, clear soup, mashed potato with bacon and onion, rice porridge with cinnamon sugar, soup of asparagus with chicken, milkshake, rum mousse, apple porridge with vanilla cream, protein drink, rye bread soup with whipped cream, raspberry jelly with vanilla cream, prune trifle, yoghurt/strawberry drink, strawberry porridge with vanilla cream, chocolate mousse, lemon mousse, panna cotta, strawberry parfait, vanilla ice cream. Each item contained between 1.9–7.9 g protein and 165–1409 kJ per portion and all weighed 100 g; these foods were texture modified according to Danish standards (minced and moist, pureed) as required and some recipes were fortified using a protein powder, garnished with sprinkles (e.g., blueberry dust) or layered with other additional foods (e.g., whipped cream). All foods were frozen and thawed the day before service, then served as necessary (e.g., potato was warmed, ice cream was frozen).

Table 3. Outcomes of innovative food and drinks implemented in health and aged care.

Author, Year	Clinical Outcomes Reported	Sustainability Outcomes Reported	Acceptability Outcome Reported
Badrasawi et al. 2013 [18]	In the intervention group there was a significant decrease in GDS-R, DASS-D, DASS-S and TMD mean scores post intervention vs. the time without talbinah (p = <0.05) All POMS subcategory mean scores except POMS V significantly decreased (p = <0.05) No significant changes in any measure for the control group (p = >0.05) Significant increase (p = <0.05) in calories, zinc and magnesium intake in the intervention group	NR	NR
Saxe et al. 2017 [19]	NR	For individual recipes the global warming impact and monetised overall environmental impact were significantly different between the 10 best and worst snacks On average the best 10 snacks have a 40% less global warming impact and monetised environmental impact than the 10 worst, however snacks change between these two categories depending on weight, energy or protein content. Monetised environmental impacts were contributed by 46% global warming, 26% nature occupation, 12% respiratory inorganics and the remaining sum of the 13 impacts were 16%. Ingredients with the most environmental impacts were cream, and protein powders (protein drinks, whey and casein). Products were packaged on 8 g plastic trays and in 0.5 g plastic film adding a global warming impact of 0.02 kg CO_2-eq and a monetised environmental impact of 0.002 EUR per meal. The delivery of items via medium vans also added 0.026–0.435 kg CO_2-eq and 0.005–0.09 EUR per meal.	NR

Table 3. *Cont.*

Author, Year	Clinical Outcomes Reported	Sustainability Outcomes Reported	Acceptability Outcome Reported
Uenobe et al. 2019 [20]	No significant difference in total HDS-R score between start and end of either WR or DBR consumption. Significant increase in HDS-R total score for the low cognitive function group consuming DBR compared to WR ($p = 0.01$). Low cognitive function participants consuming DBR had significantly improved HDS-R scores compared to decreased or no change in score from baseline ($p = 0.17$).	NR	NR
Wittig-Wells et al. 2019 [21]	There were no significant differences ($p = <0.05$) between groups BFI or CAS scores. 68.2% of patients had a bowel movement in the first 3 days (intervention group) vs. control 58.3%, not significantly different. Bowel movements ranged from 1 to 9 with the medians for both groups being 1, not significantly different. Time to first bowel movement ranged 17.8–98.7 hrs, intervention group were 59.9 hrs compared to control 70.2 hrs, not significantly different.	NR	NR
Okkels et al. 2018 [22]	NR	NR	Vanilla ice cream, strawberry parfait and panna cotta were the most preferred between meals. Appetite was not significantly associated with flavour ratings. In-between meals with higher fat and energy content but not protein were significantly correlated with higher flavour likings. Lower temperature foods had higher liking and there were significant differences between liking of foods with sprinkles or which were layered. Sour and sweet tasting in-between meals scored significantly higher than salty items. Rum mousse and clear soup had significantly higher appearance scores when compared with their flavour.

GDS-R, Geriatric depression scale–residential, POMS, Profile of mood states, TMD, total mood disturbances, DASS, depression anxiety and stress scale, POMS V, profile of mood stat-vigour, NR, Not reported, DBR, Dewaxed brown rice, WR, White rice, HDS-R, Revised Hasegawa's dementia scale (HDS-R) score, BFI, bowel function index, CAS, constipation assessment scale.

4. Discussion

This scoping review found that despite the demand for healthy and sustainable food products in health and aged care, the research into the next phase of food innovation is constrained. Whilst these settings are responsible for the dietary intake of a large proportion of the nutritionally dependent population (including individuals with special nutritional requirements), the priority food system components of food procurement and foodservice [23,24] need transformation to protect future population and planetary health [25].

Results suggest that suppliers (food industries including horticulture and food manufacturers) are operating in parallel with the demand (foodservices within hospital and aged care) component of this vast industry. Greater intersection of these industries would be transformative for food in health and aged care. The development of products would have benefits in terms of commercial outcomes, while contributing practical solutions to tackling dietary risk factors and environmental disruptions to food systems. New and emerging technologies for food sector transformation can help to bridge the 'gap' between nutritional food standards and the food sectors. These areas include food preservation through new ways to retain nutritional value, safety and flavour; reduced and/or sustainable food packaging; shelf-life improvement, processing of raw food and retaining nutritional value; easy and healthy accessibility (e.g., ready to eat food); and reduction in cosmetic imperfections visible in some farm produce [26–29].

We suggest that the food industry can optimise its capabilities to create more value-added products that meet consumer and market demand within the context of rapidly evolving interest in health, safety and sustainability considerations [30]. Authors have also identified scope for new food production methods to emerge [31]. Through the types of food and beverages they provide, including to health and aged care facilities, food industries have a critical role to play in implementing evidence-informed healthy and sustainable food supply chains. Despite this need, previous efforts to bring about change have achieved mixed outcomes and have not always been well coordinated with policy guidelines and demands from the health and aged care sectors [32]. One of the reasons for this setback has been the lack of proper consideration for consumer acceptability and factors that influence this acceptability, such as cultural background.

The inclusion of only one study in this review considering the health and sustainability of foods and food systems within health and aged care was surprising [19] as this has been a focus internationally [33–35] and locally [36,37] within Australia. There are significant market opportunities for the food industry to meet projected increasing demands for healthy and sustainable food products and practices. Over the next three decades, all regions of the world are expected to experience an unprecedented and sustained change in the age structure of their populations, with the proportion of the global population aged $\geq$65 years increasing from 9.3% in 2020 to 16.0% in 2050 [38] with associated increases in spending and investment to support the care needs that arise from this ageing population [39]. It has been argued that the general ageing of the population results in an increase in the size of the 'mature aged' consumer segment who continue to demand convenient, healthy, and functional food. Hence, there are opportunities to meet the demands of the ageing, health-conscious population through an expanded range of convenient, nutritious, and functional food. Moreover, through the institutional health care sector (including in aged care facilities), there is demand for tasty, nutritious food, including partially prepared foods [40].

Brokering of greater connections between industry, government regulators and health and aged care providers is needed to actively translate this type of nutrition evidence into the development of innovative fortified food products and beverages, that are acceptable to the target market. The availability and consumption of these types of healthier food by the aged care residents will directly and indirectly improve their health and well-being, in turn potentially reducing the costs associated with the provision of medical and related services.

This review has highlighted some opportunities for future research in this sector. Implementation research may support the translation of new products into these settings, particularly through understanding the barriers to implementation. Opportunities also exist for greater engagement with consumers (patients and residents) to understand their food preferences, ensuring alignment with dietary requirements. Multiple research gaps also exist from a sustainability perspective, particularly evaluating the true environmental cost of product development and implementation, which may differ from the economic cost.

This scoping review utilised a wide-ranging search strategy across multiple databases, and was performed and reported against relevant reporting guidelines. Authors acknowledge that the entire library was not reviewed in duplicate and that there is a risk that some research may have been omitted.

5. Conclusions

This review found that currently there are few healthy and sustainable food product innovations to support foodservices in health and aged care settings. Into the future it is predicted that demographic shifts will result in an increasing proportion of populations around the world demanding healthy food products in health and aged care settings. It is also anticipated that ongoing environmental disruptions will place increasing demands for the development of these healthy food products to be resilient to changing environmental circumstances and have minimal environmental footprint. Transformations of the food systems within the health and aged care sectors are needed.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/foods11223604/s1, Table S1: Database search strategies; Table S2: Excluded full text references.

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Review

A Review of the Challenges Facing Global Commercialization of the Artificial Meat Industry

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Abstract: The sustained growth of global meat consumption incentivized the development of the meat substitute industry. However, long-term global commercialization of meat substitutes faces challenges that arise from technological innovation, limited consumer awareness, and an imperfect regulatory environment. Many important questions require urgent answers. This paper presents a review of issues affecting meat substitute manufacturing and marketing, and helps to bridge important gaps which appear in the literature. To date, global research on meat substitutes focuses mainly on technology enhancement, cost reduction, and commercialization with a few studies focused on a regulatory perspective. Furthermore, the studies on meat substitute effects on environmental pollution reduction, safety, and ethical risk perception are particularly important. A review of these trends leads to conclusions which anticipate the development of a much broader market for the meat substitute industry over the long term, the gradual discovery of solutions to technical obstacles, upgraded manufacturing, the persistent perception of ethical risk and its influence on consumer willingness to accept meat substitutes, and the urgent need for constructing an effective meat substitute regulatory system.

Keywords: artificial meat; technology; market; risk; regulatory system; review

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1. Introduction

Rising incomes and social development induced rapid growth in the global consumption of meat and meat products. However, scarcity of resources, outbreaks of animal epidemics (e.g., swine flu), and natural disasters (e.g., typhoons) disrupt the supply of meat. In this paper, artificial meat refers to meat substitutes manufactured using technology converting raw materials, such as plant protein and animal cells, to eliminate the shortcomings of traditional meat protein products. At present, global meat substitutes mainly include plant-based meat (PM) and cultured meat (CM) substitutes [1]. While many researchers regard PM or CM meat substitutes as new food products, few define them as artificial meat products [2–4]. However, from the perspective of meat alternatives, they are highly similar and comparable to meat in terms of functional attributes [1].

In recent years, food companies have invested in artificial meat research and development and expect a rapid expansion in retail and food service sales. However, the global commercialization of artificial meat is facing technological innovation challenges, lack of consumer awareness, and inadequate regulation [5]. At the same time, there are several important questions requiring answers and timely solutions that support sustained purchasing and consumption of artificial meat. Among them is the issue of artificial meat safety. Does artificial meat carry ethical and technical hazards? Furthermore, would such hazards negatively affect the sales of artificial meat?

This paper examines four key and intertwined challenges facing the global PM and CM substitute industry: technology, commercialization, hazards, and regulatory oversight. The study conducts a review of relevant published studies. The four subject areas pertaining to the artificial meat sector, limited to PM and CM meat substitutes, are reviewed, specifically: (1) the concept and development process of artificial meat; (2) the technical and market trials in developing the global artificial meat industry; (3) safety hazards faced by the artificial meat industry in the short and long term; (4) and review of regulatory status.

2. The Development of Artificial Meat

Growing incomes and changing preferences of the global population increased the demand for protein. Animal protein is the main source satisfying this demand, and its rate of production is expected to grow in the foreseeable future [6,7]. Farmland and labor limitations restrict animal husbandry, reaching a saturation point in recent years [8]. Food producers are required to assure animal welfare and protect land and biological resources [2], making it difficult to increase meat production and supply in the short term.

Meanwhile, COVID-19, African swine fever (ASF), and other outbreaks have already had an impact on the production and supply of global meat products. Traditional animal husbandry, meat production, and processing methods have a negative impact on the environment, health, and animal welfare. Meat substitutes, PM or CM, offer opportunities to reduce the environmental burden of livestock production by using less land and emitting less GHGs [9]. The production of meat substitutes requires less energy overall, and therefore has the potential to address a major global growth constraint.

Meat products not only exact high costs on the environment [10], but also affect public health. Excessive consumption of meat may cause obesity and compromise consumer health. Consumers emphasis on dietary protein [1] and the risk of supply shortages provide opportunities for the development of artificial meat [11]. The development of CM products has been a long process since British Prime Minister Churchill first put forward the concept of CM substitute in 1931 [12]. In 2013, Professor Mark Post finally made the concept a reality [13]. Professor Zhou Guanghong of Nanjing Agricultural University of China cultivated the first cultured meat (CM) in China in 2019 [14]. Meat substitutes offer a solution to the consumer's desire to eat meat while protecting global food security, and assuring protein supply in the future [5,15].

The development of the artificial meat industry is associated with several hazards. Technical hazards result from unproven technology [16]. New ingredients, especially in the case of CM, present biological hazards [17]. Unclear product positioning and a lack of regulations yields ethical risk [18]. Distrust affects cooperative relationships [19,20] between consumers and artificial meat producers. Therefore, regardless of short-term technical difficulties, an effective regulatory system is necessary for long-term safety [5].

3. Types and Technology of Artificial Meat

Artificial meat is a meat substitute [5,15]. The use of raw materials and technology distinguishes artificial meat types as PM and CM products [21–23]. Plant-based meat substitutes are also termed "plant-based meat", "vegan meat", and "simulated meat". PM substitutes are mostly made from soybeans. The high moisture extrusion of protein concentrate and water mixtures promotes the development of fiber intermediates to imitate the texture and firmness of meat, and high humidity extrusion technology is used to make meat imitation products retain fragrance to imitate meat flavor [24,25]. Additionally, PM substitutes help overcome resource constraints and limit waste disposal [26,27].

The CM substitute is also known as "synthetic meat", "in vitro meat", and "cultivated meat", but "cultured meat" is most widely accepted and used in the industry. Real-world research into CM substitutes was initiated by NASA [21]. NASA used skeletal muscle tissue engineering, stem cells, cell co-culture and tissue culture to obtain meat culture in vitro [28]. Those efforts aimed to fully mimic the physical sensation of meat, such as visual appearance, smell, texture, and taste [28]. CM substitutes have the potential to replace, at least partially, livestock production and increase animal protein availability to consumers.

Meat substitutes using plants as raw materials have used bean curd, bean skin, and other bean products [29]. Traditional foods such as bean curd and other bean products can be considered as the concept prototype of PM products. Vegetable protein meat analogues have a long history, and are not a new food category [30]. However, PM products constitute a new category, quite different from traditional vegetable protein products, and are produced using a different technology. PM products have a fiber-like structure. The structure imitates the texture and taste of real meat. Yeo and Kim (2020) [31] applied 3D technology that has already been widely used in food production to the manufacture of PM products. The application of electrospinning [31], extrusion technology [26], and 3D printing technology [24,32] transitioned the PM substitute from a concept to reality.

CM substitutes are in a critical stage of technological breakthrough and commercial application development [33]. The production of CM products can be divided into three stages. The first requires identifying the cell acquisition source. CM products are produced by culturing animal muscle stem cells, but there is a hazard associated with inadequate source cell and culture environment safety [34]. Stem cell acquisition [35] and muscle stem cell maintenance [36,37] solved those problems [23,38,39]. Second, the cell culture and myoblast technology involve a serum-free medium [37,40,41], seed cell mass culture (i.e., microcarrier suspension culture, immobilized culture, or aggregate suspension culture) [39,40,42–44], and large-scale differentiation of seed cells into myotubes [45–48] to gradually improve the culture environment. Finally, through commercial processing and scaling-up, it is possible to produce CM substitutes on a large-scale [39,40]. CM substitute manufacturing involves a co-culture of myoblasts and fibroblasts as the main techniques [49].

While CM production is supported by a large number of new technologies, technical difficulties in cell source acquisition and cell culture have been overcome, very gradually, in bringing CM product to reality. Imperfect technology and manufacturing costs are factors keeping CM products still in the laboratory stage, making it difficult to scale-up production in the short term [35]. Currently, CM technology faces challenges in the preparation of stem cells, optimization of culture conditions, and development of a cost-effective and efficient culture medium [50]. For example, the effective culture of CM products depends on the culture source and composition of the culture medium [23]. A simple and efficient method to generate skeletal muscle cells from mouse skin has been developed providing a source of cell culture [47]. Improvements in CM production capacity and cost reduction are needed to take advantage of market demand. In the UK, an independent technology innovation center and founding member of the UK Government's High Value Manufacturing Catapult (CPI), has announced the commencement of a project in collaboration with 3D Bio-Tissues Ltd. (Miami, FL, USA) (3DBT) to develop an improved growth media for culturing meat cells in a lab environment. The project aims to increase CM yields and remove the need for animal-derived products, making cellular agriculture as sustainable and economic as possible [51].

4. Markets, Consumers, and Artificial Meat

4.1. Consumer Expectations Regarding Meat Substitutes

The demand for animal protein is projected to require that nearly two-thirds of farmland be used for animal husbandry by 2050 [52]. The remaining one-third may be insufficient to meet demand for plant-based food production [3]. Consumers have diverse opinions on whether trends in meat consumption needs to be changed [9]. Traditional meat meets basic requirements regarding taste, flavor, nutrition, and cost. Consumers are willing to choose meat substitutes to offset the negative effects of meat consumption [53]. With the improvement of living standards, consumer expectations will be higher for meat substitute attributes [9,54].

Lynch & Pierrehumbert (2019) [55] believe that meat substitutes, as a high-tech replacement for traditional meat, must be competitive in the market by being affordable for consumers and profitable for manufacturers. The commercialization of products is greatly enhanced by consumer acceptance [56,57]. The number of PM products has been growing on the global protein food market [29]. The growth reflects the innovation of meat substitute manufacturers [54]. The number of enterprises joining the PM product market increases year by year, and the types of PM products sold on the market have expanded [29]. Since 2015, the number of meat substitute products (mostly PM products) has more than quadrupled (an increase of 429%). PM products that mimic the characteristics of traditional meat products have already found a place in the protein food market [29]. There are differences across countries and regions in perception and acceptance of meat substitutes [18]. Consumers in the United States and Australia have a high acceptance of PM products, but some still express concerns about the limited variety [58,59].

Several companies, such as Impossible Foods [60] and Beyond Meat [61] have begun PM substitute production. Beyond Meat issued an IPO in 2019 [62] and further promoted technical research into PM substitutes. According to Businesslive's report on 9 December 2020, Nestle is committed to seizing the Chinese market and has launched Nestle PM products. Their Harvest Gourmet series includes six kinds of PM products. Meanwhile, the company planned to launch related food products through the Tmall online platform and the HEMA Xiansheng off-line supermarket in Beijing and Shanghai [63].

At present, the ability of either PM or CM products to meet the needs of consumers is progressing at different paces. CM products have not yet entered the market on a large scale. Vainio, Irz & Hartikainen (2018) [64] suggested that information would change the behavioral intention of "meat skeptics", and that the way in which that information is expressed determines its effectiveness in changing behavior. Bryant & Barnett (2018) [56] posit that with the commercialization of technology, consumers will be more interested in the acceptance of CM products. While German consumers show moderate acceptance of CM products, they also express concerns about the global spread of unregulated CM products [10]. The overwhelming majority of Chinese urban consumers are unacquainted with meat substitutes including CM [4]. Mancini & Antonioli (2019) [65] found that more than half of surveyed Italian consumers (54%) indicated that they would like to try the CM products. Most were young consumers with high educational attainment who were familiar with livestock farming. In a survey of 5586 consumers in German and French speaking areas of Switzerland, the consumption of meat, health awareness, gender, age, and education affected consumer acceptance of meat substitutes [16]. Among Chinese consumers, acceptance largely depends on their trust in the product.

However, there are a few companies that entered the market offering CM products. According to the AFN website on 2 December 2020, the Singapore Food Administration has approved the US start-up Eat Just to sell its laboratory-grown chicken in Singapore, making Singapore the first country in the world to allow the sale of laboratory grown meat. An Israeli start-up company, Future Meat Technologies (FMT, https://future-meat.com/, accessed on 10 January 2021), plans to launch a production line of 100% CM products in 2022, reducing the cost to less than $22 per kilogram [66].

4.2. Meat Substitute Taste

Consumer preferences are mainly affected by taste, price, and other factors [56]. Currently, meat substitute products cannot meet consumer expectations regarding taste and price, explaining the guarded consumer response. Large-scale production of PM and CM products with all the characteristics of meat taste and flavor poses a great challenge for manufacturers [23]. PM substitutes strive to achieve a true meat appearance and taste [7]. CM products have yet to meet consumer taste expectations and experience insufficient production capacity contributing to the high cost in the short term [5]. There has been some progress; for example, Yang et al. (2011) [67] studied meat flavoring systems, which promote the production of meat flavor compounds. Volunteers evaluated the CM product obtained from swine muscle stem cells from Professor Zhou Guanghong's team, concluding that it was consistent with ordinary meat [14]. Aleph Farms, an Israeli start-up, obtained real meat directly from cow cells. Israel's Prime Minister Benjamin Netanyahu declared the product delicious, guilt-free, and indistinguishable in taste from traditional beef. Netanyahu was the first head of state to taste meat cultivated outside of a cow [68].

To improve the taste and to extend quality guarantee period, food additives have been viewed as important by experts and regulatory agencies. In 2017, the WHO Expert Committee on food additives proposed that the regulation of food additives should be product-specific. It is necessary to screen additives before new products are marketed. To improve the appearance of artificial meat, food additives such as dyes are used to imitate real meat coloring. For example, synthetic hemoglobin is added to artificial meats. However, additives may not be food grade, and can pose a safety hazard [69,70]. The marketing of PM products focuses on the improvement of color and a number of other attributes [23,56,71]. Consumers prefer natural additives to chemical additives in meat substitutes [72].These problems account for the reluctance of consumers to accept meat substitutes. Consequently, market size growth has failed to meet the expectations of industry experts.

4.3. Artificial Meat Cost

Production cost is the most significant challenge to meat substitute technology [16]. The high cost of production is one of the main reasons why meat substitutes are slow to be commercialized [73,74]. Although the price of PM products is somewhat higher than that of traditional meat, the price is acceptable to vegetarians and animal welfare advocates, creating a niche market. However, CM products, for the time being, are very expensive. The first cultured meat took about three months to grow, and cost more than $330,000. Relevant experts and scholars believe that the production of CM products is still at a nascent stage [16,23]. The two examples of CM products listed above are more of an exception than a rule. Artificial meat has been suggested as a source of protein to replace animal protein sources.

Affordability is a prerequisite of novelty food product commercialization, and CM production costs result in prohibitively high product prices. Whether CM products are sold in a developing or developed country, they may be a new source of unfairness because they may be accessible only to the well-off. The meat substitute industry still needs to convince consumers of the value of the product in relation to its price, and make the public aware of the benefits the product offers (taste, safety, health), as well as the societal benefits it offers in terms of protection of the environment and food security [2,75].

5. Artificial Meat Ethics and Safety

5.1. Ethical Considerations

Ethical safety is one of the important factors affecting consumer acceptance [16]. Consumer perception of objects is an emotional response [73]. Whether the incidents of mistreatment of livestock can reduce consumer negative emotions in consuming meat has attracted much attention [76]. Public attention to ethical issues may affect consumer behavior [77] and affect consumption choice and willingness to purchase a product. Currently, public concerns about animal welfare force the meat industry to constantly evaluate its practices in view of such concerns in China [77]. Dilworth et al. (2015) [78] noted that academic studies regarding livestock production ethics generally support PM and CM production from the perspective of animal welfare and environmental safety. However, consumer concerns regarding the ethics of meat substitutes also involve the uncertainty of the attribution of meat substitutes [77].

Many consumers have a range of ethical concerns about meat substitutes. Pliner and Hobden (1992) [79] proposed that consumer acceptance of new food was affected by "new food technology phobia". The perception of ethical risks involving meat substitutes ought to be vigorously researched. Potential unknown risks are often attached to new foods and technologies [75,80]. Ethical factors also affect consumer acceptance of meat substitute products [81]. First, consumers have expressed doubts about whether manufactured meat substitutes can be eaten, which also includes consideration of the ownership of meat substitutes. Second, with the improvement of food technology, social development, and living standards, consumers have a new psychological standard for the cognition and requirements of meat substitutes [3].

Once cultured beef was publicly eaten in 2013 [82], the concept of CM was transformed into reality. The problem of "how to produce safer, healthier, and more efficient artificial meat" has been solved, and the focus of consumers has shifted to the discussion and evaluation of "whether or not to make artificial meat". Cruz Hernández et al. (2019) [83], examining plant-based protein, identified consumers health concerns, safety and nutritional characteristics as important factors. Van der Weele & Driessen (2013) [84] see the need to ponder the purpose, feasibility and practicability of the production of CM substitute. Is the purpose of meat substitute to ease world hunger, or to profit the industry? For developing economies, the former purpose is of primary concern, while consumer acceptance of the product blurring the boundaries of morality is ignored [16].

Consumers pay attention to the production mode and ingredients of meat substitutes. Fetal bovine serum (FBS) is one of the main supplements of CM products. Its acquisition method is considered by many to be inhumane, causing some consumers to reject meat substitute products. Mohorčich and Reese (2019) [85] believe that consumer response to CM products may involve concerns about nature and human character, similar to attitudes towards genetically modified foods. Some consumers believe that meat substitutes, especially CM products, are unnatural and may harm human health, and therefore oppose the development of substitutes [56,78,85,86].

The emergence of meat substitutes allows the public to avoid the ethical dilemma of slaughtering animals to provide meat. Meat substitutes address the competition between humans and animals and offers a more humane relationship with livestock animals [87]. To solve world hunger and environmental problems, potential safety hazards need to be rationally addressed through science [73]. The technology involved in the production of meat substitutes should not blur moral boundaries, and should meet ethical requirements.

Understanding information is the foundation of trust. Consumers generally decide whether to trust a product based on their understanding of the technical principles involved in the production process, information confirmed by the label, and the credibility of information sources [88]. Consumers tend to accept authoritative information sources, but tend to focus on the potential long-term negative health effects of CM products in the face of unknown risks [73]. Although the consumption rate of meat substitutes is still low, consumers are becoming increasingly aware of the link between meat consumption and personal, animal, and environmental health problems [89]. The number of respondents in UK who trust alternative protein sources has reached 53.8% [90]. The study of consumer attitudes towards CM products in Belgium, Portugal, and the UK [73] revealed that consumers would consider gaining direct personal benefits from purchasing meat substitutes, but they pay extra attention to the naturalness and wholesomeness of meat substitutes. Such questions regarding quality leads to fear of meat substitutes, and this continues to affect their perception of these products. The trust of consumers will determine the market success of meat substitutes [2,75,91]. A review of relevant studies from various countries can identify misunderstandings among consumers which diminish trust in meat substitutes [10,16,92]. Consumers in some countries have gradually changed their meat consumption patterns due to historical factors (e.g., meat safety crises) [75]. In other countries, the meat substitute industry needs to tackle the negative perceptions of consumers [75,93]. Consumers supported the study of meat substitutes, but the majority believed that most consumers would not buy such products [94]. The uncertain health effects, taste, and opaque production processes of meat substitutes affect, to a varying extent, consumer acceptance [72,95,96].

To address consumer distrust of meat substitutes, it is necessary to gather information which can lead to solutions. In the early stage of development, enterprises or R & D institutions should invite consumer participation to promote the understanding of technology [95] and the food development process [80]. At the same time, relevant government agencies should be responsible for disseminating pertinent scientific information about meat substitutes to improve consumer acceptance and understanding of the product. Consumers' misgivings regarding ethical hazards call for thoughtful consideration by practitioners, standardization officers, and regulators [97].

5.2. Nutrition and Health

Research on consumer preference for meat substitutes is needed [53]. Those concerned about food safety seek products offering safety, nutrition, and quality [75]. Mohorčich and Reese (2019) [85] argued that the concepts of "unnatural" and "unknown" should not be distorted when considering potential long-term consequences for producing meat substitutes. There are still some reservations about whether meat substitutes offer a high-quality protein comparable to meat. A recent study suggests that the safety of "artificial meat" and food safety hazards have not been determined [98]. Bohrer (2019) [29] and Curtain and Grafenauer (2019) [54] state that modern meat substitutes can provide almost the same nutrients as traditional meat products. It is especially important, prior to CM product sales, to conduct credible health and safety inspections and to implement quality control. Extraction techniques have been applied to improve the separation of individual protein components and eliminate dysfunctional phenolic compounds [11]. Consumers are concerned about the potential negative long-term effects of CM substitute on their health [99]. Inhibition of pathogenic and polluting bacteria can improve the safety of meat substitute production and extend the expiration date [100]. The US start-up Eat Just, in the application documents to Singapore to prove that its production of CM products is a stable manufacturing process, indicated that it had constructed more than 20 1200-L bioreactors. At the same time, the company also proved to the Singapore Food Authority that its products meet the existing poultry industry standards, and that the CM products have lower microbial content and are cleaner than traditional animal derived meat [101]. The low microbial content and elimination of the need for space, feed, waste disposal, and bird processing result in reduced risk of environmental pollution. They also conserve natural resources. The process is particularly attractive to an agricultural resource-constrained Singapore.

6. Hazards in Meat Substitute Manufacturing

6.1. Hazards in PM Manufacturing and Distribution

The stages of PM product manufacturing include planting (raw material acquisition), production, processing, and distribution.

The raw material contamination requires attention during raw material acquisition of the plant protein ingredient (Figure 1). For example, soybean and other plant-based raw materials during the fermentation process may be affected by inadequate control, causing protein damage, and could result in contamination of the fermented material [102,103].

In the production stage, attention must be paid to the proportion of ingredients, preservation of semi-finished products, and specification of ingredients. Incorrect ingredient distribution ratios may lead to differences in nutrient absorption between PM and ordinary meat [41,104]. Additionally, improper operation may lead to CM contamination during fermentation [105,106]. Also, the degree of protein deformation may exceed or be lower than the desired range. At the product distribution stage, there could be problems of package damage and product deterioration [103].

6.2. Source of Hazards in CM Manufacturing and Distribution

Figure 2 shows possible sources of hazards at different CM product manufacturing and distribution stages. In the cell breeding stage, the key is to qualify the cell source. During the seed cell transformation, the introduction of high-risk biological contaminants is possible, which would cause cell pollution and variation [102].

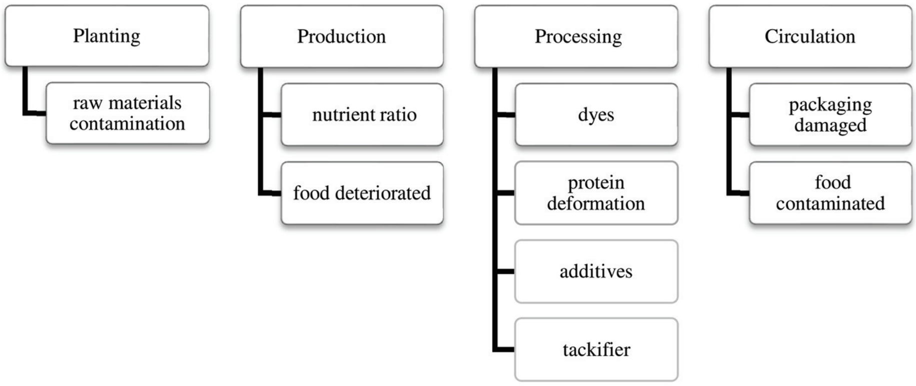

Figure 1. Sources of hazard in the manufacturing and distribution of PM products.

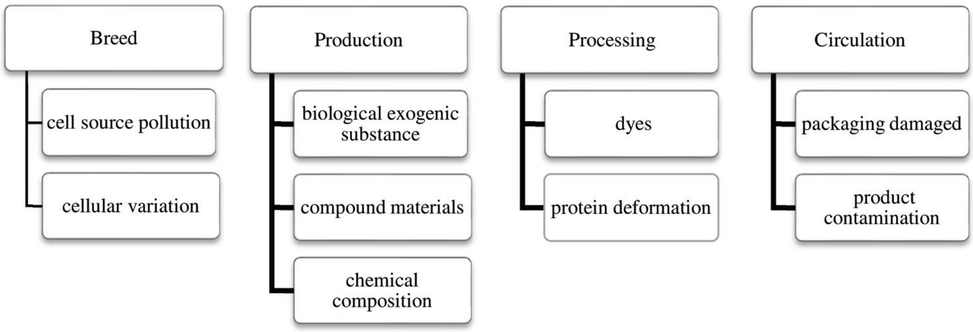

Figure 2. Hazards affecting quality and safety of CM products.

The production stage must focus on the ingredients and composition. There is uncertainty associated with the compound composition, scaffold material, and mold material [47,107]. There are also possible differences in nutrient absorption between CM and ordinary meat [69,70]. It is necessary to monitor the culture environment, because CM is easily affected by various microorganisms [108,109].

7. Regulation of the Artificial Meat Industry

To promote meat substitutes, examination of the status quo of the meat substitute industry under existing policies and endorsement of regulatory changes to local, national and international food systems are urgently needed. The meat substitute industry faces uncertainty, due in part to the regulatory system [110,111]. Policy and regulatory changes will affect the entry of meat substitutes into the market [16]. Feasibility, rationality, value, integrability and sustainability were proposed as criteria to improve the market acceptance of a product and can be applied in the case of the meat substitute [112]. According to the rules and regulations of good cell culture practice (GCCP), it is necessary to develop meat substitute production system [37].

Stephens et al. (2018) [16] believe that meat substitutes should be classified as food rather than a medical product, relaxing regulatory requirement needed for medical applications. In terms of obtaining source cells, muscle stem cells are essential for CM meat substitutes. To determine stem cell high proliferation ability, pluripotent cells (mesenchymal stem cells, etc.) have commonly been studied [113–115]. The use of certain cell sources, like the tissue culture of meat, could have crucial ethical implications and impacts on health, and needs to be controlled by new regulations.

7.1. Regulation Status

Meat substitute products have not been clearly classified. PM and CM technology differs from that used in production of traditional meat-like items, and their attribution and identification are needed. The standards of CM products differ in various countries and regions. Petetin (2014) [116] concluded that it was not possible to assess the regulations applicable to meat substitutes. To maintain regulatory power over production facilities, regulatory authorities need to classify meat substitute products. In Europe, meat substitute was classified as a new type of food in October 2018. In Australia and New Zealand, cultured meat can comply with existing food standards and specifications after obtaining approval before entering the market [117]. In China, the regulatory system of meat substitute is still in the early stage of exploration, and it is necessary to promote the scientific development of technology, standards, and supervision of CM substitutes. There could be a need to implement different regulatory approaches based whether the facility is categorized as an agricultural or food processing entity. In the United States, the FSIS and FDA proposed in March 2019 to jointly supervise manufacturing of meat substitute products originating from livestock and poultry cell lines, and divide the regulatory content [118].

From a public opinion and trade policy perspective, regulations are largely viewed as inadequate [77]. The assessment and management of CM products should be independent from PM product rules and include CM product manufacturing [16]. The development of a new type of food creates many problems in the supervision of meat substitute production, and imperfect supervision can be detrimental to industrial development.

7.2. Regulatory Framework

In order to deal with technical standards, standardization, manufacturing hazards, biological safety, and ethical issues, the regulatory system of the meat substitute industry should be constructed with reference to a common international framework. Although the composition and priority development areas of food control systems vary from country to country, most of them include a regulatory system, management system, scientific support system, an information education exchange, and a training system. According to Guidelines for Strengthening National Food Control Systems [119], the implementation framework of a supervisory system for the meat substitute industry should involve the construction of standards, a regulatory system, and a management system.

Standards improve consumer awareness and prevent businesses from using banned substances. Also, the guidelines for labeling meat substitute products are chaotic. It is necessary to ensure that the label content is consistent with the product [95,120]. A label allows consumers to distinguish new products from traditional meat products, and supports meat substitute public acceptance. Through multi-channel and multi-angle publicity, consumers can gain an understanding of meat substitutes, further improving product acceptance.

A regulatory system forms the basis of the food safety system and improves the mandatory laws and regulations related to food. The legislation of meat substitute product regulations should provide a high level of health assurance [119]. Moreover, guidelines will assure consistency and legal rigor, transparency and independent risk assessment, and help in risk management and risk communication. Guidelines should include preventive provisions, provisions on consumer rights and interests, and provisions on traceability and recall. Additionally, the guidelines should explicitly stipulate the responsibility of food producers and manufacturers for product quality and safety. Finally, the guidelines should stipulate the obligation to ensure that the meat substitute products are sold and distributed safely and fairly. The law should be recognized by governments and through international obligations, especially trade-related, ensuring transparency and uninterrupted access to new information.

Different countries have different regulatory methods for meat substitutes, but the development of the meat substitute industry is complex, and a “main authority” mode should be advocated in which departments with expertise in this field should supervise all other departments [16]. In terms of legal and regulatory system construction, the EU provides framework provisions for member states, but the new food regulations need to be improved. The legal construction in the United States is more detailed. In general, there are two ways for food management agencies in Europe and the United States to deal with emerging food products. One is to compare the new products with the existing products that have been tested and adopt the already existing safety management regulations; the other is for a new food to be classified as such, in which case new regulations should be formulated.

The cell sources, culture methods, labeling, quality management, and hygiene of CM products have stimulated the establishment of appropriate regulations and a regulatory framework [118]. To address management issues, the U.S. Department of Public Health, together with the Food and Drug Administration (HHS-FDA) and the USDA Food Safety Inspection Service (USDA-FSIS) announced on 7 March 2019 that they would jointly supervise the production of meat substitute from livestock and poultry cell lines. Among them, FDA supervises cell collection, the cell bank, and cell differentiation and growth, while FSIS is responsible for the follow-up supervision of cell collection [118].

8. Conclusions

Since the 1990s, the world's meat consumption has increased rapidly, providing an opportunity for the development of the meat substitute industry. In recent years, artificial food and insect food have developed rapidly in the world food market, while in vitro meat production technology has improved continuously. Technology improvement, cost reduction, regulations, safety, and consumer acceptance are the main factors affecting the development of the meat substitute industry. However, consumer concerns pose the most important long-term challenge to the meat substitute industry.

According to the OECD-FAO forecast, world meat consumption will continue to grow in the future. The supply gap of meat products for China, for example, may exceed 38 million tons in 2030. If the penetration rate of meat substitutes reaches 5%, the value of the meat substitute market will reach $100 billion. The COVID-19 epidemic, among other factors, resulted in a pork shortage. The discrepancy between protein demand and meat supply could lead to a rapid growth of the "meat substitute" market. With consumer acceptance increasing and resistance to meat substitute marketization weakening, an opening for meat substitutes is being created.

Currently, there is room for meat substitute technology improvement. First, there is a need to efficiently simulate animal muscle tissue growth and scale up production in bioreactors. Secondly, the taste of meat substitute products still does not match that of traditional animal meat. If the meat substitute taste does not resemble that of real meat, the meat substitute can only be considered a novelty and possibly assure food security, but cannot replace real meat. Third, the technology of in vitro meat production (culture of myoblasts and fibroblasts) has yet to be applied on a large scale.

Experts across the world are committed to providing breakthrough solutions to improve the environmental effects, taste, commercialization and consumer acceptance of meat substitutes. European and American investors allocated substantial resources to develop efficient and safe cell culture technology. The development of the meat substitute industry in Europe and the United States shows that demand preferences in the early period of meat substitute development have changed greatly. Demand drivers stimulate the research and industrialization of meat substitutes, gradually overcoming the technical and technological problems.

The ethical and social problems arising from the production and consumption of meat substitutes are both novel and complex. The attributes, ethical and moral problems, psychological acceptance, and aversion of consumers of meat substitute products need to be explored and resolved. In the short term, it is unrealistic to expect to eliminate consumer concerns about meat substitutes, or to resolve the debate over the morality of the development and application of meat substitute technology. Over time, stakeholders can find the most appropriate way to deal with the science and technology of meat substitutes. An effective regulatory system to manage safety risks of the meat substitute industry is needed. The global climate, lack of environmental protections, and continuous population growth multiply safety risks associated with livestock and meat production. The development of "alternative meat" has become a global trend. A meat substitute may eliminate meat supply shortages, making it worthwhile to develop the technology necessary to establish a sustainable meat alternative. The development of a sustainable meat alternative depends on risk prevention and control, standards, laws and regulations. Dealing with the regulatory issues in a forward-looking manner, the meat substitute industry can contribute to better lives, ensuring safety, while also protecting the environment.

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foods

Systematic Review

Exploration of Food Security Challenges towards More Sustainable Food Production: A Systematic Literature Review of the Major Drivers and Policies

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Abstract: Food security is a central priority for international policy as one of the world's most significantly urgent targets to achieve. It is considered one of the most pressing issues in many countries, the degree of food security representing the level of self-sufficiency and well-being of citizens. In particular, in the current COVID-19 pandemic era, it has more than ever become a mission-critical goal. In this research, we report on the food security drivers and the current state of recommended policies addressing chronic food insecurity aimed at ensuring the sustainability of future food production. Mapping the determinants of food security contributes to a better understanding of the issue and aids in the development of appropriate food security policies and strategies to enhance the sustainability of food production in all facets; namely environmental, social, and economic. Adopting the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) data screening and selection guidelines and standards, we carried out a comprehensive, reliable, systematic, and rigorous review of research from the last ten years in order to identify the most frequently mentioned drivers and policies of food security in the literature available in two databases: Scopus and Web of Science (WOS). The number of extracted articles was 141 papers in total. An analysis revealed 34 drivers of food security and 17 most recommended policies for the mitigation of food insecurity. The existence of food loss and waste (FLW) policies was the primary driver of food security, followed by food security policies (FSP) in their different forms. However, FSP were the most recommended policies, followed by FLW policies. The identified food security drivers and recommended policies should be used by policy-makers to improve food security, thus contributing to sustainable food production. Our research findings, reflected in the latest version of the Global Food Security Index (GFSI), resulted in more tangible policy implications, suggesting the addition of two dimensions regarding food security. We also identified elements not listed under the GFSI that could be considered in its future revision, including environmental policies/indicators, consumer representation, and traceability throughout the entire supply chain. Overall, it can be concluded that food security is a complicated and multi-faceted issue that cannot be restricted to a single variable, necessitating the deeper integration of various multi-disciplinary interventions.

Keywords: sustainable food supply chains; agri-food sector; policy recommendation; sustainability; food security

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1. Introduction

Food security (FS) is "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" [1] p.3. It is a significant priority for international policy [2], and has been perceived as being among the key challenges worldwide [3] as it represents a country's degree of self-sufficiency and the well-being of its citizens [4]. Securing a nation's self-sufficiency has become a top priority in the context of the current COVID-19 global epidemic era, even more so than earlier [5]. Economic expansion, rising incomes, urbanization, and growing population are driving up the demand for food, as people adopt more diverse and resource-intensive dietary habits [2,6]. The world's current population is steadily increasing, placing significant pressure on the available natural resources to feed the growing population [7–9]; however, this dramatic growth in the global population is anticipated mainly in developing countries, which already suffer from devastating hunger and food insecurity [7]. One of the biggest obstacles to ensuring global food security is the need to roughly double food production within the coming few decades, particularly in the context of the developing world's rapidly increasing demand [10,11]. The natural resources such as land, water, energy, and other resources used in food production are all subject to increasing competition [12,13]. Climate change poses difficulties for agricultural production [14], mainly in developing nations, while some existing farming practices harm the environment and contribute significantly to greenhouse gas emissions (GHG) [15,16]. There is a real danger that less developed countries may be forced to reverse direction. The FAO's statistics on world hunger in 2009 showed a dramatic rise to 1.023 billion people, demonstrating precisely such a situation. When commodity prices fell the following year, this number dropped to 925 million, which was still more prominent than in 2007 (i.e., before the price spike) [17]. According to recent data published by the Global Hunger Index, the number of malnourished people grew from 785 million in 2015 to 822 million in 2018. Moreover, 43 out of 117 countries reported extreme hunger [18]. Approximately 20% of developing countries lack the resources and physical access necessary to provide their citizens with the most basic food. Children in developing countries face vitamin and nutritional deficiencies and being underweight, which puts them at risk for various sicknesses due to food insecurity [12]. National and global imbalances brought on by food insecurity are expected to worsen human suffering and make it harder for people to survive [12]. Despite the efforts of multiple global organizations such as the FAO and the UN, the problem of food insecurity is worsening [19], which means that more effective and sustainable solutions must be provided to ensure the alleviation of food insecurity and the sustainability of food production. Hence, policy-makers must understand that in a world that is becoming more globalized, food insecurity in one region could have significant political, economic, and environmental impacts elsewhere [2].

Throughout the twentieth century, policy-makers used the concept of food security as a key notion in formulating food-related policies [17]. Lang and Barling [17] have proposed two main schools of thought on food security: the first focused on increased production as the primary solution to under-consumption and hunger, while the second is a newer one that is more socially and environmentally conscious and accepts the need to address a wide range of issues, not just production. The former is primarily concerned with agriculture, while the latter is concerned with food systems. One approach to solve the food security challenge is to intensify agricultural production in ways that impose much less environmental stress and do not jeopardize our long-term ability to continue producing food [2]. The above sustainable intensification strategy comprises a policy agenda for several governments worldwide, but has also drawn criticism for being overly production-focused or incoherent [2]. The central mission of the twenty-first century is to establish a sustainable food system, which calls for a more concrete policy framework than that which is currently in place [17]. This mission has been disrupted by competing solutions for policy focus and policies that have, so far, failed to incorporate the complex array of evidence from social, environmental, and economic components into such an integrated and comprehensive policy response [17]. Millions of people are being pushed into a cycle of food insecurity and poverty due to climate change; however, we can combat both food insecurity and climate change by implementing climate-friendly agricultural production methods [12]. Tsolakis and Srai [20] have stated that any comprehensive food security policy should entail multi-dimensional policies considering aspects such as resilience, trade, self-sufficiency, food waste, and sustainability. As it is traditionally understood, food security concerns individuals, while ecological and environmental concepts operate locally and at supra-national, regional, and international levels [1]. According to Guiné, Pato [21], the four pillars of food security—availability, access, utilization, and stability—should be reconsidered to include additional factors such as climate change. Clapp, Moseley [22] has also stressed that it is time to officially update the existing food security definition to involve two further dimensions—sustainability and agency—containing broader dynamics that have an impact on hunger and malnutrition [23]. Sustainability relates to the long-term ability of food systems to ensure food and nutrition security in a way that does not jeopardize the economic, social, and environmental foundations that generate food and nutrition security for upcoming generations [22,23]. Agency represents the ability of people or groups to decide what they consume, what they produce, and how they produce, process, and distribute their food within food systems, as well as their capacity to participate in processes that shape the food system's policies and governance [22,23]. Instead of dismissing food security as being insufficient, Clapp, Moseley [22] has contended that the inclusion of two extra dimensions—agency and sustainability—into food security policy and assessment frameworks will help to guarantee that every human has access to food, not just now but also in the future. Sustainability can be viewed as a pre-requisite for long-term food security [1]. Environmental aspects—particularly climate and the availability of natural resources—are pre-requisite for food availability and biodiversity protection [24]. The availability of food for everybody depends on economic and social sustainability. Food utilization, too, is influenced by social sustainability. The three components of sustainability—social, economic, and environmental—ensure the continuity of the three food security dimensions and the food system stability on which they rely. As confirmation of the vital relationship between food security and sustainability, "The International Food Policy Research Institute" has launched a 2020 Vision of Food Security to achieve food security, stating that "a world where every person has economic and physical access to sufficient food to sustain a healthy and productive life, where malnutrition is absent, and where food originates from efficient, effective, and low-cost food and agricultural systems that are compatible with sustainable use and management of natural resources" [12] (p357). Many policies, priorities, technologies, and long-term solutions must be developed and implemented worldwide to achieve the 2020 food security vision [10–12]. However, there is a scarcity of systematic studies analyzing the food security drivers and the recommended policies to improve food security.

Following a review of the academic literature, we discovered a scarcity of research that systemically summarizes the major drivers of food security, outlines the recommended policies to improve food security, ensures the sustainability of future food production, and provides policy recommendations to enhance food security based on a country's context. In response to this gap in the literature, we carried out a comprehensive, reliable, systematic, and rigorous review of previous research from the last ten years in order to identify the most frequently mentioned drivers/policies in the scanned literature. The rationale behind this study is to identify and list food security drivers and the current state of recommended policies that address chronic food insecurity to ensure the sustainability of future food production, utilizing a systematic literature review (SLR) methodology. Moreover, we hope to identify drivers/policies in order to aid policy-makers in selecting the most appropriate policies based on each nation's context (e.g., agricultural production, natural resource availability, climate, political stability, and so on). Most importantly, policy-makers can use the identified drivers of food security and the recommended policies in the literature to customize appropriate policies that ensure the sustainability of future food production and, hence, ensure food sustainability for future generations. Based on the evidence reported in the literature, the identified food security drivers and recommended policies will aid the policy- and decision-makers of various countries in sustainably improving the food security situation. The need to identify the main drivers of food security arises from the notable increase in households and individuals suffering from food shortages and insecurity globally [25]. Finally, the findings of this research will be used to inform the

GFSI developers in order to include more comprehensive indicators expected to contribute to the sustainability of future food production.

2. Materials and Methods

This research aims to report on food security drivers and the current state of recommended policies that address chronic food insecurity in order to ensure the sustainability of future food production through the use of a systematic literature review (SLR) methodology. We highlight existing food security drivers and outline recommended policies to alleviate food insecurity following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) data screening and selection guidelines [26]. The extraction process was meticulously documented in order to ensure the transparency and replicability of this systematic literature review [27]. A panel of researchers was formed, following the systematic review guidelines [26], to define the research field and questions, select keywords and the intended databases, and develop the sets of inclusion and exclusion criteria.

The research began by formulating the research questions to guide this systematic review based on identified gaps in the literature, guiding us in an attempt to answer the following research questions:

Q1. What are the main drivers of food security?
Q2. What are the main recommended policies to alleviate food insecurity?

By answering these questions, this paper provides a reference that policy-makers and practitioners can use to identify the main drivers of food security and the recommended policies in the literature in order to customize and choose appropriate policies that ensure the sustainability of future food production. The identified food security drivers and recommended policies are expected to aid policy- and decision-makers in improving the state of FS. This study also provides a roadmap for future research based on the evidence reported in the literature.

A specific research criterion was used to ensure that the research sources selected were sufficient and comprehensive enough to capture all of the significant and salient points to adequately answer the research questions [26]. To this end, we provide a critical review of the existing literature that has been published in two databases—Scopus and Web of Science (WOS)—between 2010 and 15 March 2021, to answer the abovementioned research questions. The time limit was set to cover the period following the global financial crisis of 2008/2009 and its effect on rising food prices, increased unemployment rates, and increasing food insecurity worldwide [28–30]. This period allows for consideration of policies designed to ensure global food security following the food shortage crisis. The use of Scopus and Web of Science (WOS) databases helped us to include most potential published works in a broad scope of journals, thereby limiting the risks of bias and possible exclusions associated with the use of fewer journals.

We employed a set of identified keywords, which are summarized in detail in Table 1. A critical analysis was conducted regarding the most relevant concepts that are available in the literature and which affect each of the four dimensions of FS: Food availability, food access, food utilization, and food stability. For instance, the research string "Agrifood supply chain" OR "Agri food supply chain" OR "Agri-food supply chain" was added as a secondary search string, because food availability is highly dependent on the food supply chain and how well its activities are managed. The food supply chain is exposed to many factors that can negatively impact the country's food security level, such as severe weather conditions [31,32]. Therefore, it is critical to consider some characteristics of the food supply chain, such as biophysical and organoleptic features, shelf life, transport conditions, production time, and storage, to efficiently and effectively manage it [33]. Effective supply chain management is seen as a significant contributor to gaining and enhancing industrial competitive advantage and efficiency at the company level, possibly impacting food security positively [34]. "MENA Region" OR "Middle East and North Africa" OR "Middle East" OR "North Africa" research string was added due to the severity of food insecurity there and to ensure the inclusion of papers that address the problem in these countries and propose strategies to overcome food insecurity. According to the GFSI data [25], MENA region countries are experiencing a decline in food security; moreover, the number of households and individuals suffering from food shortages and insecurity is dramatically increasing.

Table 1. Primary and secondary search strings used in this research.

Keywords	Primary or Secondary
(“Food security” OR “Food insecurity” OR “Food Availability” OR “Food affordability” OR “Food Access” OR “Food Utilization” OR “Food Stability”)	Primary search string
“Agrifood supply chain” OR “Agri food supply chain” OR “Agri-food supply chain”	Secondary search string
“MENA Region” OR “Middle East and North Africa” OR “Middle East” OR “North Africa”	Secondary search string
“Sustainable supply chain” OR “Resilient supply chain”	Secondary search string
“Food Safety” OR “Food diversity” OR “food quality” OR “Food standards” OR “Micronutrient availability”	Secondary search string
“Agricultural infrastructure” OR “Agricultural production volatility” OR “Vulnerability assessment”	Secondary search string
“Food loss” OR “Food waste”	Secondary search string
“Policy description” OR “Policy assessment” OR “Policy recommendation” OR “Policy making”	Secondary search string

The research string “Sustainable supply chain” OR “Resilient supply chain” was added due to much research that stressed the impact of designing a proper supply chain structure due to its significant impact on the future improvement of its performance [33]. The central mission of the twenty-first century is to establish a sustainable food system, which calls for a more concrete policy framework than what is currently in place [17]. Sustainability can be viewed as a prerequisite for long-term food security [1]. The environment, particularly climate and the availability of natural resources, is a prerequisite for food availability and biodiversity protection [24]. The availability of food for everybody depends on economic and social sustainability. Food utilization, too, is influenced by social sustainability. The three components of sustainability—social, economic, and environmental—assure the continuity of the three food security dimensions and the food system stability on which they rely. Moreover, food security is increasingly considered a prerequisite for long-term sustainability [1]. Adopting a “sustainable production and consumption approach throughout the global food supply chain” is a solution that will help reduce the amount of food waste along the food supply chain [35,36]. Cooper and Ellram [37] argued that building a resilient supply chain has many advantages such as decreasing inventory time, which will lead to cost and time savings, increasing the availability of goods, reducing the order cycle time, improving customer service and satisfaction, and gaining a competitive advantage. Stone and Rahimifard [38] stressed the importance of having a resilient agricultural food supply chain to achieve food security due to the incremental increase in volatility across the supply chain.

The research string “Food Safety” OR “Food diversity” OR “Food quality” OR “Food standards” OR “Micronutrient availability” was added due to one of the food security dimensions: utilization, which is concerned with all aspects of food safety, and nutrition quality [39]. According to FAO (2019), the utilization dimension should assess food diversity, food safety, food standards, and micronutrient availability. It is inadequate to provide enough food to someone unable to benefit from it because they are constantly sick due to a lack of sanitary conditions. It indicates that in the country, individuals are taking advantage of the food they receive or have access to, with extra emphasis on the dietary quality that contains nutritious ingredients such as vitamins (vitamin-A) and minerals (Iron, Zinc, Iodine) [40]. According to the World Health Organization, people diagnosed with malnutrition usually suffer from micronutrient deficiencies, protein deficiency, obesity, or undernutrition. The lack of micro-ingredients can increase the risk of developing severe chronic and infectious diseases for people in general and children in particular (toddlers 9–24 months). These diseases have an irreversible negative impact on people's health, which enhances the persistence of poverty and food insecurity. It is critical to invest in the health and nutrition elements on a global scale by ensuring safe drinking water, immunization, enhancing sewage discharge, improving public health services, and reducing poverty levels [41].

The research string "Agricultural infrastructure" OR "Agricultural production volatility" OR "Vulnerability assessment" was chosen because much research has emphasized the importance of investing in a strong agricultural infrastructure to improve food security levels, especially in light of current challenges such as climate change, increased urbanization, water scarcity, and the shift away from using cropland for non-agricultural activities [7,8,41]. Food security is vulnerable to severe weather conditions, whereas harsh weather conditions may adversely impact the food supply chain in weak areas [31,32]. Therefore, it is critical to assess the vulnerability level of each country to protect the food supply chain. The use of the "Food loss" OR "Food waste" OR "Food waste and loss" research string was due to the general agreement among researchers on the importance of reducing food waste to improve food security [35,42,43]. According to the Food and Agriculture Organization (2013), around one-third of the food produced globally (1.3 billion tons) is wasted or lost. Most wasted food is either fresh and perishable or leftovers from eating and cooking [36,42]. Basher, Raboy [43] argued that eliminating just one-fourth of the food waste would be enough to feed all the currently undernourished people. One of the Sustainable Development Goals established by the United Nations, "SDG 12.3 Food Waste Index" stresses that decreasing the amount of food loss and waste will help reduce hunger levels, promote sustainable production and consumption, and enhance food security [44].

The use of "Policy description" OR "Policy assessment" OR "Policy recommendation" OR "Policymaking" OR "Policy-making" OR "Policy making" research string was due to the impact of adequate and proper policy formulation on food security (Table 1). Establishing effective and efficient food policies that ensure that each individual has an optimal level of food security is critical in every country because it directly enhances the country's competitive advantage and efficiency [34,45]. Timmer [46] emphasized that designing the proper set of policies to end hunger based on each country's context is challenging and requires collaborative participation from multiple stakeholders. Murti Mulyo Aji [34] stressed the role of the government's policies in developing a collaborative supply chain that creates value throughout the supply chain by improving information, logistics, and relationship management. Effective and efficient supply chain management significantly impacts managing long-term partnerships and corporations among a wide range of firms that vary in size and sectors (public or private). This collaboration will enhance prediction of changes in customer demands in domestic and international markets. If previous policies were insufficient to ensure that country's true competitive advantage, it could cause market distortion [34,47]. Countries are encouraged to gradually reduce the adoption of inequitable trade policies to focus on enhancing their true competitive advantage, demonstrating fair competition, and increasing economic efficiency, particularly in the spirit of trade liberalization [34].

The selection of research sources was accomplished in March 2021, and the search for keywords was enabled for titles, abstracts, and full texts in both electronic search engines (i.e., Scopus and WOS). Several keywords were identified to retrieve the available literature, and search strings consisted of primary and secondary keywords. The primary search string used was as follows: "food security" OR "food insecurity" OR "food availability" OR "food affordability" OR "food access" OR "food utilization" OR "food stability". The reason behind including these multiple strings was to cover the maximum number of articles that handle the topic of food security or any of its four dimensions.

Specific exclusion and inclusion criteria were applied in order to develop high-quality evidence [26]. A reasonable number of articles were limited for deep analysis by following the specific exclusion and inclusion criteria to control the quality of the review in the food security field, as detailed in Table 2 above. Only peer-reviewed journal articles were included within the time frame (2010–15 March 2021) and only those written in English. Furthermore, due to this study's nature and to ensure consistency with the topic area, the most common and effective approach for examining drivers and recommended policies were limited to the business, management, accounting, and agricultural fields [48]. We have used the "business, management and accounting" research field in the Scopus database to ensure that all the included articles were business-related. Then, we restricted the research field to" Economics, business, and agriculture Economics" in the WoS database to ensure the inclusion of agriculture-related papers and maximize the inclusion of a diverse range of articles. Another round of retrieval was applied using a set of secondary keywords in order to narrow down the search to specific areas of food security. For this purpose, the primary keywords were escorted each time with "AND" and other secondary keywords, as listed in Table 2.

Table 2. Inclusion and exclusion criteria.

Criterion	Inclusion	Exclusion
Study type	Only peer-reviewed journals, both empirical and theoretical/conceptual studies AND industry reports.	Any non-peer-reviewed journals, conference articles, magazines, news.
Language	English written sources.	Any other language.
Research field	Limit to business, management, accounting, and agriculture.	Exclude other fields.
Date	Until 15 March 2021.	Before 2010.
Relevance	Include relevant studies related to food security and food technology domains.	Exclude irrelevant studies.

The initial search using the primary keywords ("food security" OR "food insecurity" OR "food availability" OR "food affordability" OR "food access" OR "food utilization" OR "food stability") revealed a total of 113,709 documents (Scopus, n = 63,860; WOS, n = 49,849). Strict selection criteria were applied to the first search pool in order to maintain transparency and guarantee the selection of relevant material that answers the research questions. To ensure academic rigor, the search was restricted to including only peer-reviewed publications [49] (Scopus, n = 47,673; WOS, n = 40,305). The research was then restricted by publication date to between 2010 and 15 March 2021 (Scopus, n = 34,789; WOS, n = 31,278). Only journal articles published in English were selected (Scopus, n = 33,292; WOS, n = 30,313). Then, advanced research was conducted by combining the primary keywords with one of the secondary keywords. The results and the number of articles identified in each search step are detailed in Figure 1. After removing duplicate articles from each database, a total of 281 journal articles (Scopus, n = 140; WOS, n = 141) were revealed. After combining both databases, 248 journal articles were obtained. These collected 248 journal articles were scanned by reading their abstracts in order to check their applicability to answering the research questions. At this point, 107 articles were excluded as they were considered irrelevant and outside the scope of the research. Finally, the total number of extracted articles was 141, as can be seen in Figure 1. Data extraction and analysis were performed by a single reviewer (SW), and all extracted data and revealed results were double-checked by three researchers (FA, IM, and BS) to enhance the research and reduce bias in study selection. A complete description of the validity threats (Construct, Internal, External, and Conclusion Validity) following the validation process of Zhou, Jin [50] is provided in detail in Table 3.

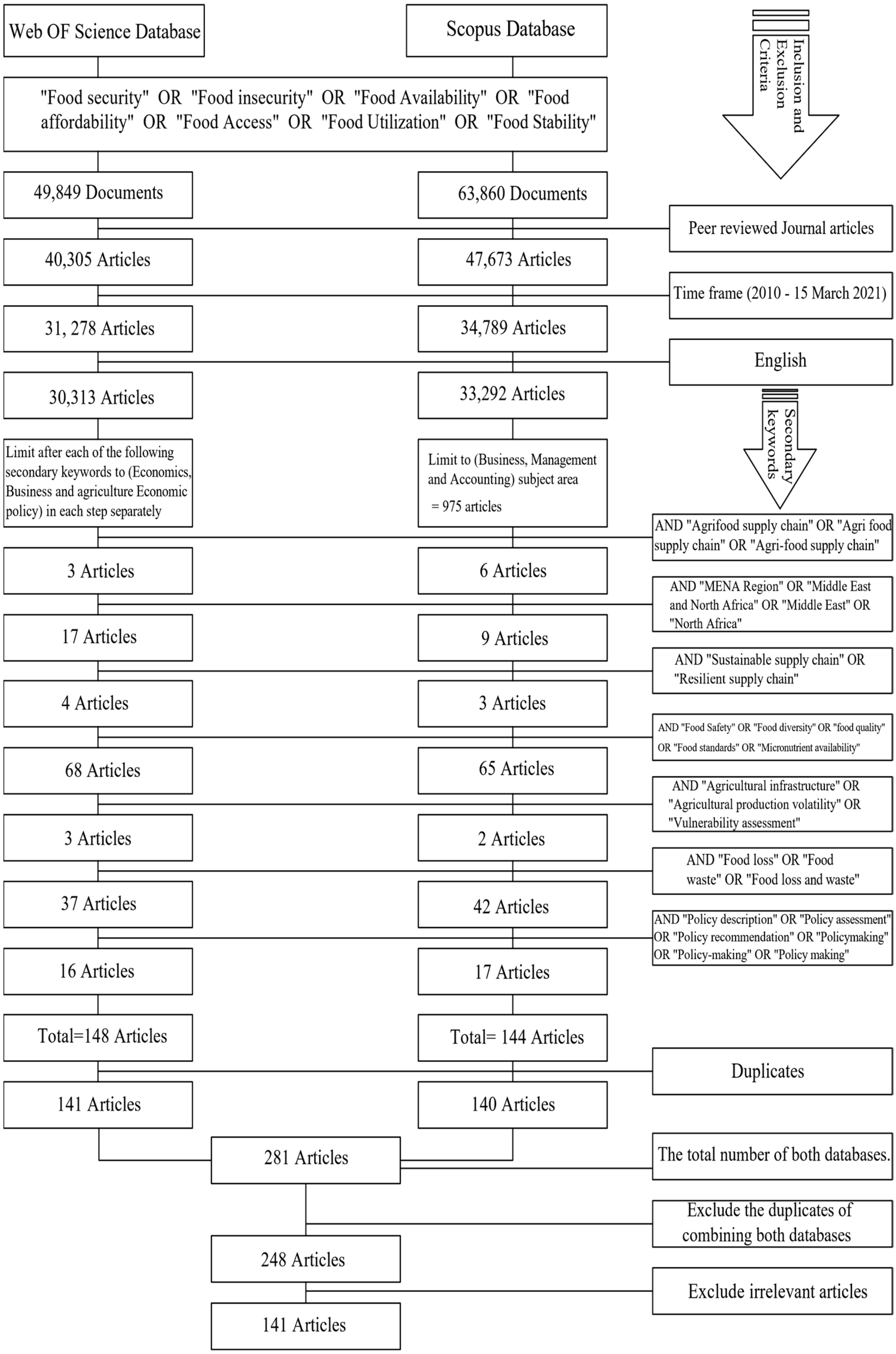

Figure 1. Research protocol following the PRISMA guidelines.

Table 3. A reporting of validity threats in this systematic literature review.

The Validity	Taken Precaution
Construct Validity	• The SLR setting was specified, and sufficient information was given. • We ensured that appropriate and complete search terms were used in the automatic search. • Two databases were used to extract articles answering the research questions. • The correctness of the search method was checked by multiple authors. • A thorough search strategy was used in conjunction with a multi-step selection process to ensure that the inclusion and exclusion criteria were appropriate. • To ensure appropriate research question formulation, the researchers (experts in the research area) held several internal discussion meetings.
Internal Validity	• The SLR setting was specified, and sufficient information was given. • We ensured that appropriate and complete search terms were used in the automatic search. • The correctness of the search method was checked by multiple authors. • We used two databases to extract articles and a set of modified search keywords to ensure the appropriate sample size of the retrieved articles. • The articles retrieved from the two databases were checked twice to identify and eliminate duplicates. • Data extraction and analysis were performed by a single reviewer (SW). All extracted data and revealed results were double-checked by three researchers (FA, IM, and BS) to enhance the research and reduce the bias in study selection and extraction, as well as reducing subjective interpretation. • The researchers came from three different cultural backgrounds, which helped to minimize the cultural bias.
External Validity	• Precautions were taken into consideration to enhance the reliability and validity of the research; however, the research findings still need to be validated by replicating this research using different data sets and validating the result through three rounds of Delphi research. Such validation will boost the study's generalizability. • The researchers contacted some authors to obtain articles that were not accessible online. • The systematic literature review provides objective, accurate, and in-depth information, presented in the analysis section.
Conclusion Validity	• The articles retrieved from the two databases were checked twice in order to identify and eliminate duplicates. • Data extraction and analysis were performed by a single reviewer (SW). All extracted data and revealed results were double-checked by three researchers (FA, IM, and BS) to enhance the research, reduce the bias in study selection and extraction, and reduce subjective interpretation.

Among the selected 141 articles, 28 (19.86%) were published in the *Journal of Cleaner Production*, 20 (14.18%) were published in *Food Policy*, and 5 (3.55%) were published in *Quality-Access to Success*. The rest of the journal names are visualized in Figure 2.

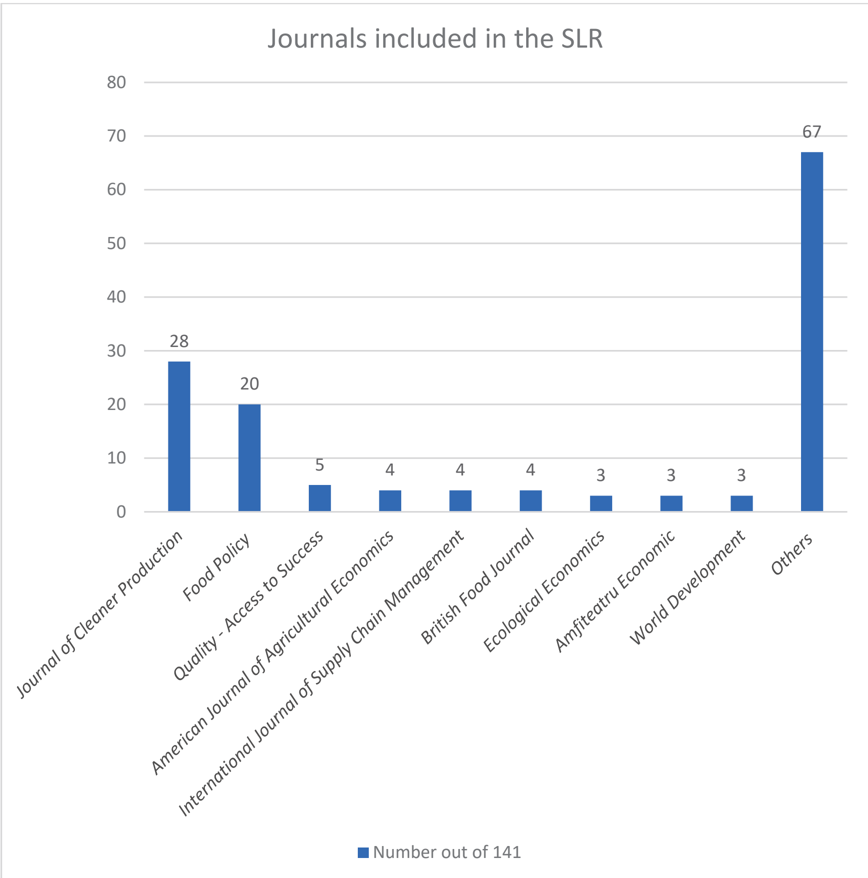

Figure 2. The most popular journals publishing the 141 included articles. Others denotes journals that were cited once or twice.

3. Results

After the 141 articles have been extracted, they were analyzed and summarized individually by listing all the discussed food security drivers, as well as the recommended policies for the improvement of food security and sustainable food production. Then, we synthesized the extracted information from all sources in order to identify the gaps, list the similarities between all the resources, and extract significant insights regarding the main drivers of food security and the recommended policies [26].

3.1. The Major Drivers of Food Security

Analysis of the retrieved literature revealed 34 different drivers of food security, as visualized in Figure 3. Detailed information, along with a full citation list for all the drivers, is provided in Appendix A.

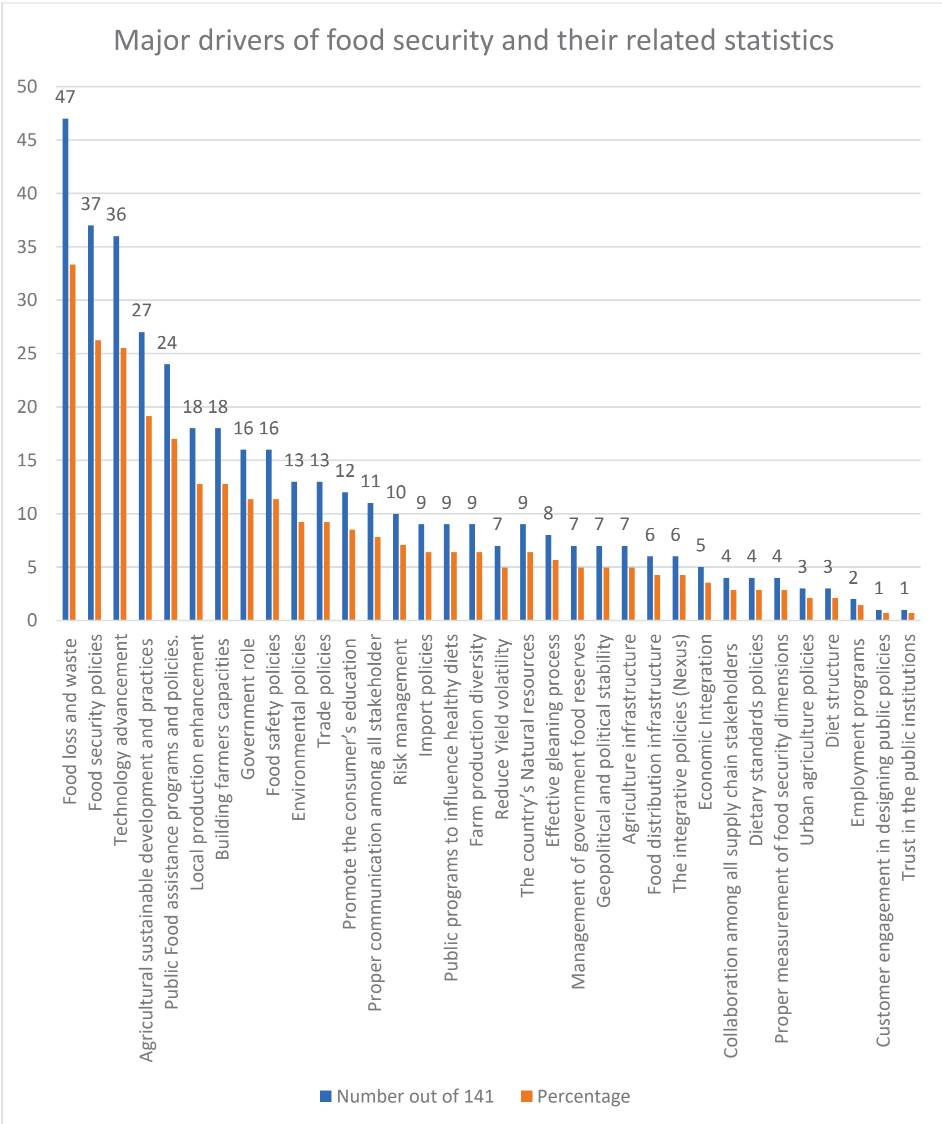

Figure 3. Summary of the major drivers of food security.

Most papers discussed food loss and waste (FLW) and emphasized its impact on food security [6,19,51–95]. Around one-third of the food produced globally (1.3 million tons) is wasted or lost [96]. Basher, Raboy [43] has argued that, if we could save just one-fourth of the wasted food, it would be enough to feed all the world's undernourished people, contributing positively to FS. The previous finding supports our research findings that FLW is the primary driver of FS. To reduce FLW, Halloran, Clement [6] has argued that effective communication, more efficient food packaging, and a better consumer understanding of food packaging could lead to solutions. To decrease food loss, Garcia-Herrero, Hoehn [62] has suggested improving food labelling, enhancing consumer planning, and developing technological advances in packaging and shelf life for perishable products. Morone, Falcone [83] has suggested the repetition of large-scale research to help define a set of policies encouraging the transition to a new model for consumption that promotes sustainably procured food and dramatically reduces the amount of waste (more details are provided in Section 3.2).

Additionally, several authors have considered food security policy (FSP) as a driver of food security in its different forms [56,63,65,69,70,74,79,85,94,97–124]. The primary goal of establishing food security policies that consider the factors influencing individuals and groups is to reduce poverty and eliminate hunger. One example is safety-net programs or public food assistance programs (FAPs). The main goal of providing safety-net programs is to increase food consumption among poor people and improve food security [102].

Many papers have discussed the importance of technological advancement as an enabler of food security [56–58,63,69,71,74,77,85,90,94,95,109,116,119–121,123–141]. The use of technology to promote behavioral changes has increasingly become a vital instrument to reduce food waste and indirectly improve food security [130]. Mobile applications offer households helpful guidance on increasing shelf life and experimenting with dishes using leftovers [58]. Shukla, Singh [130] has elaborated that, at present, farmers have access to mobile applications that provide them with reasonably and timely priced information.

Some authors have discussed sustainable agricultural development and practices as enablers of food security [56,57,59,64,71,73,94,97,105,109,111,119–121,124,130,132,134,136,137,139,142–147]. Some authors have discussed local production enhancement as a driver of food security to enhance the self-reliance of countries [57,69,85,87,89,94,98,103,105,109,112,117,120,134,137,144,148,149]. For example, Ahmed, Begum [98] has emphasized how, following the GCC ban, Qatar took several successful steps to foster local production, support domestic businesses, and promote the consumption of locally produced food by its citizens. Some authors have argued that building the capacities of small farmers is essential to achieving FS. Education policies are critical for educating farmers, building their capacities, and increasing their human capital; moreover, educational programs should also include food preparation and health education programs in order to ensure the safety of consumed food [101].

The government's role in managing a country's agriculture can also be seen as a driver of food security [67,75,84,86,100,109,116,117,119,121,137,138,147,150–152], as it is responsible for various aspects such as designing, testing, and implementing the right policies to ensure the welfare of its citizens, while providing the necessary assistance to small-scale farmers and ensuring their safety and security in all aspects of life. Governments in developing nations must focus on R&D, agriculture infrastructure (e.g., technologies for irrigation and soil preservation), expansion services, early warning systems, or subsidized farm income in order to alter the production function of the population [101].

Many authors have discussed the importance of food safety policies as an enabler of food security [61,64,69,103,105,111,112,129,149,153–159]. Food safety policies include food and water safety at several points throughout the supply chain where food-borne diseases might develop [69]. Environmental policies are also seen as a fundamental enabler of food security [59,73,121,124,130,135,139,147,159–163]. Regardless of the various approaches discussed by the authors, they all agreed that environmental protection would help to ensure food availability for current and future generations. According to some authors, trade policies [69,94,95,103,111,112,114,123,129,141,146,161,164] and import policies [69,95,100,103,120,124,126,129,146] are enablers of food security. Regulating international trade can help to ensure food security. Lowering trade barriers, for example, has been proposed as a way to mitigate the adverse effects of market regulation caused by climate change [141].

Many authors have recognized policies that promote consumer education on sustainable consumption and increase consumer awareness and knowledge of the environmental impact of their purchases as a driver of food security [52,60,67,69,86,133,144,151,163,165–167].

Others have stressed proper communication among all stakeholders as a driver of food security [6,56,68,69,84,92,129,130,156,157,168]. Some authors have considered risk management as an enabler of food security [94,117,118,137–139,145,154,155,157]. For example, the aims of building a disaster risk reduction framework in the Pacific include boosting resilience, protecting investments (e.g., in infrastructure, operations, and FS), and decreasing poverty and hunger [169].

Some authors have proposed the effective gleaning process as a driver of food security [70,72,74,80,84,92,142,170]. Gleaning is the collection of the remaining crops in agricultural fields after their commercial harvest, or just in crop fields where their harvest is not cost-effective. Some old cultures have fostered gleaning as an early form of social assistance [80]. Some authors have considered the management of government food reserves to be a food security driver [64,104,112,117,118,124,136]. Despite the high cost of storing food, any country must maintain adequate food reserves to serve the country in case of a crisis scenario [171]. Some authors have considered integrative policies (i.e., food–water–energy, food–energy, or water–food) as a driver of food security due to their impact on environmental improvement through natural resource handling efficiency [56,73,133,139,172,173]. Some authors have considered establishing dietary standard policies as an enabler of food security [69,151,163,174]. The government should impose policies on healthy food consumption to prevent obesity, such as prohibiting trans-fats. Moreover, they should restrict trans-fat usage in food outlets, establish institutional food standards, implement menu labelling regulations for chain restaurants, and ensure that disadvantaged people have better access to healthy meals [151].

Authors have highlighted various additional arguments or policies that are considered drivers for FS such as establishing public programs to influence diets in a healthy manner, reducing yield volatility [85,94,105,119,124,126,175], the country’s natural resources [85,105,119,124,137,145,162,163,176], geopolitical and political stability [69,98,104,117,123,124,142], agricultural infrastructure [64,114,116,118,142,146,175], food distribution infrastructure [71,75,76,112,177,178], economic integration [109,112,123,179,180], collaboration among all supply chain stakeholders [75,130,134,157], proper measurement of food security dimensions [123,181–183], urban agriculture policies [56,147,148], adjustments in dietary structure [59,86,163], establishing employment programs for poor household representatives [110,152], customer engagement in designing public policies [158], and trust in public institutions [166].

3.2. The Recommended Policies to Alleviate the Food Insecurity

Analysis of the 141 retrieved papers revealed 17 major recommended policies, as visualized in Figure 4. We also determined sub-policies under each category which were grouped based on common characteristics, relevance, and how they were categorized in the papers. The complete list of sub-policy categories and related references is provided in Appendix B.

Most authors recommended establishing FSP, in general, as a primary solution for food insecurity in developing and developed countries [56,57,63–65,69,81,85,87,89,91,94,97–99,101–124,126,127,130,131,133,134,137,142,144,145,148,149,151,152,175,177,180,182,184,185]. Many authors have suggested food consumption policies that offer safety-net programs or public food assistance programs (FAPs) such as food price subsidies, cash-based programs, structural pricing adjustments, or micro-credits as enablers of FS. The main goal of providing safety-net programs is to increase food consumption among poor people and improve food security [102]. Given the solid bidirectional causal link between poverty and malnutrition, FAPs have been recognized as critical components of the overall poverty reduction strategy. Food aid policies and initiatives can fill the gaps left by the for-profit food system and the informal (non-profit) social safety nets, ensuring food security for disadvantaged individuals, families, and communities [108]. Several authors have recommended establishing policies to enhance the performance and asset bases of small-scale farmers, such as loans, subsidies, access to information, and knowledge-sharing, to address food insecurity. Governments should adopt direct interventions such as structural price adjustments and targeted food subsidies to enhance the food access of farmers by lowering market prices and stabilizing consumption during high food price inflation [116]. Others have recommended establishing government input subsidy programs (input subsidy policies) that provide farmers with subsidies for investment into high-yielding technology (e.g., automation, fertilizers, high-yield seed). They all claimed this as an effective policy instrument for agricultural development, but each focused on a different mechanism. Shukla, Singh [130], for example, has discussed public distribution programs; Sinyolo [131] has emphasized policies aimed at increasing the amount of land planted with enhanced maize varieties among smallholder farmers; Wiebelt, Breisinger [124] has suggested investments in water-saving technologies, while Tokhayeva, Almukhambetova [137] have proposed the development of an agricultural innovation system. Others have recommended rural development policies to reduce yield volatility and improve the agricultural infrastructure (e.g., irrigation and water-saving technologies). Governments in developing nations must focus on R&D, agricultural infrastructure (technologies for irrigation and soil preservation), expansion services, and early warning systems [101]. Technological advancement, in general, is seen as a vital element in reducing yield volatility [85]. Capacity-building policies (e.g., educational, training, and technical support) have received considerable attention in the literature as a fundamental component of urban farming initiatives, and as attempts to promote self-reliance and networking. Capacity building in many areas connected to urban agriculture is essential for equipping residents with knowledge and expertise [148]. To enhance FS, some researchers have suggested policies supporting locally produced food, diversified agricultural production policies, policies that impact farm-level commodity pricing, food stock policies, establishing policies to increase the income of farmers, buffer stock policies, and resource allocation policies (for a complete list of references, see Appendix B).

Many authors have proposed different policy recommendations to reduce food waste and, thus, food insecurity [6,19,51,52,56–58,60–77,79–88,91–94,103,130,138,144,150,160,167,168,170,177]. Many have agreed on the importance of policies that promote information and education campaigns that spread awareness at household and public levels by improving meal planning and management in consumers. However, each author suggested a different approach. For example, Schanes, Dobernig [58] have discussed face-to-face door-stepping campaigns (online and in traditional newspaper leaflets), word-of-mouth, and television shows or movies. However, Septianto, Kemper [66] have highlighted the importance of social marketing campaign design and framing (having vs. not having) in conveying the intended message to consumers. Tucho and Okoth [73] have asserted the advantages of producing bio-wastes and bio-fertilizers from food waste and human excreta (in a food–energy–sanitation nexus approach), and also advocated for educating families on how to do so at the household level. Xu, Zhang [86] has argued that governments should help society to develop a logical perspective on food consumption and aggressively promote the habit of eating simple meals, particularly in social catering. Von Kameke and Fischer [52] and Zorpas, Lasaridi [60] have emphasized the importance of teaching customers about efficient meal planning to reduce food waste. Von Kameke and Fischer [52] have proposed using the Nudging tool rather than campaigning. Xu, Zhang [86] have suggested initiating suitable policy instruments to nudge individuals to adopt sustainable consumption habits, with important implications for decreasing food waste and increasing food security in China. Smart (innovative) food packaging and labelling policies have received significant attention in the literature, as they are critical in reducing food waste and, thus, improving FS. The nature, size, and labelling of the packaging impact the lifetime of the food. Smart packaging innovations and new technologies are steadily penetrating markets, thus increasing the shelf-life of foods through enhanced protection, communication, convenience, and control [58].

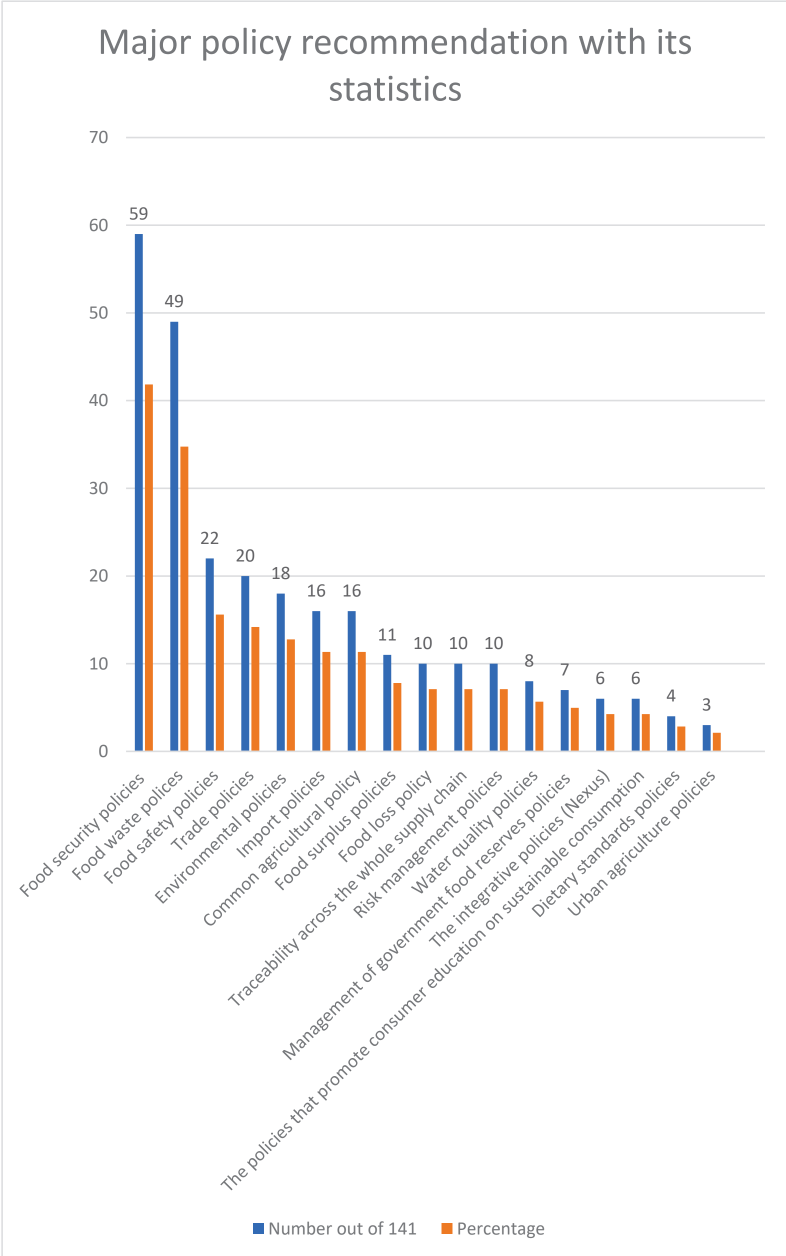

Figure 4. The main 17 recommended policies and statistics.

Food banks, food sharing, and food rescue policies have also received significant attention in the global literature, as they help reduce food waste and improve FS. Food banking is a critical long-term rescue policy for re-distributing surplus food to those in need and reducing poverty and food insecurity [80,92]. Several authors have recommended positive sanctions such as financial rewards, tax credits, federal and state funding, vouchers, or reduced taxes to decrease food waste and improve FS. Positive sanctions consist mainly of financial incentives to encourage restaurants and grocery retailers to donate their leftover food [60]. Addressing liability concerns might be one incentive, as the research participants have highlighted this as a universal barrier and that this issue, in particular, must be handled [51]. Negative sanction policies have received considerable attention in the literature as a tool for reducing food waste and improving FS. These include fines and fees imposed on companies and individuals accountable for food waste [58]. Taxes and fines are a potential way to manage and motivate restaurants and retailers to donate their leftover food to charities and community centers [65].

The establishment of policies that regulate the sharing of information and knowledge among supply chain stakeholders has received some attention in the literature in terms of reducing food waste and improving food security. Comprehensive food waste legislation has been discussed as a potential enabler of food security. A possible regulatory tool would be to revise and remove unnecessary food safety requirements that result in excessive food waste levels [58]. According to Halloran, Clement [6], food waste increased due to European food safety regulations and standardization. Food waste recycling policies have been used as a method to reduce food waste. Food waste can be utilized for value generation at any point of the food supply chain process through efficient techniques, then reincorporated into the cycle [77]. Food waste has a long history as a source of ecologically friendly animal feed [61].

A few authors have highlighted the impact of technological advancement (e.g., mobile applications) as a strategy to reduce food waste. Some authors have proposed implementing gleaning operation policies that provide tax incentives and government assistance to gleaners in order to decrease food waste. Some authors have proposed implementing peak storage reduction policies, such as stock-holding incentives. Nudging tools (which nudge people toward forming sustainable consumption behaviors) have been mentioned by a few authors.

Food safety policies received significant attention in the retrieved literature [61,64,69,70,103,105,111,112,120,125,129,130,137,138,149,153–159]; however, they have been discussed in various different forms. Few authors have discussed food quality and food hygiene compliance certifications. Compliance with sanitary standards is required to maintain the best practices for preventing food-borne diseases and food security threats [155]. Other authors have discussed the importance of food safety standards. Meanwhile, few authors have emphasized the importance of food safety throughout the supply chain, but each proposed a different strategy to achieve it. For example, some authors have suggested using an effective IT system [130], RFID [138], or developing food safety training policies [155].

Many authors have advocated for the implementation of trade policies to address food insecurity in developing and developed countries [94,95,101,103,111,112,119,123,129,136,141,146,148,149,152,157,161,164,178,180], but in different contexts. For example, some have suggested establishing infrastructure development policies that target agricultural logistic infrastructure, or improving the speed and quality of shipping logistics. In contrast, some authors have agreed on the importance of state trading and private trade-supporting policies. Others have suggested the removal of tariff and non-tariff barriers, while a few authors recommended reliable marine connection and transportation logistics policies.

Environmental policies are a fundamental enabler of food security [59,73,94,120,121,124,130,135,139,141,145,147,159–163,166]. However, authors have focused on many different aspects of these policies. Some authors, for example, have emphasized the importance of establishing policies to mitigate the effects of climate change. Others were too specific, suggesting greenhouse gas reduction policies, and proposed penalizing non-compliance. Due to the strong links between climate change, poverty, and food insecurity, some authors have proposed establishing coordinating policies among the three. Other authors have stressed the consideration of policies that encourage the optimization of fertilizer use.

Many authors have considered food import policies as a solution to food insecurity [94,95,100,103–105,109,112,116,117,119,120,124,126,134,146]; however, most authors provided different opinions regarding the most effective policy to implement. For example, some authors have stressed the importance of policies that provide direct government financial assistance to local agriculture, or the importance of policies that sustain local agricultural product prices compared to imported products. Some have recommended providing temporary tax benefits for agricultural investment, while others recommended import ban (substitution) policies. A few authors have recommended direct budget subsidies, subsidized loan interest rates, and strategies for the diversification of imported food origin.

Many authors have discussed the importance of establishing a common agricultural policy (CAP) to address sustainable agriculture [56,57,64,89,109,111,118,119,132,142,143, 149,161,172,184,186]. Others have stressed the importance of food surplus policies in enhancing a country's food security status [51,58,70,72,75,76,79,82,84,90,91]. Some authors have suggested strategies to regulate a company's liability regarding the donation of surplus food. A few authors have proposed food policies that subsidize the purchase of surplus food—also known as "ugly food"—by controlling for prices and surplus item characteristics. Some authors have suggested establishing food loss policies. However, few authors have specified the need for policies promoting food loss quantification.

Many authors have discussed the policies that promote traceability across the whole supply chain as an enabler for food security [56,69,103,128–130,137,138,168,178]. However, the different authors discussed different technologies such as investment into information technology such as RFID, effective IT systems, ICT systems, and blockchain technology. Government policies should promote investments into traceability systems that focus on rapid withdrawal in unsafe food scenarios such as product recall regulations, fines imposed on hazardous product distributors, and food-borne food risk monitoring [129]. Many authors have discussed various risk management strategies to improve a country's food security [94,117,118,137–139,145,154,155,157]. However, each considered a different approach to overcome the risk. Specifically, they have discussed food scandal policies, the COVID-19 pandemic, programmed risk identification, proactive policy measures to handle flood crises, early warning systems for natural disasters, or risk management throughout the food supply chain. Some authors have highlighted water quality policies such as efficient water-use policies, improving water resources policies, using water-efficient crops, investments into water-saving technologies, and food and water safety throughout the supply chain.

Some authors have discussed the management of government food reserves as an enabler of food security [64,104,112,117,118,124,136], and others have discussed integrative and coherent policies between food, water, and energy (as a nexus) [56,73,133,139,172,173]. Meanwhile, other authors have discussed policies that promote consumer education on sustainable consumption, improving consumer status awareness and knowledge regarding the ecological impact of their purchases [60,69,133,144,163,165]. Few authors have addressed the importance of dietary standard policies [69,151,163,174], urban agriculture policies [56,147,148], and food-aid policies [118,150].

Some policies were suggested in one paper only such as devising the right population policy in China [85], flexible retail modernization policies [158], policies that facilitate short-term migration [187], policies to stimulate equitable economic growth through manufacturing and services [95], and sound research governance policies [140].

4. Discussion

In this section, we discuss the polices and drivers in the greater areas, then compare them based on specific contexts. This approach serves to provide better understanding, thus informing decision-makers about the importance of choosing the right policies through considering many food security dimensions. By looking deeply at the extracted food security drivers and policies and the way in which they can be applied to each country's context, we take an example from the MENA region. The MENA region includes a diverse range of nations, including low-income and less-developed (e.g., Sudan, Syria, and Yemen), low–middle-income (e.g., Algeria, Egypt, Iran, Morocco, and Tunisia), upper middle-income (e.g., Jordan, Lebanon, and Libya), and high-income (e.g., the UAE, Qatar, Oman, Bahrain, Israel, Kuwait, and Saudi Arabia) countries [126]. As food availability is a serious problem in the MENA region low-income countries (Syria and Yemen), due to war and violent conflicts [188], policies aimed at increasing food availability continue to pique the interest of policy-makers. In these countries, where citizens are incapable of fulfilling their basic food needs [189], the existence of food security policies in different forms is crucial for achieving food security [53,97,98,124,184], more than FLW policies. Policy-makers should focus on ensuring the availability of either locally produced or imported food, which requires appropriate trade policies to deal with food shortages and improve the availability dimension in these countries. Trade policies should focus on creating infrastructure development policies that target agricultural logistic infrastructure, improve the speed and quality of shipping logistics, and establish reliable marine connections and transportation logistics policies that remove tariff and non-tariff barriers.

Policy-makers should establish import policies that sustain local agricultural product prices compared to imported products, provide direct government financial assistance to local agriculture, and provide temporary tax benefits for agricultural investment.

Additionally, the governments should improve food access in the MENA region low-income countries by reducing or stabilizing consumer and producer food prices. To enhance food access, FSPs (e.g., education policies in general and capacity-building policies) may help to improve individual human capital. Governments also must provide supplemental feeding programs, typically targeting vulnerable groups in need of special diets, such as pregnant women and children [101].

Moreover, the government should improve credit access through the following means: policies that enhance the performance and asset base of small-scale farmers; the existence of policies that impact farm-level commodity pricing, thus retaining farmers and increasing local production; the existence of government input subsidy programs for individuals, and the existence of policies supporting locally produced food. These are all possible policies to improve the MENA region FS. Governments and global health organizations should promote food utilization in MENA low-income countries through the development of policies that monitor overall food quality, such as access to clean water and micronutrient fortification, or through individual educational programs on safe food preparation [155]. Finally, enhancing food quality can optimize the individual nutrient absorption [101].

In contrast, discussions of food security in the MENA region high-income countries have indicated that food availability, access, and utilization are generally higher and not a problem. However, food stability is low, which requires the attention of policy-makers to improve FS. Food stability impacts the other food security pillars (access, availability, and utilization). Moreover, it requires the economic, political, and social sustainability of food systems, which are vulnerable to environmental conditions, land distribution, available resources, conflicts, and political situations [190]. Food stability necessitates increased efforts and expenditures to achieve food security in the sustainable development goals, especially in light of increased academic and governmental interest in incorporating sustainability values into policies.

As food waste is prevalent in these countries, FLW policies are more critical than FSP, which is in alignment with our findings regarding food security drivers. FLW makes it difficult for the poor in developing countries to access food by significantly depleting natural resources such as land, water, and fossil fuels while raising the greenhouse gas emissions related to food production [115]. Addressing food loss and waste in these countries can hugely influence the reduction of wasted food and indirectly enhance food security. The number of food-insecure individuals may be reduced in developing regions by up to 63 million by reducing food loss, which will directly reduce the over-consumption of cultivated areas, water, and greenhouse gas emissions related to food production [115]. According to Abiad and Meho [189], food waste produced at the household level differs across MENA-region countries. For example, it ranges from 68 to 150 kg/individual/year in Oman, 62–76 kg/individual/year in Iraq, 194–230 kg/individual/year in Palestine, and 177–400 kg/individual/year in the UAE. It is critical to take more aggressive but scientifically sound initiatives to minimize FLW, which will require the participation of everyone involved in the food supply chain such as policy-makers, food producers and suppliers, and the final consumers [191,192]. Food waste reflects an inefficient usage of valuable agricultural input resources and contributes to unnecessary environmental depletion [191,193]. Furthermore, food loss is widely recognized as a major obstacle to environmental sustainability and food security in developing nations [194]. Preventing

FLW can result in a much more environmentally sustainable agricultural production and consumption process by increasing the efficiency and productivity of resources, especially water, cropland, and nutrients [115,191,192,195]. Preventing FLW is crucial in areas where water scarcity is a prevalent concern, as irrigated agriculture makes up a sizeable portion of total food production, and yield potential may not be fully achieved under nutrient or water shortages [191,196,197]. According to the study of Chen, Chaudhary [197], food waste per capita in high-income countries is enough to feed one individual a healthy balanced diet for 18 days. Chen, Chaudhary [197] also found that high-income countries have embedded environmental effects that are ten times greater than those of low-income countries, and they tend to waste six times more food by weight than low-income countries. Consequently, implementing proper FLW policies in high-income countries can help to alleviate the food insecurity problem while maintaining the economic, social, and environmental sustainability of future food production.

Implementing effective food storage techniques and capacities is considered a key component of a comprehensive national food security plan to promote both food utilization and food stability; furthermore, proper food storage at the household level maintains food products for a more prolonged period [198]. Encouragement of economic integration between MENA region countries is very applicable considering the heterogeneity of these countries. For example, countries with limited arable land and high income, such as the UAE and Saudi Arabia, can invest in countries with a lower middle income, such as Egypt, and use its land to benefit both countries. On the other hand, Boratynska and Huseynov [101] have proposed food technology innovation as a sustainable driver of food security and a promising solution to the problem of food insecurity in developing countries. Due to the higher food production demand to support the expanding urban population while having limited water and land availability, higher investments in technology and innovation are needed to ensure that food systems are more resilient [190]. Boratynska and Huseynov [101] have argued that, in general, using innovative technologies to produce healthy food products is frequently a concern. However, improving the probability that innovative food technology will enable the production of a diverse range of food products with enhanced texture and flavor while also providing a variety of health advantages to the final consumer is essential. Jalava, Guillaume [193] have argued that, along with reducing FLW, shifting people's diets from animal- to plant-based foods can help to slow environmental degradation.

The MENA region example described above can be adapted to different regions based on their food security situation, and relevant policies can be devised to improve food security more sustainably.

5. Conclusions

Food security is a complicated and multi-faceted issue that cannot be restricted to a single variable, necessitating the deeper integration of many disciplinary viewpoints. It is essential to admit the complexity of designing the right policy to improve food security that matches each country's context [46] while considering the three pillars of sustainability. Furthermore, it is of utmost importance to implement climate-friendly agricultural production methods to combat food insecurity and climate change [12]. Mapping the determinants of food security contributes to better understanding of the issue and aids in developing appropriate food security policies to enhance environmental, social, and economic sustainability.

This research contributes to the body of knowledge by summarizing the main recommended policies and drivers of food security detailed in 141 research articles, following a systematic literature review methodology. We identified 34 food security drivers and outlined 17 recommended policies to improve food security and contribute to sustainable food production. Regarding the drivers, one of the foremost priorities to drive food security is reducing FLW globally, followed by food security policies, technological advancement, sustainable agricultural development, and so on (see Appendix A). Regarding the recommended policies, most studies have detailed the contents and impacts of food security policies, food waste policies, food safety policies, trade policies, environmental policies, import policies, the Common Agricultural Policy (CAP), food surplus policies, and so on (see Appendix B).

5.1. Policy Implications

We assessed the obtained results in comparison to the latest version of the GFSI. Using the GFSI (2021) indicators as a proxy resulted in the identification of gaps and specific policy implications of the results. The idea was to identify which of the policies and drivers have been already implemented and which have not (or, at least, have not been very successfully implemented). We used the GFSI as it is a very well-established benchmarking tool used globally by 113 countries to measure the food security level. We examined the indicators mentioned under each of the four dimensions of food security, and listed associations with the identified policies and drivers found in the literature. Accordingly, we suggest the addition of two dimensions to the current index:

- Sustainability

The first dimension relates to measuring the sustainability dimensions that each participating country adopts in its food production process. We noticed that many authors stressed the importance of the existence of clear environmental policies that drive long-term food security. However, the current GFSI lacks indicators measuring this dimension. The reviewed literature suggested environmental indicators considering optimized fertilizer use, carbon taxes, aquaculture environment, bio-energy, green and blue infrastructure, gas emissions reduction policies, policies to reduce the impacts of climate change, and heavy metal soil contamination monitoring.

- Consumer representation

The second dimension is related to consumer voice representation within the GFSI. The reviewed literature suggested implementing policy measures that promote consumer education on sustainable consumption and improve the consumer status, consciousness, and knowledge regarding the ecological impact of their purchases. Any sustainability initiative should be supported and implemented by the final consumer.

Additional gaps in the policies and drivers of food security were identified and allocated under the relevant indicators in the GFSI based on the four dimensions of food security. Under the affordability dimension, we found a lack of policies in the reviewed literature addressing the Inequality-adjusted income index. Regarding the Change in average food costs indicator, we observed that the policies that exist in the literature concern the farmer level only (e.g., policies that impact farm-level commodity pricing and policies supporting locally produced food), and not all of the citizens at the national level. Additionally, policies that promote traceability across the whole supply chain were missing. There were no policies in the reviewed literature under the food quality and safety dimension representing the following: the dietary diversity indicator; micronutrient availability (e.g., dietary availability of vitamin A, iron, and zinc); regulation of the protein quality indicator; the food safety indicator (specifically the two sub-indicators of food safety mechanisms and access to drinking water), and illustration of the national nutrition plan or strategy indicator. Therefore, future research should pay more attention to and emphasize the importance of such policies, particularly in developed countries seeking to improve their food security status and score high on the GFSI.

Moreover, the reviewed literature suggested "developing food safety training policies" to improve food safety and FS; however, no indicators or sub-indicators within the GFSI represent such training policies. The GFSI developers should pay more attention to safety training practices and include them in the index's future development. Under the availability dimension, the reviewed literature suggested establishing a food loss policy that promotes the quantification of food loss under the food loss indicator. This indicator should be enhanced through well-articulated policies that address the problem of food loss and attempt to mitigate its impact. However, while there were various policies concerning food waste or surplus, there were no indicators within the GFSI that represented food loss. As food loss and waste was identified as the primary driver of food security in this study, we recommend expanding the GFSI to include food loss quantification and reduction policies under the availability dimension. Finally, under the political commitment to adaptation dimension, some policies were identified in the reviewed literature in two sub-indicators: early warning measures/climate-smart agriculture (e.g., proactive policy measures to handle flood crises, programmed risk identification, and early warning systems for natural disasters) and disaster risk management (e.g., food scandals, COVID-19, and risk management throughout the food supply chain). However, under the other two relevant sub-indicators—commitment to managing exposure and national agricultural adaptation policy—there were no identified policies.

5.2. Contributions of the Study

The key contributions of this study to the existing literature are threefold. First, we identified the (34) main food security drivers and the (17) most-recommended policies to improve food security and enhance the future food production sustainability. Several studies have partially covered this area, but none have employed a systematic literature review of 141 papers covering such an scope in this topic. The gravity of food security worldwide is well established; hence the contribution of this work. Second, we provide a reflection of policies/drivers on the latest version of the GFSI, resulting in more tangible policy implications (see Section 5.1). Third, through a systematic literature review, we identified elements not listed under the GFSI that could be considered in its future revision. Examples include environmental policies/indicators such as optimized fertilizer use, carbon taxes, aquaculture environment, bio-energy, green and blue infrastructure, gas emission reduction, policies to reduce the impact of climate change, and heavy metal soil contamination monitoring; consumer representation, as the reviewed literature suggested policy measures that promote consumer education on sustainable consumption, as well as improving consumer status, consciousness, and knowledge regarding the ecological impact of their purchases; and traceability throughout the entire supply chain.

5.3. Study Limitations and Future Research

In this study, we identified the major drivers and the recommended policies to improve food security and enhance the future food production sustainability based on the reviewed literature. However, we recommend conducting a Delphi research study in consultation with policy-makers and industry experts. A Delphi study can be used to validate the findings of this systematic literature review based on a specific country's context. This research was conducted using only 141 articles from two databases; therefore, we suggest replicating this research using different databases, which will allow for the inclusion of more related papers. Moreover, this research included only peer-reviewed articles, which may be considered, based on the guidelines of Keele [185], as a source of publication bias. Future research may consider including gray literature and conference proceedings. This research did not include the three sustainability pillars within its research string; therefore, we recommend considering the inclusion of the three pillars in future research. Future research should also investigate the use of alternative protein food technology innovation, such as plant-based protein, cultured meat, and insect-based protein, as a sustainable solution to the food security problem. Additionally, understanding the factors influencing acceptance of various technologies by the final consumer is particularly important given some regional characteristics such as harsh arid environments and the scarcity of arable land, freshwater, and natural resources.

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

Appendix A. Summary Table of Major Drivers of Food Security

The Driver of Food Security	Occurrence	Article Citations
Food loss and waste	47/141	[6,19,51–95]
Food waste management	29/47	[19,51–79,82,84,93,167,199]
Food waste policies	23/47	[6,51,52,58,60,62–66,68,69,71,75,77,79–86].
Food loss reduction policies	10/47	[62,65,68,77,79,84,89,93–95].
Food surplus policies	11/47	[58,70,72,75,76,79,82,84,90–92].
Food waste quantification	11/47	[54,58,63,68,71,78,82,84,93,167,199]
food loss quantification	5/47	[68,82,87–89]
Food security policies	37/141	[56,63,65,69,70,74,79,85,94,97–124]
Environmental policies	13/141	[59,73,121,124,130,135,139,147,159–163]
Public food assistance programs and policies	24/141	[65,81,99,101,102,104,105,107–110,112–116,118,119,122,137,144,148,151,152,182]
Risk management	10/141	[94,117,118,137–139,145,154,155,157]
Food scandals policies	2/10	[154,155]
Early warning systems for natural disasters	3/10	[94,137,145]
Risk management throughout the food supply chain	3/10	[138,139,157]
Proactive policy measures to handle the flood crises	2/10	[118,145]
Providing food aids (micronutrient supplementation) during disasters	1/10	[118]
COVID-19 pandemic	1/10	[117]
The programmed risk identification	1/10	[139]
Import policies	9/141	[69,95,100,103,120,124,126,129,146]
Trade policies	13/141	[69,94,95,103,111,112,114,123,129,141,146,161,164]
Economic integration	5/141	[109,112,123,179,180]
Agricultural sustainable development and practices	27/141	[56,57,59,64,71,73,94,97,105,109,111,119–121,124,130,132,134,136,137,139,142–147]
Technology advancement	36/141	[56–58,63,69,71,74,77,85,90,94,95,109,116,119–121,123–141]
Sustainable technology advancement	27/36	[56,57,63,69,71,74,77,85,94,95,109,119,121,124,127–139]
High-yield seed varieties	8/36	[57,94,116,119,120,126,130,131]
Investment in R&D (e.g., precision farming)	4/36	[121,123,130,137]
Information technology and IT advancement	3/36	[130,137,138]
The use of mobile applications	3/36	[58,90,130]
The use of nanotechnology in agriculture	2/36	[130,140]
The use of biotechnology in agriculture	2/36	[130,141]
The use of genetically modified (GM) crop.	2/36	[57,125]
Local production enhancement	18/141	[57,69,85,87,89,94,98,103,105,109,112,117,120,134,137,144,148,149]
Farm production diversity	9/141	[57,64,69,105,106,116,118,120,185]
Building farmers capacities (small scale farmers)	18/141	[56,73,94,104,105,111,114,116–121,131,137,180,184,185]
Employment programs for poor households' representatives	2/141	[110,152]
Public programs to influence diets in a healthy manner	9/141	[69,85,110,144,151,156,163,167,182]
Geopolitical and political stability	7/141	[69,98,104,117,123,124,142]

The Driver of Food Security	Occurrence	Article Citations
Food safety and food safety policies	16/141	[61,64,69,103,105,111,112,129,149,153–159]
Reduction of yield volatility	7/141	[85,94,105,119,124,126,175]
Agriculture infrastructure	7/141	[64,114,116,118,142,146,175]
The integrative policies (nexus)	6/141	[56,73,133,139,172,173]
The proper measurement of food security dimensions	4/141	[123,181–183]
The country's natural resources (cultivated agriculture area)	9/141	[85,105,119,124,137,145,162,163,176]
The proper communication among all stakeholders	11/141	[6,56,68,69,84,92,129,130,156,157,168]
Management of government food reserves	7/141	[64,104,112,117,118,124,136]
Collaboration among all supply chain stakeholders	4/141	[75,130,134,157]
Promotion of the consumer's education about sustainable consumption and healthy diet	12/141	[52,60,67,69,86,133,144,151,163,165–167]
Effective gleaning process (increasing the food bank's processing resources)	8/141	[70,72,74,80,84,92,142,170]
Food distribution infrastructure	6/141	[71,75,76,112,177,178]
Adjustment in the diet structure	3/141	[59,86,163]
Dietary standard policies	4/141	[69,151,163,174]
Urban agriculture policies	3/141	[56,147,148]
The government role	16/141	[67,75,84,86,100,109,116,117,119,121,137,138,147,150–152]
Government capital investment in agriculture	7/16	[100,109,116,117,119,121,147]
Government and public administration's commitment in enhancing the operational process of food distribution	3/16	[75,84,150]
Government regulation for food businesses and households that produce food waste	2/16	[67,86]
Government support for the research that enhances the country food security level	1/16	[137]
Government vision and commitment to adopt RFID technology	1/16	[138]
Government commitment in policy development to prevent obesity	1/16	[151]
Government knowledge of the correlation between market price and sustain the food prices during crises	1/16	[152]
Customer engagement in designing the public policies	1/141	[158]
Trust in the public institutions	1/141	[166]

Appendix B. Summary Table of Most-Recommended Policies

The Policy	Occurrence	Article Citations
Food security policies	59/141	[56,57,63–65,69,81,85,87,89,91,94,97–99,101–124,126,127,130,131,133,134,137,142,144,145,148,149,151,152,175,177,180,182,184,185]
Food consumption polices that offer safety net	24/59	[65,81,99,101,102,104,105,107–110,112–116,118,119,122,137,144,148,151,152,182]
Policies to enhance small-scale farmer performance and assets base such as loans, subsidies, access to information and knowledge sharing	16/59	[89,104,105,109,111,114,116–119,121,131,137,149,180,184]
Government input subsidy programs (input subsidy policy) that provide farmers with subsidies to investment in high-yielding technology (e.g., automation, fertilizers, high-yield seed)	14/59	[89,101,109,114,116,121,124,126,127,130,131,137,149,175]
Rural development policies to reduce yield volatility and improve the agriculture infrastructure (e.g., irrigation and water-saving technologies)	14/59	[69,85,87,101,106,114,118,124,130,137,142,145,149,175]
Capacity building policies (educational, training and technical support)	14/59	[91,94,103,105,116,117,121,123,127,131,137,144,148,184]
Policies supporting locally produced food	12/59	[57,69,87,89,98,103,105,112,120,134,148,149]
Education policies in general	8/59	[69,97,101,105,117,127,130,133]
Diversified agriculture production policies	6/59	[57,64,106,116,118,185]
Policies that impact the farm-level commodity pricing	5/59	[63,105,116,120,175]
Food stock policies which help in predicting global food production information	4/59	[56,64,124,126]
Establishing policies to increase farmer income	4/59	[104,105,109,119]
Buffer stock policies	1/59	[104]
Resource allocation policies (income taxes)	1/59	[97]

The Policy	Occurrence	Article Citations
Trade policies	20/141	[94,95,101,103,111,112,119,123,129,136,141,146,148,149,152,157,161,164,178,180]
Establishing infrastructure development policies that target agriculture logistic infrastructure and improve the speed and quality of shipping logistics	8/20	[94,112,119,136,146,149,157,164]
State trading and private trade supporting policies	7/20	[101,103,112,129,148,149,180]
Removal of tariff and non-tariff barrier	7/20	[94,95,111,123,146,152,161]
Trade infrastructure development policies	4/20	[94,112,123,141]
Reliable marine connection and transportation logistics policies	2/20	[164,178]
Food waste polices	49/141	[6,19,51,52,56–58,60–77,79–88,91–94,103,130,138,144,150,160,167,168,170,177]
Information and education campaigns that spread awareness at households and public level	21/49	[52,58,60,62,64–69,71,73,82,85–88,91,93,130,144]
Food waste reduction policies	17/49	[52,57,63–65,67,68,70,71,76,77,79,81,82,84,160,167]
Smart (innovative) food packaging and labelling policies	9/50	[6,56,58,62,77,88,91,94,103]
Food banks, food sharing or food rescue policies	8/49	[70,72,74,80,83,92,150,170]
Positive sanctions such as financial rewards, Tax credits, federal and state funding, vouchers, fewer taxes	8/49	[51,58,60,67,72,77,86,91]
Information and knowledge sharing among supply chain stakeholders	6/49	[6,56,74,92,138,168]
Comprehensive food waste legislation	6/49	[6,58,62,63,65,79]
Negative sanction policies by imposing fines and taxes such as disposal taxes	6/49	[51,58,60,65,77,86]
Food waste recycling polices	5/49	[61,62,67,77,84]
Technology advancement (mobile applications)	2/49	[58,130]
Gleaning operations policies (provide tax incentives and governmental support)	2/49	[72,92]
Nudging tool (nudge people in forming sustainable consumption behaviour)	2/49	[52,86]
Policies for peak storage reduction such as incentives for stock holding	2/49	[85,177]
Food waste management policy	1/49	[75]
Food upcycling with regards to market segmentation based on age	1/49	[19]
Food loss policy	10/141	[62,65,68,79,82,84,88,89,94,95]
Policies promoting the quantification of food loss	3/10	[68,82,88]
Food surplus policies	11/141	[51,58,70,72,75,76,79,82,84,90,91]
Policies to regulate company's liability of donating surplus food	5/11	[51,75,82,84,91]
Food policies that subsidize purchases of surplus food "ugly food" by controlling for prices and the attributes of surplus items	2/11	[58,76]
Food safety policies	22/141	[61,64,69,70,103,105,111,112,120,125,129,130,137,138,149,153–159]
Food safety standards	7/22	[69,111,112,120,155,158,159]
Safety throughout the food supply chain	3/22	[130,138,157]
Developing food safety training policies	1/22	[155]
Mandatory state registration for major types of food additives	1/22	[103]
Food quality and food hygiene compliance certifications	5/22	[69,103,105,154,155]
The integrative and coherent policies between food, water, and energy system nexus.	4/141	[56,133,172,173]
Water–food (WF) nexus approach.	1/141	[139]
Food–energy–sanitation nexus approach	1/141	[73]
Water quality policies	8/141	[69,71,118,124,130,133,137,139]
Common agricultural policy (CAP) that addresses sustainable agriculture	16/141	[56,57,64,89,109,111,118,119,132,142,143,149,161,172,184,186]
Green and blue infrastructure (GBI) policies	1/16	[172]
Common agricultural policy (CAP) hinders the sustainable intensification	1/141	[121]
The policies that promote consumer education on sustainable consumption and improving consumer status consciousness and knowledge of their purchases ecological impact	6/141	[60,69,133,144,163,165]
Environmental policies	18/141	[59,73,94,120,121,124,130,135,139,141,145,147,159–163,166]

The Policy	Occurrence	Article Citations
Gas emission policies, such as greenhouse gas reduction policies	2/141	[135,161]
Policies to reduce climate change impact	4/141	[124,139,162,163]
The coordination of policies between climate change, poverty and food insecurity due to their strong interlinking	4/141	[124,141,162,163]
Efficiency in agriculture water use, irrigation systems	3/141	[59,124,139]
The investments in water-saving technologies	2/141	[124,139]
Policies to minimize the impacts of anthropogenic activities on urban soils and enhance the urban agriculture practices	2/141	[147,159]
Soil contamination of heavy metals (cadmium)	1/141	[159]
Optimization of the fertilizer use policy	6/141	[59,73,94,120,130,145]
Carbon tax policy (promotes green economy)	2/141	[121,160]
Aquaculture environmental policies	1/141	[166]
Bio-energy policies	2/141	[73,161]
Management of government food reserves	7/141	[64,104,112,117,118,124,136]
Policies that promote traceability across the whole supply chain	10/141	[56,69,103,128–130,137,138,168,178]
Import policies	16/141	[94,95,100,103–105,109,112,116,117,119,120,124,126,134,146]
Direct governmental financial assistance to local agricultural assistance	8/16	[94,100,109,116,117,119,124,134]
Sustaining local agricultural product prices compared to the imported products	7/16	[95,100,104,105,116,120,146]
Providing temporary tax benefits for agriculture investment	4/16	[100,109,116,124]
Import ban (substitution) policies	4/16	[103,112,120,146]
Direct budget subsidies	2/16	[100,146]
Subsidizing loan interest rates	2/16	[100,117]
Diversification of imported food origins strategy	1/16	[126]
Risk management policies	10/141	[94,117,118,137–139,145,154,155,157]
Food scandals	2/10	[154,155]
COVID-19	1/10	[117]
Programmed risk identification	1/10	[139]
Proactive policy measures to handle the flood crises	2/10	[118,145]
Early warning systems for natural disasters	3/10	[94,137,145]
Risk management throughout the food supply chain	3/10	[138,139,157]
Dietary standard policies	4/141	[69,151,163,174]
Urban agriculture policies	3/141	[56,147,148]
Food aid policies	2/141	[118,150]
Policies discussed by one author only		
Devising the right population policy in China	1/141	[85]
Flexible retail modernization policies	1/141	[158]
Policies that facilitate short-term migration	1/141	[187]
Policy to stimulate equitable economic growth through manufacturing and services	1/141	[95]
Sound research governance policies: to address the expected and unexpected complications of new technologies (nanotechnology)	1/141	[140]

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Review

Nutritional Profile of Commercialized Plant-Based Meat: An Integrative Review with a Systematic Approach

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Abstract: Given the high cost of production of animal-based meats and the increase in the number of adepts of meatless diets, the need for plant-based meat substitutes is growing. In this prosperously growing market, there is a lack of knowledge about the nutritional value of these meat substitutes and their ingredients. This study aims to review the nutritional composition and ingredients of meat substitutes commercialized worldwide. An integrative review was performed with a systematic literature search in PubMed, EMBASE, Scopus, Science Direct, Web of Science, and 11 studies were selected to compose the sample of this review. Data on meat substitutes' nutritional composition and ingredients from different categories were collected and analyzed. The results showed that meat substitutes commonly present lower energy values and higher amounts of carbohydrates and dietary fiber. Protein values varied according to the meat substitute category, with some showing a higher concentration than others, more specifically in substitutes for bovine meat. Higher values were found in the Pieces category and lower in Seafood substitutes. Unlike animal meat, vegan meat has a proportion of carbohydrates higher than protein in most samples, except for chicken substitutes. Meat substitutes presented similar total and saturated fat content compared to their animal-based counterparts. Higher amounts of fat were found in the "Various" category and lower in "Pieces". Ingredients such as soy, pea, and wheat were the primary protein sources in meat substitutes, and vegetable oils were their primary fat source. Methylcellulose, various gums, and flavorings were the most used food additives. In general, meat substitutes presented high concentrations of sodium, possibly collaborating with an excessive sodium intake, highlighting the need for developing sodium-reduced or sodium-free alternatives. Most of the included samples did not describe the concentration of iron, zinc, and vitamin B12. Further studies are needed to develop meat substitutes with better nutritional composition, fulfilling the need for equivalent substitutes for animal-based meat.

Keywords: plant-based; meat substitutes; nutritional composition; ingredients

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1. Introduction

The demand for plant-based meat substitutes is growing worldwide for several reasons, such as welfare, sustainability, and health benefits [1,2]. Meat is a food that is ostensibly present in the eating habits of western populations, being responsible for providing several key nutrients such as proteins, fats, minerals such as iron and zinc, and vitamins A and B12 [3]. Its world consumption is about 25 kg per capita per year [3]; however, its production can harm the local environment and world sustainability.

Meat production demands the concomitant use of a series of resources, such as land, water, and energy, and this model has already proven to be economically unfeasible since between 75 to 90% of the energy and resources invested in cattle is lost in the animal's body maintenance and manure production [4]. In addition, it is estimated that the production of 200 g of beef involves the expenditure of 792 L of drinking water, 4 kg of grains for feeding, the deforestation of 6.6 m^2, and the emission of 50 kg of CO_2 into the atmosphere [5].

In the world, although there are no global data on followers of meat-free diets, data on vegetarianism show significant numbers in Asia (19% of the population), Africa (16%), South and Central America (8%) and North America (6%) [6]. Furthermore, the number of adherents to diets that remove all or part of meat or meat products is continuously growing [7]. Moreover, given the influence of food on the social interactions of human beings, the search for plant-based meat substitutes is also increasing [3,8]. Therefore, this population needs products that replace meat and its technical and nutritional aspects.

Typically, plant-based meat substitutes consist of products based on a mix of legumes and cereals, using different technologies depending on the final product characteristics, added (or not) by food additives to improve flavor, texture, and appearance [9].

However, several questions are raised about the nutritional quality of these products. Given the objective of complete meat replacement, these plant-based products must have similar or better nutritional quality in the composition and amount of nutrients [10]. In addition, potential health problems related to the additives used to mimic the sensory characteristics of meats are commonly observed in studies [3,11]. In addition, a possible heterogeneity in the nutritional composition of these meat substitutes is expected because of different matrices combinations, making it difficult for consumers to choose the best choice from a nutritional point of view.

In this sense, the objective of this review is to compile and analyze different plant-based meat substitutes (including substitutes for chicken, seafood, and pork) mapped by studies carried out in different countries and, from that, provide better information to consumers to facilitate their understanding of the market.

2. Materials and Methods

An integrative literature review was performed with a systematic approach for the best scientific rigor. The search phase for this integrative review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Checklist [12].

2.1. Inclusion and Exclusion Criteria

Only experimental studies related to the quantitative determination of nutrients and ingredients of commercial vegan meat substitutes that imitate products of animal origin were included. Studies with analysis of meat substitutes (including chicken, fish, and pork) were included. Studies categorized as reviews, letters, conference abstracts, case reports, brief communications, and books were excluded from the review; studies that did not quantitatively analyze the nutrients or ingredients in vegan products that seek to mimic products of animal origin were also excluded.

2.2. Information Sources

Adapted and individual search strategies were developed for six databases: PubMed, EMBASE, Scopus, Science Direct, Web of Science, and gray literature (Google® Scholar). Patents were searched using the Google Patent® tool. The last search was performed on 1st September 2022. In addition, reference lists of included articles were examined for possible studies not retrieved before.

2.3. Search Strategy

At this stage, combined or isolated keywords were used in all the databases in English, and the necessary adaptations were made in each database. The keywords were the following: "Product", "vegan", "substitutes", "meat", "beef", "chicken", "pork", "plant", "based", "commercialized", "commercial", "sold". Endnote Web® and Rayyan Web® software were used to manage bibliographic references.

2.4. Study Selection

The selection of studies was performed in two stages. At first, two reviewers (B.R. and M.L.T.) independently analyzed the titles and abstracts of all references identified and available in the analyzed databases. Articles that did not meet the inclusion criteria were discarded. Then, after decisions were made by the first (B.R.) and second (M.L.T.) reviewers, a third reviewer (D.d.C.M.) analyzed possible disagreements and determined the potential inclusion or exclusion of the articles. In phase 2, the same reviewers (B.R. and M.L.T.) applied the eligibility criteria to the full texts of the selected articles. In cases of disagreement, the third reviewer (D.d.C.M.) was consulted to resolve disagreements. In addition, two experts (R.B.A.B. and R.P.Z.) on the subject were available to resolve disagreements that could not be dealt with by the third reviewer (D.d.C.M.) and for the inclusion of full texts deemed relevant. The final decision on the articles comprising the sample was made based on the full texts. The flow diagram of the literature search and selection criteria is shown in Figure 1.

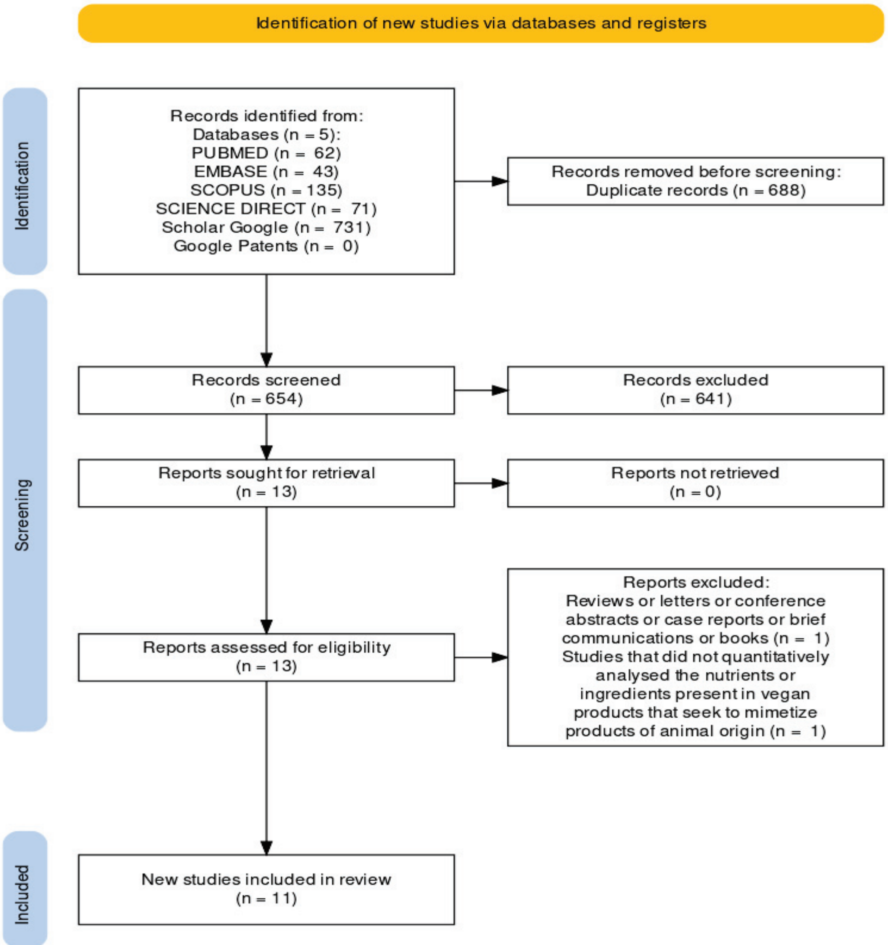

Figure 1. Flow diagram of the literature search and selection phases adapted from PRISMA guidelines [13].

2.5. Data Collection

The following data were collected from the included works: authors and year of publication, country of study, source of information of the nutritional composition analysis (label or laboratory analysis of chemical composition), the nutritional composition of the products (energy, carbohydrates, sugars, protein, dietary fiber, total fat, saturated fat, sodium, iron, zinc, and vitamin B12). When available, the main ingredients used in the studied products were collected. The complete table with all collected results is available in Table S1 (Supplementary File). Different meat substitutes were grouped into different categories to evaluate the nutritional composition better. The categories and their components are listed in Table 1.

Table 1. Developed categories and their respective components.

Burgers	*Bovine meat burgers, "beef" burgers, red meat burgers*
Meat Balls	*Red beef minced balls*
Minced	*Bovine meat minced beef*
Pieces	*Red meat fillets, medallions, scallops*
Chicken Cutlets	*Chicken wings, chicken breast, chicken hamburgers*
Chicken Nuggets	*Breaded chicken, breaded chicken balls,*
Cold Cuts	*Hams, bologna, turkey breast*
Sausages	*Sausages, pepperoni*
Seafood	*Fish cakes, canned fish, tuna, shrimps, calamari, fish fingers, fish sticks, salmon, caviar, and fillet*
Cutlets	*Bovine meat cutlets*
Others	*"Vegan Roast," "Bacon-Style Rashers," and "Polony."*
Schnitzel	*German chicken schnitzel*
Various	*Meat substitutes without discrimination about the category of the product.*

The collected data were synthesized in tables using Microsoft Excel® software (Santa Monica, CA, USA, 2022). Calibration exercises were performed with the designated reviewers (B.R., M.L.T., and D.d.C.M.) to ensure the consistency of the information collected.

2.6. Data Classification and Statistical Analysis

The nutritional composition of the collected meat substitutes from included studies was categorized in grams (g) for carbohydrates, protein, dietary fiber, total fat, and saturated fat. Iron and zinc were collected in milligrams (mg) and vitamin B12 in micrograms (mcg). In studies where energy was described as kilojoules (Kj), their respective values were converted to kilocalories (Kcal), using the conversion factor of 4,184 (1 Kcal = 4184 Kj). In products where only the salt (g) content was available, its value was converted to sodium (mg), considering each gram of salt respective to 400 mg of sodium.

The median, maximum, and minimum values of the nutritional composition of meat substitutes were calculated. For comparison purposes, animal-based equivalent nutritional data was collected from the USDA food composition table [14]. The median, maximum, and minimum values of the available products for each corresponding category of vegan products were also calculated. Microsoft Excel® software (Santa Monica, CA, USA, 2022) was used in this stage.

A scatterplot matrix was generated based on the nutritional values collected for each product category. For graphical visualization, a word cloud was generated based on the frequencies of the implemented ingredients on included samples, given that higher frequencies are represented with more prominent words [15]

3. Results

In all electronic databases, we identified 654 articles. We did not find a registered patent for meat substitutes. In Phase 1, we selected 13 articles for their potential interest. In Phase 2, two articles were excluded for not meeting the specified criteria. Our experts did not include additional articles. Therefore, 11 articles were eligible for a complete reading.

All of these met the eligibility criteria, and all the included studies were published between 2019 and 2022.

3.1. Studies General Characteristics

A total of 10 countries published studies regarding the nutritional value of meat substitutes around the world: Denmark [16] (n = 1; 9.09%); USA [17,18] (n = 2; 18.18%); Spain [19] (n = 1; 9.09%); Latvia [20] (n = 1; 9.09%); Italy [21] (n = 1; 9.09%); Brazil [22] (n = 1; 9.09%); Australia [23] (n = 1; 9.09%); Sweden [24] (n = 1; 9.09%); UK [25] (n = 1; 9.09%) and Norway [26] (n = 1; 9.09%).

From all included studies, 64% (n = 7) studied only the nutritional composition of meat substitutes [16–19,24–26]. The remaining four studies (36%) analyzed nutrients and ingredients [20–23]. Only one study [16] performed chemical analysis to obtain the nutritional value of analyzed meat substitutes. The remaining studies (n = 10; 91%) utilized food labels as their information source.

3.2. Meat Substitutes Samples Characteristics

Regarding the categories of most frequently included meat substitutes, 54.54% (n = 6) of the studies included "burgers" in their samples [18,21–25]; 54.54% (n = 6) of the studies included "minced" [16,17,22–25]; 45.45% (n = 5) of the studies included "sausages" [16,22–25]; 36.36% (n = 4) of the studies included "meat balls" [16,21,24,25]; and "cold cuts" [16,21,22,24].

In lesser frequency, 27.27% (n = 3) analyzed "seafood" [19,22,23], "chicken cutlets" [22,23,25], and "Chicken nuggets" [22,24,25]; 18.18% (n = 2) of the studies evaluated "pieces" [16,24] and "various" [20,26].

The categories "Cutlets", "Others" and "Schnitzel" were present in only one study each [21,23,24]. The collected nutritional composition for studied meat substitutes and their respective medians, maximum and minimum values are in Table 2. Table 2 also presents the nutritional composition of animal-based counterparts. The complete composition of the analyzed meat substitutes of the included studies, by category of sample, is available in Table S2 (Supplementary File).

Regarding meat substitutes and animal-based meat, higher energy values were found among the samples of "Chicken nuggets". In contrast, in the meat substitute groups, lower values were present in the "Minced" category, while in the animal protein, lower values were found in "Pieces" (Table 2). Regarding the carbohydrate concentration in meat substitutes, higher values were shown in the "Seafood" category, whereas in "Cold cuts", the values for this nutrient are the lowest (Table 2). In animal-based protein products, higher values were found among the "Chicken Nuggets" samples.

In the vegan meat substitutes, the highest values for sugar were found among the "Others" samples. At the same time, categories such as "Chicken cutlets" and "Chicken nuggets" presented less than 1 g of sugar among all samples. Considering animal-protein equivalents, only "Meatballs" presented some amount of sugar.

The protein concentration was higher among the plant-based meat substitutes "Pieces" category, and the samples in "Seafood" presented the lowest content for this nutrient. In the animal protein group, samples belonging to the "Cutlets" category presented the highest protein concentration. Dietary fiber was most present in samples of the "Chicken cutlets" category, while most samples of "Seafood" substitutes did not present dietary fiber. Total and saturated fats were more present in samples of the "Various" category, while "Cold cuts" showed the lowest values. The total content of dietary fiber was shallow among animal-based meats, with only samples from "Meat balls", "Chicken nuggets" and "Schnitzel" containing this compound in their composition.

Table 2. Nutritional composition of meat products and their vegan substitutes with their medians, maximum and minimum values in 100 g of the product.

Type of Product	Energy (Kcal)	Carbohydrates (g)	Sugars (g)	Protein (g)	Dietary Fiber (g)	Total fat (g)	Saturated Fat (g)	Sodium (mg)	Iron (mg)	Zinc (mg)	Vitamin B12 (mcg)
Vegan Burgers	196 (216–175)	11.13 (18.22–0)	0.94 (3.4–0)	13.15 (18.21–9.6)	4.45 (5.6–3.8)	9.17 (13–7.2)	1.6 (3.2–0)	410 (440–372)	0.039 (3.6–0)	0 (0)	0 (0)
Meat Burgers	259 (281, 189)	0 (0)	0 (0)	17.6 (18.6, 14)	0 (0)	20 (22, 16)	12 (15, 8)	93 (113, 21)	1.69 (2.83, 0.67)	2 (3,1)	2.5 (3, 0.67)
Vegan Meat Balls	187 (211–171)	10.32(14.6–0)	1.15 (1.8–0)	13.75 (14.8–11.4)	5 (7.7–4.2)	9.8 (11.35–8.4)	0.55 (1.4–0)	430 (440–0)	0 (2.1)	0 (0)	0 (0.38)
Meat Balls	235 (301, 211)	8.24 (11, 2.8)	3.53 (4.0, 1.1)	16.5 (17, 15)	2.4 (2.5, 1.3)	15.3 (19, 11.2)	8 (9, 4)	682 (711, 233)	2.1 (3.1, 1.1)	2.3 (2.6, 0.88)	2.2 (3.5, 0.8)
Vegan Minced	170 (230–109)	8.95 (12.91–0)	0.2 (1.9–0)	14.9 (20.8–12.6)	5.68 (14–2.5)	5.85 (14–2.5)	0.65 (3.01–0)	272.50 (572.96–0)	0 (10)	0 (0.7)	0 (0)
Minced	183 (296, 112)	0 (0)	0 (0)	19 (22, 13)	0 (0)	8 (12, 5)	6 (10, 3)	119 (221, 45)	2.3 (2.9, 1)	3 (3.4, 0.64)	2.4 (2.9, 0.87)
Vegan Pieces	171 (198–136)	6.4 (8.4–5.3)	0.7 (1.1–0.2)	20 (28–16.05)	5 (8.1–2.3)	5.7 (7.2–2.8)	0 (0)	0 (445)	0	0 (3)	0
Pieces	125 (180, 88)	0 (1, 0)	0 (0)	24 (28, 15)	0 (0)	16 (21, 10)	10 (12, 2)	244 (321, 88)	2.2 (3, 1)	3.8 (4.4, 0.88)	2 (2.4, 0.66)
Vegan Chicken Cutlets	180 (201–161)	9.48 (12.6–0)	0 (0)	18.47 (21.77–13.4)	5.84 (6.79–4.7)	7.49 (9.4–5.17)	1.2 (5.04–0.63)	483.33 (520–372.38)	0 (4.8)	0 (0)	0 (0)
Chicken Cutlets	184 (211, 147)	0 (0)	0	24 (25, 18)	0 (0)	9 (10, 5.6)	4 (6, 3)	98 (112, 33)	1.09 (2, 0.88)	2.07 (3.23, 1.66)	0.38 (0.5, 0)
Vegan Chicken Nuggets	217 (233–216)	10 (17.38–0)	0 (1.1)	13.2 (16–12.97)	5.1 (5.3–4.32)	10.7 (11–10)	1.28 (1.3–0)	480 (499.62–420)	0 (2.1)	0	0 (0.38)
Chicken Nuggets	326 (411, 281)	14.3 (15, 9.1)	0 (0)	16.5 (18.1, 12)	1 (1, 0)	22.6 (24, 18)	16 (17, 14)	708 (881, 637)	0.62 (0.8, 0.55)	0.61 (0.9, 0.55)	0.33 (0.38, 0.21)
Vegan Cold Cuts	173 (251–142)	5.85 (17.5–4.1)	1.1 (5.9–0)	9.5 (19.64–3.1)	2.6 (5.5–2.1)	10.42 (14.2–4.6)	0 (1.73)	210 (840–0)	0 (0)	0 (0)	0 (0)
Cold Cuts	221 (289, 194)	0 (1.4, 0)	0 (0)	16.5 (19, 10)	0 (0)	16.7 (17, 14.6)	14 (18, 9.5)	1190 (1300, 685)	0.83 (0.9, 0.5)	1.94 (2.3, 1.77)	0.92 (1.4, 0.66)
Vegan Sausages	182 (212–136)	7.8 (11.4–0)	1.15 (2.2–0)	13.2 (16–12)	4.90 (6.9–4.2)	9.925 (15.4–7.9)	0.865 (2.6–0)	493.50 (572–0)	0 (3.4)	0 (0)	0 (1.25)
Sausages	309 (401, 299)	0.94 (1.4, 0.2)	0.24 (0.24, 0)	12 (14.1, 9.3)	0 (0)	28.2 (30, 21.1)	19 (21, 10)	827 (900, 582)	0.59 (1, 0.33)	1.31 (1.9, 0.76)	0.66 (0.71, 0.46)
Vegan Seafood	194 (243–13)	13.83 (25.35–1)	0.8 (3.3–0)	8.9 (14.9–1)	0 (6.41–0)	8.9 (11.75–0.75)	1.1 (2.63–0)	420 (1360–136)	0 (0)	0 (0)	0 (0)
Seafood	101 (214, 87)	0.2 (0.3, 0)	0 (0)	24 (26, 12)	0 (0)	14 (18, 0.28)	9 (10, 4,8)	111 (138, 47)	0.51 (1.1, 0.23)	1.64 (1.8, 0.7)	0.2 (0.3, 0)
Vegan Cutlets	196 *	15.7 *	0.9 *	10.1 *	3.5 *	9.4 *	1.2 *	420 *	0 *	0 *	0 *
Cutlets	151 (183, 99)	0 (0)	0 (0)	31.9 (35, 19)	0 (0)	4.64 (4.9, 2.63)	1.6 (2, 0.5)	88 (100, 65)	1.39 (1.8, 0)	3.29 (4, 1.1)	2.72 (3.1, 0.88)
Vegan Others	185 *	13 *	3.2 *	14.5 *	4.9 *	7.9 *	1.6 *	568 *	3.2 *	0 *	0 *
Others	233 (311, 189)	0 (0)	0 (0)	15.3 (18, 9)	0 (0)	16.3 (18, 14.3)	3.8 (4.4, 1)	724 (800, 63)	2.06 (2.88, 0.91)	6.08 (7, 4)	2.38 (3, 1,4)
Vegan Schinitzel	196 *	11 *	1.2 *	17 *	5.5 *	11 *	0 *	440 *	2.1 *	0 *	0.38 *
Schinitzel	211 (284, 93)	6 (8, 4)	0 (0)	17 (19, 11)	0.8 (1.1, 0.6)	14.75 (16, 10)	2.8 (3.1, 2)	500 (550, 480)	4.4 (4.8, 3)	3 (3, 0)	1.6 (2, 1,13)
Vegan Various	214 (228–201)	7.95 (8.4–7.5)	1.45 (1.9–1)	17.7 (22.4–13)	1.8 (3.6–0)	10.75 (11.3–10.2)	1.65 (2.2–1.1)	900 (1200–600)	0 (0)	0 (0)	0 (0)
Various	380 (488, 212)	2 (3, 1)	0 (0)	26 (32, 16)	0 (0)	18 (22, 9.4)	3.6 (5.2, 2.8)	589 (630, 86)	4.8 (5.4, 1.7)	3.33 (5.6, 1.45)	2 (2.88, 0.75)

* Only one study included this category of product; “Vegan Roast,” “Bacon-Style Rashers,” and “Polony.”; Meat substitutes without discrimination about the category of the product.

Higher values were found in the "Various" samples regarding sodium content, but not all studies provided sodium values for their included samples. In animal-based products, the highest concentration of sodium was found among samples from the "Cold cuts" category. Furthermore, most studies did not analyze iron, zinc, and vitamin B12, since these nutrients are not mandatory on food labels.

A scatterplot related to the proportion of analyzed pairs of nutrients present in each meat substitute for 100 g of the product is available in Figure 2.

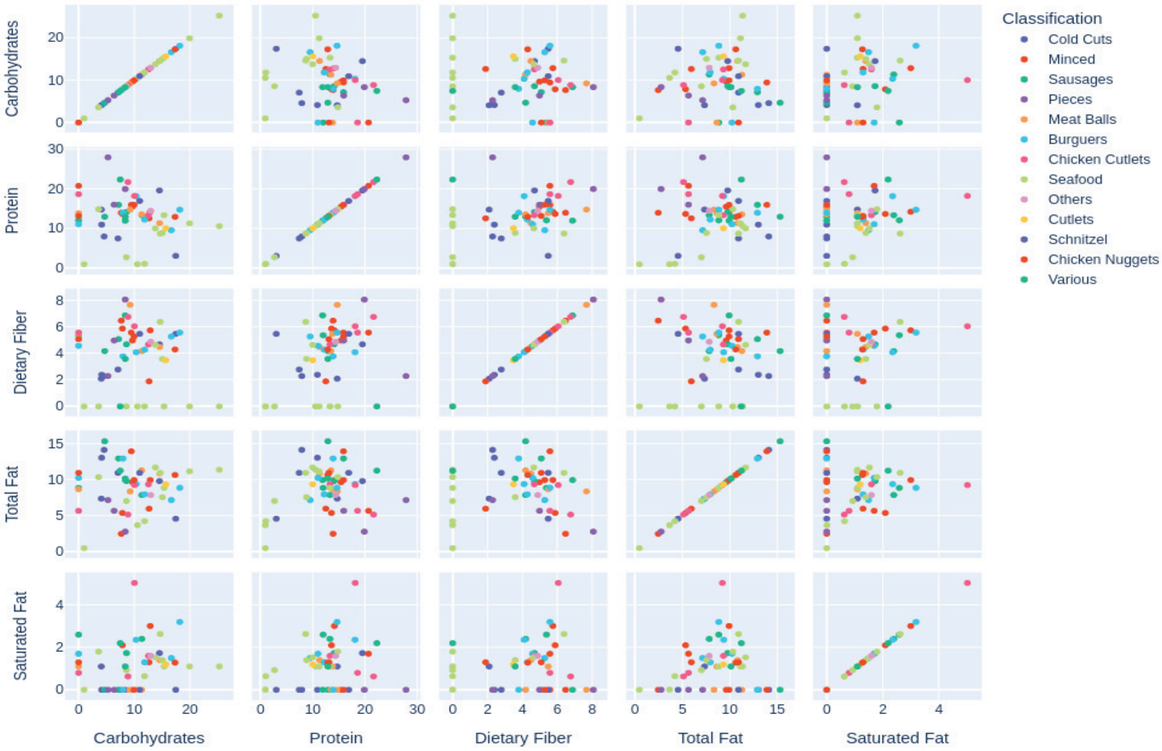

Figure 2. Scatterplot exposing the proportions for pairs of analyzed nutrients for each meat substitute category. Numbers' units are represented in g/100 g.

Regarding the proportion of carbohydrates and protein, "Seafood" presents more carbohydrates concerning its protein content, whereas "Pieces" present more protein than carbohydrates. As for the proportion of carbohydrates and dietary fiber, "Seafood" presented the lowest values, while "Pieces" presented the highest values. The proportion of carbohydrates and total fat is higher in "Seafood," with more carbohydrates than total fat content. In "Various" and "Pieces", the total fat content is higher in proportion to its carbohydrate concentration. In the "Chicken cutlets" category, the saturated fat ratio is higher than its carbohydrates, while the remaining categories tend to present less saturated fat in proportion to carbohydrates.

Regarding the proportion of protein to carbohydrates, the "Seafood" category presented more carbohydrates than protein, while "Various", "Chicken nuggets" and "Others" presented more protein than carbohydrates. Considering protein and dietary fiber, "Seafood" presented no values regarding its dietary fiber content. Therefore, this category presented more protein than dietary fiber, while the categories "Pieces" and "Cutlets" presented higher concentrations of dietary fiber than protein. The "Various" category presented the highest values for the proportion of saturated fat to protein, while "Seafood" and "Chicken cutlets" presented the lowest. "Chicken cutlets" presented the highest proportion of saturated fat compared to its protein content, while the other categories had lower values for fat.

"Various" and "Chicken nuggets" categories presented lower fiber proportions than total fat. On the other hand, most samples of "Pieces" presented a higher proportion of dietary fiber than their total fat content. A similar distribution between the proportions of saturated fat and dietary fiber was found in all samples, with all having more dietary fiber than saturated fat, with the exception of one sample from the group of "Chicken Cutlets".

Four studies analyzed the ingredients used as meat substitutes [20–23] (Table 3). A word cloud generated with the frequencies of the mentioned ingredients is available in Figure 3.

Table 3. Main ingredients in meat substitutes available in the included studies.

Authors	Included Categories	Main Sources of Protein	Main Sources of Fat	Main Food Additives
Curtain et al. [23]	Burgers, Sausages, Minced, Chicken, Cutlets, Seafood, Others,	Soy Protein, pea protein, soybeans, hydrolyzed vegetable protein, mycopr-otein, almonds.	Vegetable oil, canola oil, sunflower oil, sunflower kernels, rice bran oil, coconut oil, flax seed meal, cocoa butter, peanuts	N/A
D'Alessandro et al. [21]	Burgers, Cold Cuts, Cutlets, Meat Balls	Soy, Soy derivatives, Rice, Oats and Buckwheat	Seed Oil and Olive Oil	Modified Starch, Citric Acid, Flavouring and Coloring
Mariseva et al. [20]	Various	Soy, Wheat, Starch (Potato and Corn), Pulses, and Oats	N/A	Gellan gum, locust bean gum, guar gum, carrageenan, xanthan gum, methylcellulose, mono and diglycerides of fatty acids, mono and di acetyl tartaric acid, esters of mono and diglycerides, calcium stearoyl lactate
Romão et al. [22]	Burgers, Minced, Chicken Nuggets, Chicken Cutlets, Chicken Cutlets, Seafood, Sausages, Cold Cuts	Soy, Gluten (Wheat), Pea Protein, Isolated Soy, and Pea Proteins	Unspecified vegetal fat, Soy Oil, Sunflower Oil, Cottonseed Oil, Coconut Fat, Coconut Oil	Methylcellulose, Xanthan Gum, Gellan Gum, Carrag-eenan Gum

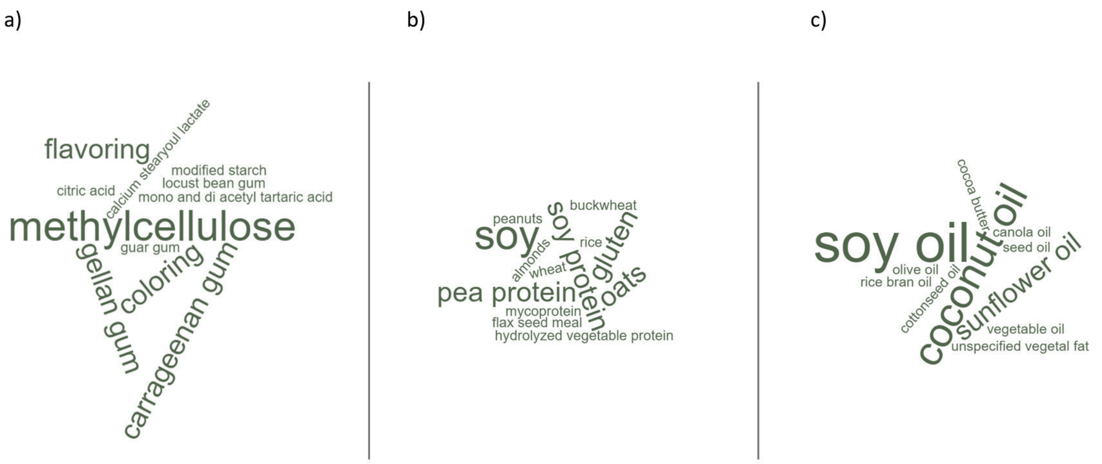

Figure 3. Word cloud generated with the frequencies of implemented ingredients in the included meat substitutes. Higher frequencies are represented with more prominent words in the cloud. (**a**) Food additives; (**b**) Protein sources; (**c**) Fat Sources.

Overall, soy-based ingredients (soybeans, soy protein, isolated soy protein) were the most implemented protein sources in the included meat substitutes, followed by pea-based ingredients (pea protein and peas). Wheat was also present as a protein source in the form of gluten. Pulses are, in general, more frequent than grains.

Thickeners and stabilizers such as methylcellulose and xanthan, gellan, carrageenan, carrageenan, and guar gums were the most frequent additives. As for the fat sources, soy oil was the most used, followed by sunflower, cottonseed, and coconut oils. However, it is important to note that the authors did not describe the ingredients in each meat substitute category. Therefore, it is not possible to provide further information on this subject.

4. Discussion

Regarding the included studies, most studies were performed in the USA [17,18]. In this country, the number of adepts of vegetarianism is around 5% of the population, and the number of vegans is about 3% [27]. Furthermore, its plant-based products market is one of the most successful in the world, with a gross revenue of USD 800 Million and a growth projection of almost 25% in size by 2025 [28]. Only one study was produced by researchers in other countries (Denmark, Brazil, Spain, Italy, Australia, Sweden, UK and Norway). In these countries, the prevalence of vegetarianism ranges from 1.4% in Spain to 4% in Brazil [29,30].

Although different prevalence levels of vegetarianism were found within these countries, a common point regarding them is the growth of the plant-based dedicated market. In average, almost 50 million USD were invested in all the cited countries, highlighting the growth of these markets and justifying the presence of the analyzed samples in the included studies [30].

Most studies analyzed only the nutritional composition of food labels. Regarding this analysis, it is important to note that food label laws worldwide present tolerance for discrepancies regarding the actual nutritional value and the values described in food labels [31]. Therefore, a possible limitation regarding the described values is noted [16–19,24–26]. In addition, only four of the included studies analyzed the utilized ingredients in meat substitutes [20–23]. For better evaluation of the meat substitutes' overall quality, it is necessary to explore the correspondence of the found nutritional value and the implemented ingredients since, in these products, a large variety of ingredients are commonly used [32].

According to reports, an estimated 720 brands are involved in the meat substitutes market, with around 3000 products already commercialized [33]. In the present study, 1625 samples were collected from the studies, highlighting the need for more studies evaluating the nutritional composition of meat substitutes commercialized worldwide. Furthermore, studies on plant-based meat substitutes were performed in 10 countries, representing only 10.97% of the globe.

In this sense, it is also essential to highlight questions about the production of vegan meat substitutes. Exporting products is one of the alternatives practiced by countries whose industries are not yet fully developed [33]. However, when observing the sustainable development objectives advocated by the United Nations Organization, the local production of inputs is a goal to be achieved [34]. Thus, given the premise that meat substitutes should be more sustainable alternatives than beef, industries in these other countries must be developed to achieve this objective fully.

4.1. Energy

In traditional diets, meat concentrates the highest number of calories in large meals such as lunch and dinner [35]. Considering the contribution of these meals as 30–40% of an individual's total daily energy value, meat typically represents up to 70% of all calories in these meals (250–400 kcal) [36,37]. Different types of meat (Table 2) present on average between 65 and 80% of water, 16 to 22% of proteins, 3 to 13% of fats, and few amounts of vitamins and minerals [38]. In this sense, the high amount of protein and fat contributes to its total energy value [38].

It is commonly observed that plant-based meat substitutes are made from a combination of legumes and cereals, naturally containing more carbohydrates than fats in their composition [22,39]. Thus, meat substitutes tend to have lower energy values than their animal counterparts [22,26]. This characteristic agrees with the characteristics of plant-based diets, whose caloric value tends to be reduced compared to diets with a more ostensible presence of meat, such as the Western diet [40]. In the present review, the values found in the item "Energy" ranged between 170 and 217 kcal, lower than those traditionally provided by meat. Therefore, using meat substitutes can constitute a viable alternative for an energetic reduction in diets, contributing to weight loss and prevention of chronic non-communicable diseases (NCD) such as obesity, type 2 diabetes mellitus, and coronary heart disease [41,42].

Furthermore, it is important to highlight that lower energy values were found in categories whose objective is to mimic in natura meats (Minced, pieces, cold cuts), constituting interesting options for substitution in meals, at least from the energy value point of view. In categories such as "Burgers" and "Chicken nuggets", higher amounts of calories were found, accordingly to their animal counterparts, constituting plant-based versions of "treats" and "junk foods".

4.2. Carbohydrates and Sugars

Carbohydrates are the most common nutrients in vegetables since they are usually present in their composition of saccharides of the most diverse sizes and complexities, such as starch and polyols [43]. Within the context of meat substitutes, the most frequent ingredients (legumes and cereals) are rich in carbohydrates, fluctuating between 50% and 85% of their proximate composition [38,44]. Therefore, it is expected that meat substitutes present higher values of carbohydrates in comparison with meat, as confirmed in this review, with values between 5.85% and 13.83%. A higher proportion of carbohydrates in vegan products compared with other present nutrients was also found, thus, reinforcing this tendency even more.

In four of the included studies [18,22,23,26], a comparison was made between the carbohydrate values of meat substitutes and their respective animal counterparts. In general, they pointed to significantly higher concentrations of carbohydrates in the plant-based versions, with values ranging from 7–15 g/100 g in plant-based meat substitutes, compared with meat, with 0–3 g/100 g [18,22,23,26]. These values are close to those found by other studies included in this review, demonstrating a higher concentration of carbohydrates in plant-based meat substitutes.

However, despite the greater amount of carbohydrates, this characteristic may not necessarily negatively influence the quality of diets that include meat substitutes. In a study where the effects of a plant-based diet rich in carbohydrates originating from whole grains and legumes and reduced in fat were analyzed, the authors mentioned the effectiveness of this diet in weight loss and better quality of life [43]. Therefore, despite the greater amount of carbohydrates in meat substitutes, since they come from legumes and cereals, the carbohydrate content would not be excessive in a diet in which meat substitutes are included, based on this ingredient alone [43].

The "Seafood" category presented the highest carbohydrate values among the analyzed categories. This is probably to obtain a gelatinous texture (like fish), given the inherent characteristic of carbohydrates to form stable gels with water and heating, in a physicochemical process called gelatinization [19,45]. The "Cold cuts" category had the lowest amount of carbohydrates. This category consists of substitutes for meats used in sandwiches and snacks, such as hams, salami, and other foods from the same class, whose nature is more protein-based and usually presents fewer carbohydrate amounts [16,21,22,24].

Sugars were present in smaller amounts in the samples analyzed by the studies. Commonly in plant-based substitutes, sugars are found most prominently in dairy substitutes, as they act as stabilizers and thickeners and try to mimic the characteristic sweetness of another disaccharide, lactose, which is present in dairy products [46]. Naturally, meats have negligible concentrations of mono and disaccharides and are not foods with a sweet taste in general. In this sense, the low use of this ingredient in plant-based meat substitutes is expected [38]. The category with the highest amount of sugars was "Seafood", an ingredient possibly used to obtain some technical characteristic unrelated to flavor. However, the studies did not explore this ingredient and its respective industrial characteristics [19,22,23].

4.3. Dietary Fiber

Dietary fibers are provided exclusively from foods of plant origin, and their applications are manifold from the point of view of health maintenance and technological improvement of meat substitutes [22]. In the context of health aspects, dietary fibers contribute in maintaining health by favoring good intestinal functioning and collaborating in maintaining healthy intestinal microbiota [47,48]. In addition, during the digestive process, soluble and insoluble dietary fibers in the intestinal lumen form bulky and viscous molecular complexes that reduce the rate of absorption of carbohydrates, saturated fats, and cholesterol, thus helping to maintain a healthy weight and prevent NCD [47,48].

In general, studies describe that the dietary pattern most practiced in Western countries consists of the consumption of industrialized foods of animal origin, fattier and with a lower amount of dietary fiber [49,50] In this sense, this dietary pattern is associated not only with increases in the prevalence of NCDs, but it also causes changes in the intestinal microbiota, permitting the disordered growth of gram-positive bacteria, especially those of the *Clostridium* and *Proteobacteria* class, whose studies point to a relationship with brain health, among other negative changes [49,50].

Meat commonly does not have dietary fiber in its composition, contrary to what was evidenced by the meat substitutes analyzed in this review, whose values ranged from 0 to 5.84 g/100 g. In animal-based meats with dietary fiber (Chicken nuggets and Schinitzel), this value is due to the addition of cereals to bread the meats. Current dietary reference intakes (DRIs) recommend daily fiber consumption of 30–35 g for men and 25–32 g for adult women. In this way, a single 100 g serving of meat substitute (Chicken cutlets) can contribute about 16.68% of the recommended daily value [51] Thus, meat substitutes may be interesting alternatives for increasing dietary fiber consumption, especially in Western diets, where fiber consumption is reduced.

Regarding the technological and sensorial characteristics of the fibers, they can retain water in products in which they are present, favoring characteristics such as texture and resistance to breakage, characteristics also present in meats [47]. However, the excessive use of dietary fibers in these products results in negative characteristics in the same way, resulting in more rigid products requiring excessive chewing [22]. Therefore, even based on plant-based matrices, which could provide even greater quantities than those found, the excessive use of fiber in meat substitutes would impair their palatability and consequently, their commercialization.

Furthermore, dietary fibers' characteristic hygroscopicity also influences cooking oil retention. Thus, in the case of raw or pre-cooked meat substitutes, which require the use of cooking methods such as grilling or frying, this may result in an amount of fat even higher than described on the labels.

4.4. Protein

In the Western diet, proteins are mainly supplied by foods of animal origin, in greater quantity by meats, followed by eggs and dairy products [21]. In addition to cultural and environmental subjects, it is important to highlight that protein stands out among the primary nutrients provided by meat, reaching almost 22% of its composition [52]. On the other hand, plant-based products commonly have lower amounts of protein, with values ranging between 0.3 and 11%, in the case of legumes, which contain the highest amount of protein [53]. In this sense, protein intake is one of the main concerns in eating meatless diets, demanding attention from health professionals and the elaboration of public health policies [54]. Meat substitutes are usually made from legumes, especially soy, peas, chickpeas, beans, and some cereals such as wheat (gluten) and oats [20–23]. As evidenced by the studies included in this review, soy and its derivatives constituted the main protein source in meat substitutes (Figure 3).

Soybean stands out among legumes for several reasons, firstly for its economic value. Currently, the soy market has an export value estimated at around 27.39 billion dollars. Its production totals about 53 million metric tons on the planet, and it is one of the primary commodities exported by countries such as China, Mexico, and the European Union [55]. In addition, this legume stands out for its protein value (about 38% of its proximate composition) [56]. However, it is essential to note that during the cooking process, soybeans absorb water and swell to around 2–3 times their original size [56]. In this sense, its nutritional density is diluted; therefore, larger portions are needed to obtain protein values comparable to what is provided to animal-based meat in 100 g. It is noted that multiple technologies can be used for better technological and sensory use of this legume. One of the most used technological processes in the soy industry is hydrostatic extrusion, which consists of an assisted grinding and friction heating process, which results in one of the most used products in the meat substitute industry, textured soy protein [56,57].

Textured soy protein is an ingredient whose texture and appearance resemble meat, and its physicochemical structure and capability of absorbing liquids and flavors enable the use of diverse ingredients for flavoring, including food additives whose composition is intended to mimic the flavor, aroma, and color of the meat [22,57]. Nevertheless, the defatted, dehydrated, and isolated soy protein extract also provides interesting sensory and technological characteristics in manufacturing meat substitutes [57]. The same technologies can be used in other legumes, such as peas, which appear as protein alternatives for the formulation of soy-free meat substitutes, as part of the population avoids soy due to health problems or personal preferences [58,59]. Wheat gluten is also one of the most used ingredients in meat substitutes, given its protein composition with viscoelastic capacities that simultaneously contribute to the nutritional composition of these products and to sensory and physicochemical characteristics (elasticity, tenacity and resistance) [60,61].

Since the meat substitutes analyzed are mainly composed of legumes and gluten, their nutritional composition is proportionally richer in protein in an attempt to fully replace meat of animal origin.

In the present review, the median values referring to the protein quantity of meat substitutes range between 8.9 g/100 g (Seafood) and 20 g/100 g (Pieces). However, analyzing the mean values of the same nutrient present in beef, the average value is 25 g/100 g [62], demonstrating that the protein value offered by meat substitutes is still lower than that usually offered by meat, especially in comparison with their animal-based equivalents (Table 2). In the case of plant-based substitutes for chicken, the median value (18.77 g/100 g, "Chicken Cutlets") is also lower than that offered by its animal-derived counterpart (20 g/100 g), reinforcing the need to develop plant-based alternatives with a higher amount of protein [62]. The same analysis is also verified when analyzing the other included categories.

Another issue involving the use of plant proteins as substitutes for their animal counterparts is their bioavailability. There are several methodologies to assess protein quality, such as the PDCAAs (protein digestibility-corrected amino acid scores) and the DIAAS (digestible indispensable amino acid scores), the latter being the most recent and most suitable for analyzing the bioavailability of plant proteins [63,64]. In general, plant proteins have a reduced amount of digestible essential amino acids, especially compared to highly digestible animal proteins, such as ovalbumin in eggs and whey proteins from cow's milk [63]. However, this limitation can be circumvented by combining two or more plant proteins, as they have different digestible essential amino acid values. Some have greater amounts than others in specific amino acids, such as branched-chain amino acids [63]. In this sense, since many meat substitutes combine at least one legume and one cereal, there is a possibility that they offer a better-quality protein combination when compared to portions of isolated legumes. However, more in vivo studies are needed to confirm this hypothesis.

4.5. Total and Saturated Fat

The total and saturated fats levels constitute one of the biggest problems concerning meat consumption. Depending on the type of cut used and the breed and diet of the animal, the meat fat content can vary between 1 and 28 g/100 g [35,37]. Values for fat concentration may also vary according to the implemented cooking method.

Currently, the DRIs do not indicate maximum values of total fat consumption by age group. However, it is known that their energy contribution should be between 20–35% of the daily value ingested [51,65]. In this sense, it appears that a portion of the category with the highest total fat content (Pieces) contributes about 4.8% of the total recommended energy value for this nutrient in a diet of 2000 kcal (10.75 g/100 g, 96.75 kcal). In comparison with a typical cut of beef, it appears that it contributes 4.9% of the recommended daily intake (10.9 g/100 g, 98 kcal). This value is close to the meat substitute with a higher total fat content [62]. However, it is important to consider the variation in fat contents between the different categories of meat substitutes, which, as well as cuts of meat of animal origin, also have alternatives with lower fat contents.

Another important point to consider is the sources of fat used in meat substitutes. The verified results show that the meat substitutes mostly used vegetable oils, such as soybean, sunflower, olive, and cottonseed oils [20–23]. Concerning the composition of these oils, they have primarily poly and mono-unsaturated fatty acids, whose metabolic effect is different from that of saturated fat, found in greater amounts in the meat [66,67].

As sources of omega-6 fatty acids, these oils mainly contribute to several organic functions, such as the structure and fluidity of the plasma membrane of human body cells [68,69] However, these same fatty acids, when consumed in excess, act in the synthesis of pro-inflammatory cytokines, in addition to data indicating that the world consumption of omega-6 fatty acids is excessive, given their presence both at home and in industrialized foods of plant and animal origin [68,69]. In this sense, even though they are composed of vegetable oils, the fat contents found in meat substitutes indicate that they should not be consumed excessively.

Another issue regarding the fat content of meat substitutes is the possible absence of omega-3 fatty acids, specifically in the "Seafood" category. Eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) are fatty acids from the class of omega-3 found in animal-based seafood [70]. As for vegetable sources, omega-3 is found not as EPA or DHA, but as Alpha-linoleic acid (ALA), which can be converted into both EPA and DHA through a metabolic pathway. In this sense, vegetable sources such as flaxseeds, chia seeds, and seaweed are known sources of ALA, so it is preferable that these ingredients are implemented in plant-based seafood to provide comparable amounts of omega-3 fatty acids [70,71]. Furthermore, a thorough analysis of the implemented ingredients in plant-based seafood substitutes is needed to quantify the amounts of ALA.

Regarding the amount of saturated fat presented by the analyzed meat substitutes, the maximum value of 1.65 g/100 g was found in the "Various" category, with emphasis on the "Burger" categories (1.6 g/100 g) and "Chicken nugget" (1.28 g/100 g). In meat substitutes, saturated fat sources typically consist of fats from coconut and palm, plant sources that behave similarly to those of animal origin [22,23]. However, compared to a typical cut of beef, which has between 3 to 9 g of saturated fat per 100 g serving, meat substitutes still have lower values, thus constituting better options [62].

In addition to the characteristics related to the nutritional quality of foods, fat also contributes to products' sensory characteristics, such as lubricity, palatability, aftertaste and shelf life. All characteristics are desirable for food marketing and acceptance [72]. Therefore, despite the lower amount of natural fat in products of plant origin, the manufacture of fat-free meat substitutes is unfeasible, as this would affect their sensory characteristics, making these products undesirable.

4.6. Sodium

Excessive sodium consumption is one of the biggest public health problems today, mainly given its ostensible use in industrialized products, as in the case with plant-based meat substitutes [72,73]. Naturally, meat has reduced sodium content in its composition. In addition, it has nitrogenous compounds responsible for flavor development and collaboration in flavor development chemical reactions, such as the Maillard reaction [74]. The biggest problem lies in processed meats, such as hamburgers, ham and sausages, which have high sodium contents, prolonging their shelf life and palatability [72,73].

The tendency to use sodium is verified in most meat substitutes, possibly in an attempt to use flavor, given the absence of natural compounds related to this aspect in products of plant origin [11,24,41].

In this review, sodium values between 210 mg (Cold cuts) and 900 mg (Various) were found, thus demonstrating a trend toward excess sodium in meat substitutes.

In the studies where implemented ingredients were analyzed, it is important to note that salt (or sodium) was absent. Probably, salt was added only on the nutritional label, in the form of salt or sodium, or the analysis was not performed. There is also a possibility that some of these products are commercialized as salt-free options for further seasoning. In this manner, a possible limitation regarding this absence is noted.

Currently, the World Health Organization recommends a daily intake of 2300 mg of sodium per day. A 100 g serving of some categories of meat substitutes can contribute up to 39% of the total recommended daily value [75].

Behaviors such as using natural seasonings, herbs, and sodium-free condiments can be alternatives for reducing sodium in meals, an attitude that is necessary for several diets, especially those aimed at controlling cardiovascular diseases [76,77]. Thus, in the current model of commercialization of meat substitutes, with built-in amounts of sodium, it is impossible to use strategies to formulate healthier meals, demonstrating a gap and a necessary improvement in the formulation of these products.

4.7. Iron, Zinc, and Vitamin B12

Iron is one of the minerals provided by meat and adapting the consumption of this micronutrient in meatless diets is a well-known challenge [78,79]. Traditionally, adherents of vegetarian diets tend to consume lower amounts of iron, not only because this nutrient is present in lesser amounts in plant-based foods but also because of the reduced consumption of source foods, such as dark green vegetables [79].

In addition, another problem is found in the chemical structure of the iron supplied by vegetables, whose electronic charge (+3) lacks specific intestinal receptors. The hemic iron present in meat of animal origin, in contrast, has an electronic charge is +2 and a specific intestinal transporter, favoring its metabolism [78,79].

Current DRIs recommend daily values of iron intake between 8 and 10 mg, depending on the age and gender of the person [51]. In the context of the meat substitutes analyzed, specimens of the "Minced" category presented about 10 mg of iron per 100 g of products [17], fulfilling fully or mainly with the daily need for this element. However, it is important to highlight that iron is not an element of mandatory declaration on food labels according to the legislation in force in several countries that produced the studies included in this review. Since most studies used food labels as a source of information, a limitation of this review is the lack of information on this mineral. The same problem occurs regarding zinc and vitamin B12, whose declaration is optional, and not present in most of the labels analyzed by the studies.

Regarding meat-free diets, it is important to highlight that legumes and cereals are the main sources of iron and zinc. Thus, since these ingredients are the most implemented in the analyzed meat substitutes, there is a possibility that these nutrients are present in adequate amounts. However, future studies with laboratory analysis are necessary to verify it [32,80].

Vitamin B12 is produced by microorganisms and is available for metabolization into products of animal origin from the bioaccumulation process through livestock feed [81]. In this sense, it is important to highlight that foods of animal origin are exclusive sources of this vitamin, and in the context of meat-free diets, they must be supplemented or acquired through fortified foods [81].

Given the absence of this vitamin in foods of vegetable origin, it is common practice to fortify meat substitutes with vitamin B12. However, given this information's absence in the studies, it is impossible to analyze the contribution of this fortification in meat substitutes [81].

4.8. Food Additives

Food additives are classified as substances that are not nutrients but are used in foods to improve its technical and sensory characteristics [82]. In meat substitutes, one food additive classification that stands out is flavorings.

Flavoring agents can be of natural or synthetic origin, and their purpose is to impart flavor to foods. In the case of meat substitutes, the characteristic flavor of the meat is to be mimicked [82]. For example, beef has nitrogenous bases in its composition that give it a characteristic flavor, thus requiring little additional seasoning. In the case of meat substitutes, given the absence of these compounds, the use of flavorings is necessary, given the objective of these products to simulate the traditional version of meat [22,38]. In the case of the analyzed meat substitutes, these were found in all samples that included the analysis of the ingredient in their scopes [20–23]. However, these may also be present in samples for which this analysis was not performed.

Another subject regarding the flavoring of meat substitutes is the absence of endogenous metabolic pathways that directly influence the meat's flavors. For example, postmortem phenomenon such as rigor mortis and fermentation in controlled conditions interferes with meats' pH, therefore, satisfactorily altering its flavor [83,84]. In this sense, artificial flavoring is needed to provide similar flavor in meat substitutes, or even further studies to evaluate the possibility of replicating such processes in plant-based matrices.

Hydrocolloids are also used in meat substitutes, such as methylcellulose and gums from diverse origins. Hydrocolloids consist of carbohydrate molecules of microbiological or plant origin, which can form gels that improve the texture, strength and tenacity of products in which they are present [85]. In the case of methylcellulose, it can remain in a solid state after gelatinization, and its appearance resembles fat complexes, commonly present in beef analogs [85].

From a nutritional point of view, hydrocolloids characterize substitutes for dietary fiber since, after hydration, they form complex and viscous molecular structures that can delay the absorption of carbohydrates, such as dietary fibers and fat [85,86]. Thus, its presence can be beneficial given the high value of carbohydrates present in meat substitutes.

5. Conclusions

This review evaluated the nutritional compositions of meat substitutes commercialized worldwide. Most studies used food labels as their information source, and few analyzed the nutritional composition and implemented ingredients in meat substitutes. The results showed that meat substitutes are not like meat, commonly presenting lower energy values and higher amounts of carbohydrates and dietary fiber, given their plant-based origin. Furthermore, protein values varied according to the meat substitute category, with some presenting a higher concentration than others, more specifically in substitutes for bovine meat. In meat substitutes, the proportion of carbohydrates is higher than the protein concentration in most samples except the chicken substitutes. Furthermore, meat substitutes presented similar total and saturated fat content compared to animal-based counterparts. Ingredients such as soy, pea, and wheat were the main protein sources utilized in meat substitutes, while vegetable oils were represented as their fat source. Methylcellulose, various gums, and flavorings were the most frequently used food additives.

In general, meat substitutes presented high concentrations of sodium, possibly contributing to excessive sodium intake, highlighting the need for developing sodium-free alternatives. The concentrations of Iron, Zinc, and Vitamin B12 were not described by most of the included samples, possibly because these nutrients do not require mandatory declaration on food labels, thus constituting a limitation of this study. Further studies are needed to develop meat substitutes with better nutritional compositions, fulfilling the need for equivalent substitutes for animal-based meat. In addition, studies evaluating the dietary impact of total replacement with the analyzed meat substitutes are needed to better comprehension of this subject in the long term.

A limitation of the study is related to the samples' nutritional data statistical analysis. In the preliminary statistical analysis phase of the study, the standard deviations for the nutritional values of meat substitutes were too far from the mean values, impairing our best analysis.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/foods12030448/s1, Table S1: Full data regarding the information collected in the included studies, Table S2: Full data regarding the nutritional composition of the samples of the included studies.

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Amorphophallus konjac: Sensory Profile of This Novel Alternative Flour on Gluten-Free Bread

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Abstract: This study aimed to evaluate the sensory profile of gluten-free bread with *Amorphophallus konjac* (AK) flour in different concentrations. This experimental study is divided into three steps: preparation of the gluten-free bread formulations, sensory analysis, and statistical analysis. The addition of Konjac flour in a gluten-free bread formulation was tested in different proportions, 12.5%, 25%, 37.5%, and 50% of the flour content. The checking all-that-apply (CATA) was conducted with 110 panelists; among these, 43 were consumers of gluten-free bread. Sensory analysis was conducted using a 9-point hedonic scale for color, aroma, texture, flavor, appearance, and overall acceptability. The AK flour influenced the sensory characteristics of gluten-free bread. Bread with characteristics closer to those found in bread with gluten was the one with 12.5% of konjac flour for both the acceptability analysis as the attributes raised through a detailed CATA map. The control sample is located next to features like dry appearance, dry texture and grainy, dark color, and salty. Therefore, 12.5% AK gluten-free bread is closer to the characteristics of the control sample, such as light crust color, light crumb color, soft and moist texture, cohesion, and brightness. The bread with the highest percentage of overall consumer acceptance was 12.5% konjac with 93% and 96% acceptance among consumers and non-consumers of gluten-free bread, respectively.

Keywords: check-all-that-apply (CATA); glucomannan; hedonic scale; bread; gluten-free

1. Introduction

Bread is a worldwide staple food, present in many civilizations since most antique eras, and is still largely consumed today. Its consumption revolves around 24 kg per capita/year worldwide, with evident growth trends for consumption and market value [1]. A similar tendency is noted regarding the dietary habits of adepts of a strict gluten-free diet (GFD), with bread highlighted as one of the most demanded and consumed gluten-free products [2,3]. However, gluten withdrawal is a challenge in bread formulations since texture, color, crumb, and alveoli structure are sensory and technological characteristics that rely mainly on gluten's presence and strength [4]. Thus, with gluten removal, impairments related to these characteristics are noteworthy and impact overall sensory aspects [5].

Gluten-free bread tends to present reduced volume and alveoli structure, brittle texture, light crust color, and usually, loaves present heavy, tenacious, and elastic mouthfeel [6,7]. Ingredients such as hydrocolloids, protein, and dietary fiber have been used to mimic gluten viscoelastic characteristics. However, although acceptance might be improved, the overall characteristics are still very apart from its gluten-containing counterpart [7,8].

Among the studied alternatives, *Amorphophallus konjac* (AK) is a mountain-based plant native to southern Asia and Africa, with numerous corms from which a water-soluble, non-cellulosic polysaccharide of high molecular weight is extracted [9]. Glucomannan is the AK main polysaccharide, usually applied to pharmaceuticals, cosmetics, and some food products, such as wheat noodles and bread [10,11]. AK's glucomannan flour was successfully tested as a starch- and gluten-replacer in gluten-free noodles due to its rheological and viscoelastic characteristics [12]. Because of its success in replacing wheat in noodles, some studies evaluated the AK's glucomannan as an additive to gluten-free bread [13–15].

Laignier et al. [16] tested AK flour's use in high amounts (up to 50% of flour) on gluten-free bread's nutritional and physicochemical properties. Despite the successful use of AK flour in gluten-free bread's nutritional and physicochemical aspects [16], sensory analysis was not performed on this product, and it is crucial to encourage consumption. Therefore, this study aimed to evaluate the sensory profile of gluten-free bread with *Amorphophallus konjac* flour in different concentrations.

2. Materials and Methods

This exploratory and quantitative study was performed in two steps: (I) Sample preparation, and (II) Sensory Analysis. The Check-all-that-apply test (CATA) was used since it is a rapid descriptive method that serves as a simple and effective alternative to screen the sensory attributes and drivers of liking various products [17]. In addition, we used the hedonic scale since it can measure the product's sensory perception and the intensity of its attributes [18]. Therefore, combining these two methods might result in a complete screening of the sensory profile of foods.

2.1. Sample Preparation

The samples were developed at the University of Brasilia, Federal District, Brazil, according to the formulations developed by Laignier et al. [16]. The control gluten-free bread (GFB) was composed of gluten-free flour (30% of potato starch and 70% of rice flour), sucrose (12 g/100 g of control flour basis), salt (3 g/100 g of control flour basis); water (34.5 g/100 g of control flour basis), soy oil (16.5 g/100 g of control flour basis), whole egg (29.5 g/100 g of control flour basis), and yeast (1.5 g/100 g of control flour basis). The same ingredients were used in the modified bread samples added of konjac flour in the proportion of 12.5%, 25%, 37.5%, and 50% of the gluten-free flour amount [16]. According to the supplier (SM pharmaceutical enterprises, imported by Almofariz Pharmaceuticals), AK flour was composed of 70% glucomannan konjac and obtained in three different lots (18F13-B022-034221, 18F13-B022-034226, MW20171011-1750).

The water content was adjusted due to the AK flour's capacity to absorb more water than the gluten-free flour used in control bread. Therefore, the water was used in 131%, 228%, 297%, and 406%, based on the weight of the flour basis. The formulations can be accessed in Table S1—Supplementary File. The ingredients were weighed on a 0.2 g precision scale (Ohaus®, Parsippany, NJ, USA), and the yeast was pre-activated with sucrose and warm water (38 °C) for 10 min. Rice flour, potato starch, konjac flour (in modified samples), and salt were mixed in another recipient. Afterwards, eggs, water, and oil were mixed with the dry ingredients. The activated yeast was added, and the dough was kneaded and rested for 50 min (27 °C). Afterwards, the dough went through a second kneading and modeling (40 g spheres). Finally, the samples were baked for 40 min. in a preheated (180 °C) gas oven Brastemp®-Sau Paulo, Brazil [16].

After baking, the samples were removed from the trays and cooled down in polyethylene containers. Bread samples were codified with 3-digit random numbers (Figure 1). Samples were served the same day they were baked, portioned in slices of 10 g each. They were served in disposable white plastic plates and two water glasses, one full with room temperature water and another empty for occasional disposal of samples.

Figure 1. Gluten-free bread—from left to right, control gluten-free bread; bread with the addition of 12.5% of *Amorphophallus konjac* flour; 25%; 37.5%; and 50%.

2.2. Sensory Analysis

First, the sensory descriptors for CATA were elaborated by applying the Kelly's Repertory Grid Method [19] with five expert panel members, all with 240 h minimum experience related to gluten-free products' development. None of the above experts were part of the following sensory test. Three sessions lasting 30-min each were held, and with the help of an expert panel moderator, 30 descriptors were raised by the grid method (7 for appearance—dark crust color, dry crust appearance, light crust color, light crumb color, dark crumb color, pretty, and shiny; 9 for flavor—seafood flavor, yeast flavor, unpleasant flavor, pleasant flavor, bitter, sour, sweet flavor, astringent, savory flavor; 9 for texture—moist, stiff, sticky, cohesive, rubbery, soft, compact, buttery, grainy, dry; and 5 for aroma—egg scent, fried food scent, seafood scent, yeast scent, and pleasant scent).

Bread samples were also submitted to an evaluation using a 9-point hedonic scale (1 = dislike extremely; 2 = dislike very much; 3 = dislike moderately; 4 = dislike slightly; 5 = neither like nor dislike; 6 = like slightly; 7 = like moderately; 8 = like very much; 9 = like extremely) to measure the acceptance for appearance, flavor, texture, aroma, and global acceptance [20,21]. Both CATA and acceptance tests were performed on the same day, simultaneously, starting at 9 am, in the sensory evaluation laboratory at the University of Brasilia, Brazil. The study was approved by a Brazilian Ethics Committee (CAAE: 01154818.7.0000.0030), and before the tests, participants signed a consent form. The recruitment questionnaire collected demographic information, and regular consumption of any bread and willingness to collaborate were prerequisites to participate. In the questionnaire, we also asked about the regular consumption of gluten-free bread.

Both CATA descriptors and samples' order were presented in a randomized and balanced order in the sensory forms. Samples were presented monadically. The panelists answered the forms according to their perception of the suggested descriptors' presence and the attributes' intensity.

110 untrained consumers participated for both simultaneous tests, and 43 (39%) were regular gluten-free bread consumers. Of the 110 participants, 68.18% were female, and 31.82% were male, from 18 and 59 years. Participants were recruited through invitations posted on social media. The individuals who arrived at the laboratory through the invitation to perform the sensory test and met the inclusion criteria were included in the sample without gender balance.

2.3. Statistic Analysis

Two groups were formed to overview the differences between the perception of all consumers—one with all the consumers (Group I; $n = 110$) and another with only regular consumers of gluten-free bread (Group II; $n = 43$). The acceptance percentage was obtained from the scores given by the panelists in the acceptance test. A product was considered accepted when it obtained at least 70% approval (6–9 on a hedonic scale) [22].

A two-way ANOVA followed by Tukey's test (95%; $p < 0.05$) was performed to compare the attributes evaluated in the hedonic scale acceptance test. SPSS (IBM® Corp, Armonk. NY, USA, 2015) was used in this step.

For the CATA analysis, descriptors were initially compared with non-parametric Cochran's Q test ($p < 0.0001$) to assess whether there were significant differences in consumers' perception of any given attribute among the different samples. Then, a multiple pairwise comparison test was performed using Bonferroni (McNemar) procedure with 5% significance. A test of independence between rows and columns was carried out with 5% of significance. Additionally, correspondence analysis (CA) based on chi-squared distances was performed to summarize a sensory map of samples.

3. Results

3.1. Hedonic Scale Acceptance Test

Table 1 presents the acceptance of gluten-free bread samples evaluated by all participants (n = 110) with a hedonic scale. Gluten-free bread that used 12.5% AK flour replacing part of the gluten-free flour presented the highest mean for appearance, texture, and global acceptance. Regarding flavor and aroma, this sample (12.5%) and the control also presented the highest means.

Table 1. Mean and standard deviation of gluten-free bread samples' acceptance (9-point hedonic scale; n = 110 tasters).

***Amorphophallus konjac* (AK) Flour (% of Flour Replacement)**	**Appearance**	**Flavor**	**Aroma**	**Texture**	**Global Acceptance**
0	7.28 ± 1.81^{b}	7.15 ± 1.74^{a}	7.07 ± 1.65^{a}	5.60 ± 2.14^{a}	6.78 ± 1.77^{b}
12.5	8.09 ± 1.85^{a}	7.36 ± 1.55^{a}	6.95 ± 1.80^{a}	7.39 ± 1.45^{b}	7.53 ± 1.22^{a}
25	6.67 ± 1.72^{bc}	5.40 ± 2.03^{b}	5.70 ± 1.88^{b}	5.47 ± 2.04^{a}	5.66 ± 1.80^{c}
37.5	7.19 ± 1.64^{b}	5.57 ± 2.14^{b}	6.13 ± 1.97^{b}	5.64 ± 2.04^{a}	5.82 ± 1.99^{c}
50	6.46 ± 1.89^{c}	4.65 ± 2.07^{c}	5.64 ± 1.99^{b}	4.92 ± 2.20^{a}	5.07 ± 1.99^{c}

In the columns, means with the same letters do not differ statistically by Tukey's test ($p < 0.05$).

Table 2 shows the acceptance percentage of the different formulations of gluten-free bread among the 43 consumers of gluten-free bread and the 67 non-consumers of gluten-free bread. Among consumers of gluten-free bread, the 12.5 of AK flour sample presented the highest percentual of acceptance considering appearance, texture, and global acceptance. Among non-consumers of gluten-free bread, the 12.5 of AK flour sample presented the highest percentual of acceptance for all attributes. Flavor and aroma acceptance was higher for the control sample in the group of gluten-free bread consumers.

Table 2. Percentage of acceptance of gluten-free bread formulations among consumers (n = 43) and non-consumers of gluten-free bread (n = 67).

Gluten-Free Bread Consumers (% of Acceptance)					
***Amorphophallus konjac* (AK) Flour (% of Flour Replacement)**	**Appearance %**	**Flavor %**	**Aroma %**	**Texture %**	**Global Acceptance %**
0	81.39	95.34	86.05	60.46	83.72
12.5	95.35	90.70	76.75	88.37	93.03
25	72.09	48.84	55.81	58.14	67.44
37.5	93.02	55.81	65.12	55.81	67.44
50	76.75	41.86	48.84	37.21	48.84
Gluten-free bread non-consumers (% of acceptance)					
0	85.07	74.63	73.13	50.74	73.13
12.5	97.02	82.58	76.11	86.57	95.52
25	76.12	47.76	44.77	50.75	49.25
37.5	80.60	50.74	61.19	55.22	56.71
50	61.19	29.85	49.25	37.31	38.81

3.2. Check-All-That-Apply (CATA)

A total of 30 CATA descriptors were raised after the Repertory Grid method. About 66% (n = 20) were perceived as different among all samples by the consumers of Group I (all consumers; n = 100) ($p < 0.0001$; Table 3). Almost half (46.6%; n = 14) of the descriptors were perceived as different by members of Group II (gluten-free bread consumers; n = 43) ($p < 0.0001$; Table 4).

In general, for both groups, the most used descriptors to evaluate AK gluten-free bread developed by this study were: "Light Crust Color", "Light Crumb Color", "Pretty", "Pleasant Scent", "Rubbery", "Plesant Flavor", "Yeast Flavor", "Unpleasant Flavor", "Sweet Flavor", and "Soft", however, a very heterogeneous distribution among the frequency of descriptors between all samples was evident. Regarding the appearance of AK Gluten-free bread, for both groups, descriptors such as "Light Crust Color", "Light Crumb Color", and "Pretty" were the most frequent ones. In group I, differences in sample's appearance were found in six descriptors: "Dark Crust Color", "Dry Crust Appearence", "Light Crust Color", "Light Crumb Color", "Dark Crumb Color", and "Pretty" (Table 3). In Group II, differences were found for the same descriptors, except for "Dark Crust Color" and "Light Crumb Color" (Table 4).

The term "Dark crust color" was most frequent in sample 12.5; however, no differences were found compared to sample 50, while differences were present in the remaining ones. Sample 12.5 (Group I) presented the highest frequency of the term "Dry Crust Appearance", while in Group II, the same was also true, while all the remaining samples did not present differences between them.

"Light crust color" was more frequent in sample 25, in group I, and equal in frequency in samples 25 and 37.5 in group II; however, differences between all samples were present in both groups. The term "Dark Crumb Color" was most frequent in sample 50; however, in both groups, sample 25 was not significantly different for the same term, although presenting a lower absolute frequency proportionally. The control sample presented a higher frequency for the term "Pretty" in all groups, though, in group I, sample 12.5 did not show significant differences for the same term.

Regarding the aroma of bread, in both groups, "Pleasant scent" presented the highest frequency among all samples, given that sample 12.5 presented the highest value for this descriptor. However, no differences were seen between samples 12.5 and control in group I, while in group II, sample 12.5 was different from all the remaining others. As for the descriptor "Seafood scent," sample 12.5 was the only significantly different from the others in both groups.

"Pleasant flavor" and "Unpleasant flavor" presented similar distributions in both groups. Samples 12.5 and control did not statistically differ, while samples 25, 37.5, and 50 were in the same group, with a "Seafood flavor" also highlighted as a frequent descriptor. Samples 12.5 and control presented no differences while the other samples were in the same group. In group I, "Yeast flavor" was a frequent descriptor, with significant differences between samples. In group II, no differences for the same descriptor were found.

The control sample presented the highest frequency for "Sweet flavor" in groups I and II. In group I, no difference was found between control and 12.5%. In group II, differences were present only between control and 25%. The highest frequencies for "Savory flavor" were in the control sample in both groups. Differences were found only between control and 50%.

Regarding texture-related descriptors, control presented the highest frequencies for "Dry", "Grainy", "Stiff", "Compact", and "Buttery" in both groups I and II. The term "Moist" was most frequent in samples 12.5% and 37.5% in group I and 37.5% and 50% in group II. The control sample presented the lowest frequency for this descriptor in both groups.

In group I, "Stiff" was most frequent in the control sample, presenting differences compared to all remaining samples. In group II, sample 25% was statistically equal, although showing a much lower frequency. “Rubbery” was present in samples 25%, 37.5%, and 50%, with no significant differences between these samples in both groups.

“Soft” was frequent in sample 12.5%, presenting differences in all remaining samples in groups I and II. The remaining samples did not present differences between them for the same descriptor. In groups I and II, the descriptor “Rubbery” did not present differences regarding control and 12.5%, while samples 25%, 37.5%, and 50% were different from these other two and statistically the same.

A heterogeneous distribution was evidenced for “Grainy”. The control sample presented the highest frequency for this term in both groups. However, in group I, control and 50% did not present differences, while in group II, control differed only from the sample 12.5%. The descriptor “Dry” was most frequent in control, differing from all remaining samples in all groups.

Correspondence analysis was carried out to generate a sensory map of samples and their relation with attributes. Groups 1 and 2 Principal Coordinate Analysis (PCA) and Symmetric Plot are in Figures 2 and 3.

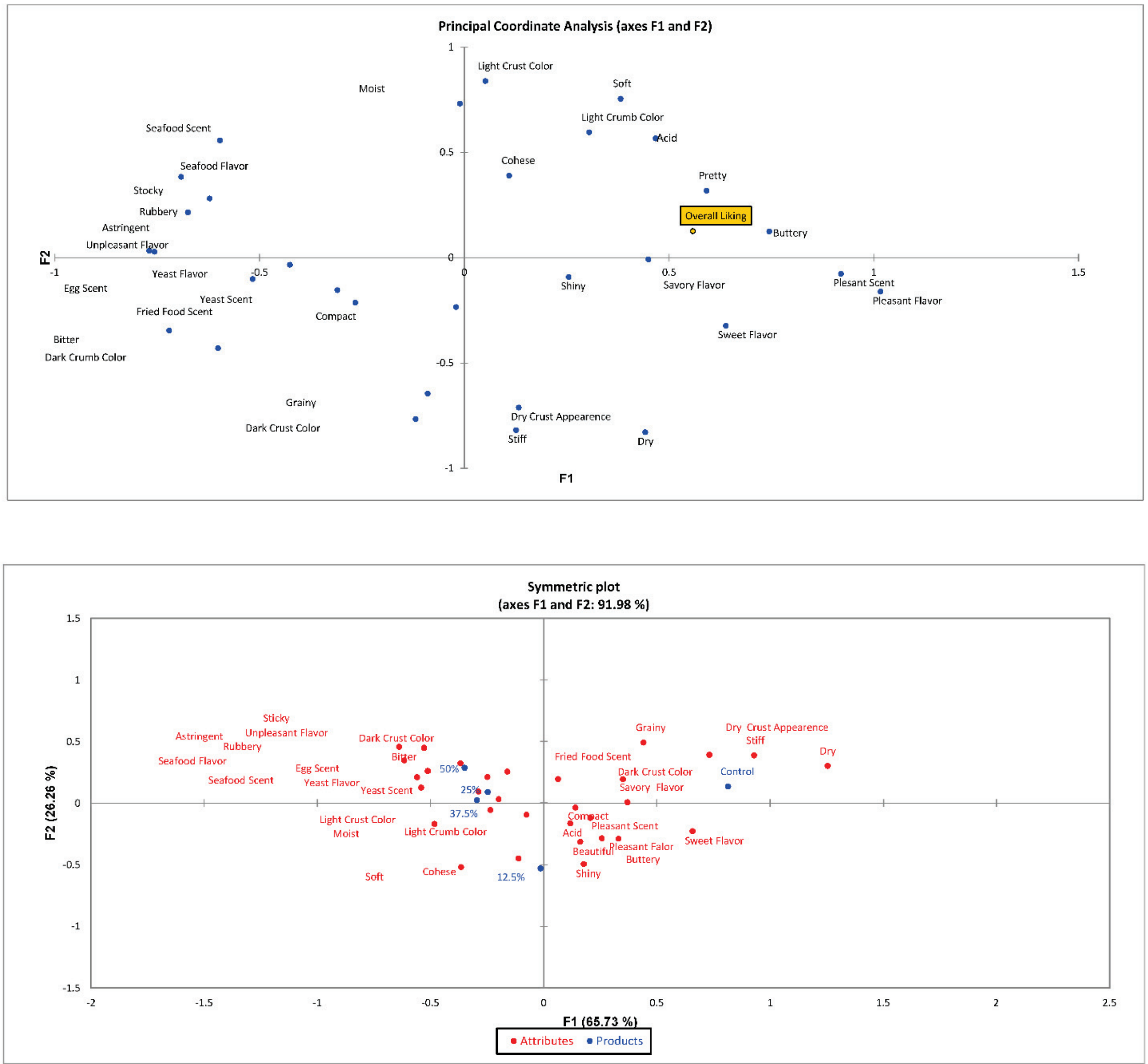

Figure 2. Sensory descriptive map resulting from Correspondence Analysis performed on the CATA data (n = 110).

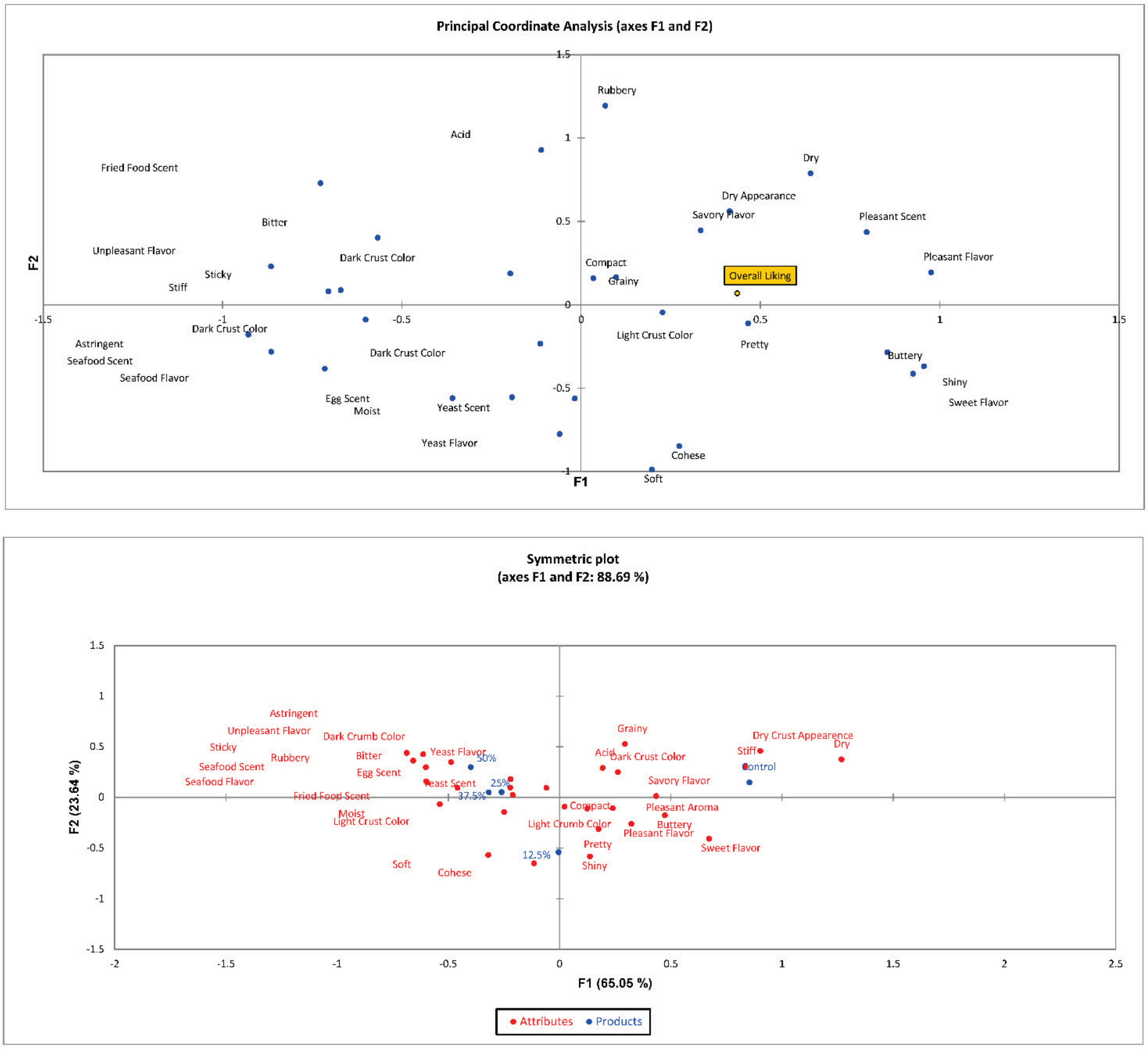

Figure 3. Sensory descriptive map resulting from Correspondence Analysis performed on the CATA data (n = 43).

Table 3. Absolute frequencies of sensory attributes checked for the different *Amorphophallus konjac* (AK) gluten-free bread among all consumers (Group I; n = 110).

	Attributes	Control	12.5	25	37.5	50	p-Values (Cochran's Q)
Appearance	Dark Crust Color	18 ^{ab}	42 ^{c}	8 ^{a}	13 ^{a}	31 ^{bc}	<0.0001
	Dry Crust Appearence	5 ^{a}	60 ^{c}	20 ^{b}	9 ^{ab}	16 ^{ab}	<0.0001
	Light Crust Color	56 ^{bc}	33 ^{a}	77 ^{d}	74 ^{cd}	42 ^{ab}	<0.0001
	Light Crumb Color	78 ^{b}	59 ^{a}	68 ^{ab}	72 ^{ab}	58 ^{a}	0.003
	Dark Crumb Color	9 ^{a}	7 ^{a}	15 ^{ab}	10 ^{a}	30 ^{b}	<0.0001
	Pretty	66 ^{c}	50 ^{bc}	28 ^{a}	33 ^{ab}	25 ^{a}	<0.0001
	Shiny	10 ^{a}	6 ^{a}	6 ^{a}	3 ^{a}	1 ^{a}	0.031

Table 3. *Cont.*

	Attributes	Control	12.5	25	37.5	50	*p*-Values (Cochran's Q)
Aroma	Egg Scent	6 [a]	7 [a]	14 [a]	11 [a]	13 [a]	0.143
	Fried Food Scent	6 [a]	13 [a]	12 [a]	9 [a]	10 [a]	0.376
	Seafood Scent	13 [b]	1 [a]	16 [b]	18 [b]	26 [b]	<0.0001
	Yeast Scent	28 [a]	30 [a]	33 [a]	29 [a]	34 [a]	0.152
	Pleasant Scent	65 [bc]	77 [c]	43 [a]	49 [ab]	35 [a]	<0.0001
Flavor	Seafood Flavor	8 [ab]	1 [a]	14 [b]	17 [b]	21 [b]	<0.0001
	Yeast Flavor	19 [ab]	13 [a]	34 [b]	26 [ab]	27 [ab]	0.003
	Unpleasant Flavor	3 [a]	6 [a]	27 [b]	34 [b]	39 [b]	<0.0001
	Pleasant Flavor	80 [b]	73 [b]	37 [a]	36 [a]	28 [a]	<0.0001
	Bitter	2 [a]	3 [a]	4 [a]	3 [a]	5 [a]	0.804
	Sour	2 [a]	2 [a]	1 [a]	2 [a]	1 [a]	0.50
	Sweet Flavor	23 [bc]	36 [c]	4 [a]	10 [ab]	6 [a]	<0.0001
	Astringent	1 [a]	1 [a]	7 [a]	9 [a]	4 [a]	0.011
	Savory Flavor	18 [a]	34 [b]	19 [ab]	12 [a]	11 [a]	<0.0001
Texture	Moist	34 [b]	1 [a]	25 [b]	34 [b]	31 [b]	<0.0001
	Stiff	2 [a]	50 [c]	15 [b]	8 [ab]	5 [ab]	<0.0001
	Sticky	6 [a]	1 [a]	26 [b]	28 [b]	49 [c]	<0.0001
	Cohese	15 [a]	5 [a]	7 [a]	8 [a]	5 [a]	0.010
	Rubbery	10 [a]	1 [a]	57 [b]	47 [b]	53 [b]	<0.0001
	Soft	82 [c]	3 [a]	40 [b]	39 [b]	34 [b]	<0.0001
	Compact	21 [a]	26 [a]	22 [a]	14 [a]	15 [a]	0.155
	Buttery	25 [b]	26 [b]	6 [a]	16 [ab]	8 [a]	<0.0001
	Grainy	2 [a]	40 [d]	9 [ab]	15 [bc]	24 [cd]	<0.0001
	Dry	8 [a]	76 [b]	9 [a]	3 [a]	6 [a]	<0.0001

Frequencies with which sensory terms were checked in the CATA question. Different letters in the same row indicate significant differences (Mcnemar Bonferroni Multiple pairwise comparison; $p < 0.05$).

Table 4. Absolute frequencies of sensory attributes checked for the different AK gluten-free bread among frequent consumers of gluten-free bread (Group II; $n = 43$).

	Attributes	Control	12.5	25	37.5	50	*p*-Values Cochran's Q
Appearence	Dark Crust Color	7 [a]	17 [a]	4 [a]	6 [a]	14 [a]	0.001
	Dry Crust Appearence	1 [a]	29 [b]	8 [a]	2 [a]	6 [a]	<0.0001
	Light Crust Color	23 [ab]	11 [a]	29 [b]	29 [b]	12 [a]	<0.0001
	Light Crumb Color	29 [a]	28 [a]	24 [a]	27 [a]	19 [b]	0.066
	Dark Crumb Color	4 [ab]	2 [a]	7 [ab]	4 [ab]	15 [b]	<0.0001
	Pretty	27 [b]	21 [a]	11 [a]	13 [a]	10 [a]	<0.0001
	Shiny	2 [a]	1 [a]	2 [a]	0 [a]	0 [a]	0.406

Table 4. *Cont.*

	Attributes	Control	12.5	25	37.5	50	*p*-Values Cochran's Q
Aroma	Egg Scent	2 ^{a}	2 ^{a}	3 ^{a}	0 ^{a}	3 ^{a}	0.532
	Fried Food Scent	3 ^{a}	3 ^{a}	6 ^{a}	5 ^{a}	4 ^{a}	0.519
	Seafood Scent	6 ^{ab}	0 ^{a}	9 ^{ab}	9 ^{ab}	13 ^{b}	0.001
	Yeast Scent	11 ^{a}	8 ^{a}	12 ^{a}	13 ^{a}	13 ^{a}	0.639
	Pleasant Scent	25 ^{b}	32 ^{c}	17 ^{a}	18 ^{a}	13 ^{d}	<0.0001
Flavor	Seafood Flavor	5 ^{ab}	0 ^{a}	11 ^{b}	11 ^{b}	11 ^{b}	0.001
	Yeast Flavor	7 ^{a}	2 ^{a}	10 ^{a}	10 ^{a}	12 ^{a}	0.038
	Unpleasant Flavor	1 ^{a}	1 ^{a}	8 ^{ab}	13 ^{b}	12 ^{b}	<0.0001
	Pleasant Flavor	31 ^{b}	32 ^{b}	13 ^{a}	13 ^{a}	11 ^{a}	<0.0001
	Bitter	1 ^{a}	1 ^{a}	3 ^{a}	0 ^{a}	2 ^{a}	0.406
	Sour	0 ^{a}	1 ^{a}	1 ^{a}	1 ^{a}	0 ^{a}	0.736
	Sweet Flavor	10 ^{ab}	12 ^{b}	1 ^{a}	3 ^{ab}	1 ^{ab}	<0.0001
	Astringent	0 ^{a}	0 ^{a}	3 ^{a}	4 ^{a}	3 ^{a}	0.083
	Savory Flavor	6 ^{ab}	13 ^{b}	7 ^{ab}	4 ^{ab}	3 ^{a}	0.003
Texture	Moist	11 ^{b}	0 ^{a}	10 ^{b}	13 ^{b}	13 ^{b}	0.001
	Stiff	2 ^{a}	20 ^{b}	6 ^{ab}	4 ^{a}	2 ^{a}	<0.0001
	Sticky	3 ^{ab}	0 ^{a}	9 ^{ab}	10 ^{b}	15 ^{b}	<0.0001
	Cohese	5 ^{a}	1 ^{a}	1 ^{a}	1 ^{a}	2 ^{a}	0.056
	Rubbery	5 ^{a}	1 ^{a}	22 ^{b}	20 ^{b}	21 ^{b}	<0.0001
	Soft	32 ^{c}	2 ^{a}	16 ^{b}	12 ^{ab}	12 ^{ab}	<0.0001
	Compact	8 ^{a}	9 ^{a}	8 ^{a}	6 ^{a}	4 ^{a}	0.573
	Buttery	7 ^{a}	11 ^{a}	3 ^{a}	6 ^{a}	1 ^{a}	0.013
	Grainy	1 ^{a}	14 ^{b}	3 ^{ab}	6 ^{b}	11 ^{b}	0.000
	Dry	2 ^{a}	30 ^{b}	3 ^{a}	2 ^{a}	2 ^{a}	<0.0001

Frequencies with which sensory terms were checked in the CATA question. Different letters in the same row indicate a significant difference (Mcnemar Bonferroni Multiple pairwise comparisons; $p < 0.05$).

4. Discussion

Hydrocolloids like AK flour in gluten-free bread are used to mimic viscoelastic and crumb texture performed by gluten to improve sensory characteristics. Our study first evaluated the sensory profile of gluten-free bread using *Amorphophallus konjac* flour in higher proportions (12.5–50%) of gluten-free flour, which makes it difficult to compare the results with other studies. *Amorphophallus konjac* flour in proportions of 12.5%, 25%, 37.5%, and 50% of the gluten-free flour content was previously tested in gluten-free bread, but only the nutritional and physicochemical properties were evaluated [16].

A study evaluated the acceptance of gluten-free bread with AK glucomannan but used in lower amounts [13]. The authors used rice and potato flour and corn and cassava starch as gluten-free flour matrices. The AK flour was used combined, with xanthan gum as an additive [13]. The product was evaluated using the 9-point hedonic scale. The increasing proportion of AK flour and the decreasing proportion of xanthan gum in the formulation decreased the panelists' preference. The highest-rated gluten-free bread was that with xanthan gum and AK flour proportion of 0.25: 0.75 [13]. Considering the 9-point hedonic scale, the lowest addition of AK flour (12.5%) presented the best acceptance. Considering appearance, 12.5% gluten-free bread had the highest average, different from other formulations. This formulation also had the best scores for flavor, texture, and global acceptance, similar to the control bread only for the flavor and aroma attributes.

Regarding flavor, bread with percentages above 25% presented lower acceptance means than control and 12.5%. Therefore, the addition of konjac flour negatively influenced the flavor of bread above 12.5%. This could be explained by the water absorption capacity of AK flour. The final volume of the dough increases because of the need for water addition. It decreases the concentration of ingredients that provide greater palatability to food, such as sugar, fat, and salt [23]. A potential influence of seafood flavor showed by CATA test could also explain this result. The more AK flour was added to formulations, the more seafood flavor was observed on samples (Tables 3 and 4). AK presents a seafood-like flavor mainly due to trimethylamine (TMA), a nitrogenous base aliphatic organic compound. Although AK flour has many advantages in food application, the fish-like flavor is the primary factor limiting its application in some food. The food industry has been searching for alternatives to reduce it [24]. It was also confirmed by CATA test, in which the bread with the highest score for the term pleasant flavor was 12.5%, and for unpleasant flavor, 50%, indicating the possible influence of AK flour on the gluten-free bread flavor. The result of CATA agrees with the result obtained in the sensory analysis, in which bread 12.5% had the highest average for flavor and bread 50% had the lowest average.

There was no difference in aroma acceptance between the control bread and the 12.5% in this study. However, there is a difference between the control bread and the bread with AK flour percentages above 37.5%, indicating that the higher the percentage of AK flour less accepted the aroma of the gluten-free bread. This was probably due to the characteristic odor of the AK flour or the lower concentration of sugars and proteins, which prevented chemical reactions that produce aroma, such as the Maillard reaction and caramelization, from adequately occurring. Regarding the aroma of konjac bread, some comments could be extracted from the evaluation forms filled in by the evaluators, "Despite the smell of fish, it has a normal bread texture"; "although there is a smell of seafood, the taste is good"; "Taste good, but bad aroma". This was confirmed by the CATA test, in which "Seafood Scent" was most frequent among samples with 25% to 50% of AK flour addition. Considering CATA, the control bread had the lowest score for seafood aroma, and in the AK flour bread, more AK flour led to more consumers perceiving this odor. The 50% bread was most punctuated for seafood aroma, and, in the sensory analysis, 50% AK flour bread had the lowest average for aroma. This can be explained by the characteristic odor of konjac flour that resembles a fish [25]. In the CATA test for aroma, attributes such as egg, frying, and yeast aroma were mentioned and considered statistically equal for all samples. The pleasant aroma was statistically equal and better evaluated in control and 12.5% samples.

The bread samples were considered statistically equal in texture, except for the 12.5% bread which presented the highest acceptance rate. This bread sample was the one that presented the highest instrumental hardness in a previous study [16]; however, in the acceptance test, it was the bread that obtained the highest average in the consumers' evaluation. Despite Bourne's [26] assertion that texture is the main attribute considered to reject food, we observed that bread with greater firmness [16] was also well accepted by consumers. These results corroborate the findings of another study [27] that obtained bread with high means of instrumental hardness but were well accepted by trained evaluators. In a previous study [16], the 50% AK flour bread had one of the lowest means of instrumental hardness (e.g., the softest bread). However, it presents the lowest percentage of texture acceptance among all consumers and gluten-free bread consumers. Analyzing the term sticky, the 50% AK bread obtained the highest frequency, differing from the control bread and 12.5%, with the control being the least sticky. This may also have influenced the best acceptance of this product compared to the others. Additionally, the bread samples considered rubberier were those with 25% or more AK flour, and the less rubbery ones, without statistically differing, were the control bread and the 12.5% bread.

The sample with 12.5% of AK flour obtained a percentage of global acceptance among evaluators who habitually consume gluten-free bread of 93.03% and among non-consumers of 95.52%. This result was the opposite of that obtained by another study [25]. Gluten-free bread was more accepted among evaluators from the celiac group who habitually consumed these foods than among non-consumers of gluten-free bread. Our result is important, showing that gluten-free bread prepared with 12.5% AK flour is well accepted by all consumers, and it could be essential to insert this product on the market.

Considering the CATA test, the data show that the dark color crust obtained a significantly higher frequency for the control bread, reflecting the same result obtained in the instrumental analysis in a previous study, indicating that this was the darkest crust color bread [16]. The possible presence of components can explain this in adequate amounts (higher concentrations than the other samples) for the occurrence of chemical reactions of non-enzymatic browning in foods. The visual presentation of a product marks the first contact with the consumer; therefore, characteristics such as color and appearance are frequently observed and are associated with personal reactions of acceptance, indifference, or rejection [28], as observed in the 9-point hedonic scale acceptance.

The term dry appearance was considerably more frequent for the control bread, which was statistically different from the others. The least pointed to this term was 12.5% bread, which was not expected since our previous study showed that, among AK flour samples, the 12.5% presented the lowest moisture content [16]. However, it was evident that the addition of AK flour in 12.5% of gluten-free flour improved the appearance of the gluten-free bread (Tables 1 and 2), probably due to a reduction in the crust cracks, the dry appearance, and the crumbly texture, characteristics of gluten-free bread [27].

For light crust color, 25% AK flour bread was more frequent. The highest frequency was found in 12.5% AK flour bread for light crumb color, and dark crumb color was more observed in 50% bread. In our previous instrumental evaluation [16], the 50% AK flour bread differed the most from the control bread, obtaining one of the lowest averages for chroma, indicating a loss of crumb color purity. The sample considered the most beautiful and bright on CATA was the 12.5% bread.

Figures 2 and 3 show the correlation of the evaluated attributes with the evaluators' preferences. A graph is generated that presents the impact of the assessed attributes (CATA) on the sensorial acceptance of the consumers. A descriptive symmetric map was generated from CATA. The map generated by the correspondence analysis elucidates 91.98% of the variation in the two dimensions analyzing all participants (n = 110) (Figure 2). Considering the gluten-free bread consumers, the results were similar (88.96% of the variation in the two dimensions). According to the map, 12.5% of AK bread is in the lower-left quadrant, close to light crust color, light crumb color, soft and moist texture, cohesive, pleasant, and shiny characteristics. Control bread is located in the upper right quadrant next to characteristics such as dry appearance, dry and grainy texture, dark crust, and salty. The remaining 25%, 37.5%, and 50% bread samples are located in the upper left quadrant, where characteristics such as fish aroma, yeast aroma, dark crumb, blackberry, yeast flavor, and unpleasant flavor can be observed. The proximity of these bread samples on the map demonstrates similarities between them.

A previous study [16] on AK flour gluten-free bread's nutritional and physicochemical properties showed that the best formulations were prepared with up to 37.5% AK flour concentrations. Additionally, the authors showed that the 12.5% AK flour presented the highest protein content among AK flour gluten-free bread samples, which could affect technological and sensory characteristics in the absence of gluten. Our study showed that the 12.5% AK flour gluten-free bread sample presented the best sensory profile among AK gluten-free bread samples. It is confirmed to be a good alternative to replace gluten-free flour in gluten-free bread in more significant amounts than previously studied as an additive.

This research presents, as a limitation, the absence of the descriptive analysis (DA), a more robust and reliable evaluation tool when precise definitions and quantification of the sensory attributes of products are required [29,30]. However, CATA was applied, since it is a rapid sensory profiling tool that can be applied by non-trained panelists, spending less time and money than descriptive analysis [29,30]. Using descriptive analysis, further research may be applied to evaluate AK gluten-free bread with a trained sensory panel.

5. Conclusions

Amorphophallus konjac flour interfered with the sensory characteristics of gluten-free bread. Adding up to 12.5% of AK flour (in partial replacement of gluten-free flour) was feasible on the gluten-free bread formulation used in this study. The most desirable attributes in the studied bread were aroma, pleasant taste, beautiful appearance, and clear crumb, found in gluten-free bread with 12.5% AK flour. In this way, the study demonstrates that it is feasible to use AK flour in higher concentrations than being used as an additive, up to 12.5%, helping to improve sensory characteristics of gluten-free products. Further studies should be conducted to evaluate the glycemic index of these gluten-free bread, determine the shelf life, and determine the purchase intention of the products so that they can go to the consumer market.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/foods11101379/s1, Table S1. Formulations of gluten-free bread with and without the addition of konjac flour.

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Article

Impacts of the Russia-Ukraine War on Global Food Security: Towards More Sustainable and Resilient Food Systems?

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Abstract: As a conflict between two major agricultural powers, the Russia–Ukraine war has various negative socioeconomic impacts that are now being felt internationally and might worsen, notably, for global food security. If the war deepens, the food crisis will worsen, posing a challenge to many countries, especially those that rely on food imports, such as those in the Middle East and North Africa (MENA) region. Simultaneously, the war came at a bad time for global food markets because food prices were already high due to disruptions in the supply chain caused by the COVID-19 pandemic, strong global demand, and poor harvests in some countries. Understanding how conflict-related disruptions in global food and fertilizer markets might affect price and availability is critical for understanding the overall impact on global food security. Further, four months into the war, its implications for food security suggest that this review is timely, urgent, and highly needed. Accordingly, this paper aims to investigate the Russia–Ukraine war's direct and indirect impact on global food security. The paper highlights that the war resulted in immediate and far-reaching cascading consequences on global food security: Ukrainian exports have stopped, conscription and population displacement have caused labor shortages, access to fertilizers is restricted, and future harvests are uncertain. First, Ukraine's export capacity has been hampered. Secondly, conscription and population displacement caused labor shortages. Thirdly, access to vital agricultural products such as fertilizers is also constrained. The war may delay spring planting and winter crop harvesting. Further, the war has indirect and cascading effects. Indeed, rising fertilizer costs may reduce their use and crop yields. Moreover, as seen during the 2007–2008 food crisis, export restrictions and speculation are driving up international prices and worsening the situation. Furthermore, the war triggered a panic buying movement at country and individual levels. Finally, the war may jeopardize the implementation of the Sustainable Development Goals (SDGs), notably SDG 1 (No poverty), SDG 2 (Zero hunger), and DG 12 (Responsible consumption and production). However, the consequences of the war on food security are being exacerbated by a variety of underlying rigidities, vulnerabilities, and inefficiencies in global food systems. Accordingly, the transition toward healthy, equitable, and ecologically sustainable food systems must be strengthened by adopting urgent and long-term reforms and policies.

Keywords: war; conflict; Ukraine; Russia; food security; export restrictions; food supply; SDG

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1. Introduction

Food security happens when "all people at all times have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life" [1]. Food security has four standard dimensions: availability (having a sufficient quantity of food available regularly); access (having enough resources to acquire suitable and healthy food); utilization (having a reasonable food use based on knowledge of essential nutrition and care); and stability of availability, access, and utilization of food [2,3]. Although these four dimensions remain fundamental, they lack other features, such as agency and sustainability, that have come to be recognized as critical for altering food systems in the direction required to accomplish the SDGs [4]. Evidence shows that wars and conflicts are the most important drivers of food insecurity globally [5]. Indeed, in 2021, 139 million people were in crisis or severe food insecurity in 24 countries and territories, with war and instability being the primary drivers [6].

In the early hours of 24 February 2022, Russia started a full-scale military invasion of Ukraine that resulted in the deaths and injuries of civilians, as well as the destruction of key infrastructure [7]. Consequently, the United States, Europe, and many other western countries (e.g., Canada and Australia) have imposed increasingly broad sanctions, targeting persons, banks, corporations, and large state-owned companies, as well as exports [8]. The most significant consequences of the war are the lives lost and the humanitarian disaster in Ukraine caused by many besieged and displaced people. Simultaneously, the war has inflicted a significant blow to commodities markets, especially food and energy, affecting global patterns of trade, production, and consumption in ways that will maintain prices at historically high levels until the end of 2024, thus threatening global food security [9–11].

Indeed, in the context of globalized agricultural markets and as a war between two major players in the global food and fertilizer industries, the war is raising widespread anxiety about global food security [12,13]. Despite their limited position in the global economy, with only approximately 2% of global GDP, Russia and Ukraine are considered both 'global breadbaskets' and are important producers and exporters of vital agricultural commodities, minerals, fertilizers, and energy, where exportable resources are often concentrated in a few countries [9]. This concentration may make these markets more vulnerable to shocks and volatility [14]. Simultaneously, the war came at a bad time for global food markets because food prices were already high due to disruptions in the supply chain caused by the COVID-19 pandemic, strong global demand, drought, and poor harvests in South America the previous year. These factors combined drive up food prices [15]. These issues will worsen due to the war between Russia and Ukraine.

Indeed, four months into the war, the consequences are clear: Ukrainian exports have ceased, future harvests are questionable, and global agricultural commodity prices have skyrocketed, threatening to push millions into hunger and poverty [13]. Further, price increases and trade interruptions might increase the number of malnourished individuals by limiting the availability of humanitarian assistance to prevent and cure acute malnutrition [16]. The World Food Programme (WFP) estimates that acute hunger will grow by an additional 47 million people from a pre-war baseline of 276 million people suffering from acute hunger. This indicates that up to 323 million people may face severe food insecurity by 2022 [6,17]. According to World Bank estimates, every one percentage point rise in food prices pushes 10 million people into severe poverty. If food costs remain this high for a year, global poverty might rise by more than 100 million [18].

There is a considerable amount of uncertainty regarding the effect of the war on food security in the medium (6 months–2 years) to long term (>2 years). This includes both the immediate costs of the war and the implications of Russia's current and future sanctions [12]. In that context, the combined impacts of sanctions and war will have a wide-ranging impact on global agri-food markets and food security, sending shockwaves worldwide, especially in import-dependent low- and middle-income countries (LMICs) [19]. For instance, several countries in the Middle East and North Africa (MENA) region import more than 50% of their cereal needs, especially wheat, from Ukraine and Russia [19].

Understanding how conflict-related disruptions in global food and fertilizer markets might have large-scale and long-term implications on price and availability is critical for understanding the overall impact on global food security. Further, the effects of the war on food systems and supply chains worldwide suggest that this review is timely, urgent, and highly needed. However, evaluating the consequences of the war on food security is challenging since the entire extent of the war's effects is not yet clear. Accordingly, this paper aims to investigate the Russia–Ukraine war's direct and indirect impacts on global food security.

The paper is based on a review of grey literature, including reports, policy documents/briefs, and working/discussion papers produced in English, French, and Arabic by a variety of organizations, including international organizations (e.g., FAO, World Bank, World Food Programme (WFP), International Food Policy Research Institute (IFPRI), International Monetary Fund (IMF), United Nations Conference on Trade and Development (UNCTAD), United Nations Development Programme (UNDP), Organisation for Economic Co-operation and Development (OECD)), regional organizations (e.g., United Nations Economic and Social Commission for West Asia—ESCWA, etc.), NGOs (e.g., Oxfam), consulting firms (e.g., Deloitte, KPMG, McKinsey, Oxford Business Group), international newspapers (e.g., *The New York Times*, *Le Monde*, *Malay Mail*, *The Guardian*, and *The Independent*), and international news platforms (e.g., *Bloomberg*, and *Euronews*).

2. Overview of the War's Immediate and Long-Term Impacts

The war has a multitude of immediate and long-term indirect impacts on global food security (Figure 1).

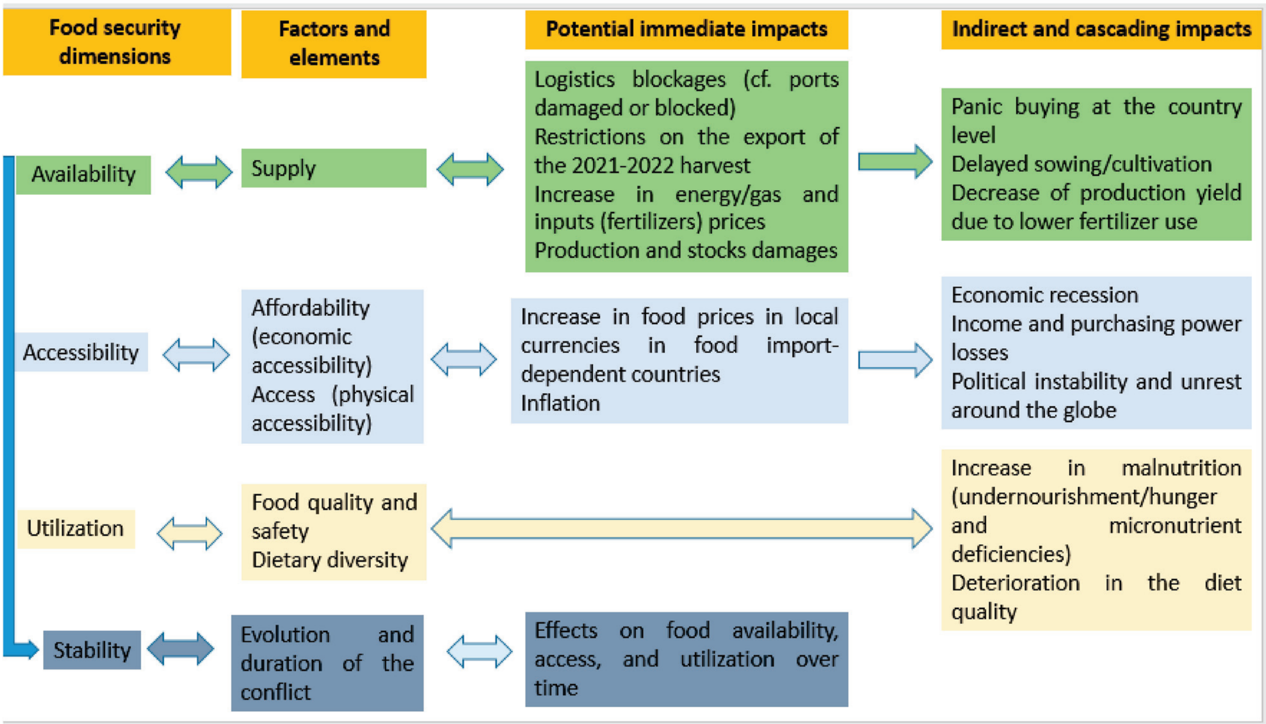

Figure 1. Impacts of the Russia–Ukraine war on global food security. Source: Authors' elaboration.

2.1. Immediate Impacts of the War on Food Security

The war has a multitude of direct and immediate consequences for food security, disturbing harvesting and shipping and severely affecting staple supplies and pricing [20]. Firstly, military actions might have both short- and long-term consequences on Ukraine's ability to transport agricultural products inside and beyond its borders, especially if port facilities and railroads are destroyed. In fact, the war immediately affected grain shipments from Ukraine, mainly for maize, typically in the spring and early summer. Indeed, 95% of Ukrainian grain exports are sent by sea via the ports of Odessa, Mariupol, and Kherson, which have suffered significant damage. In addition, all Black Sea ports have been blocked, shutting off most Ukrainian exports. Shipping grain by rail would be complicated even if inland transportation infrastructure remained intact due to a lack of an operable railway system. For instance, according to Reuters [21], on 17 May 2022, four traders announced that about 300,000 tonnes of Ukrainian wheat contracted by Egypt's state grains buyer for delivery in February and March were stranded in Ukraine, with one cargo detained in port and four others needing to be loaded [21].

Instead of utilizing Ukrainian ports, potential options include exporting food through Poland or Romania. In recent weeks, Western leaders have queued up to endorse these options. Alternative methods may enhance exports, but experts think this is insufficient to fulfill global food demand. Indeed, challenges are numerous: the rail gauge in Ukraine differs from that of most EU nations. Building storage capacity will take some time. Further, the Romanian port of Constanta lacks the capacity to manage the influx of Ukrainian crops [22]. However, with investments in port infrastructure and railway networks, it can be a key trade route, especially to North African countries. In addition, because the embargo duration is unknown, attracting private investment for the infrastructure required for such alternatives is challenging [22]. Furthermore, increased insurance costs for the Black Sea area will worsen already high transportation expenses, compounding the price of food imports [23].

Secondly, the war already prevented farmers from working in their fields, and the conscription and population displacement resulted in labor shortages. Disruptions to essential public services are also expected to affect agricultural activities negatively. This situation is aggravated by reduced access to and availability of critical agricultural inputs, such as fertilizers [24]. Accordingly, the war might disrupt the ongoing spring planting campaign and the approaching winter crop harvesting, which usually takes place in June/July [24]. For instance, although the available quantities of seeds (both local and imported) would be adequate to plant 70% of the predicted spring area, their safe delivery to farmers is a considerable challenge [25]. Consequently, according to FAO [19], one-third of crops and agricultural land may not be harvested or cultivated by 2022. Further, it is uncertain if other exporters will be able to fill in the gap.

Thirdly, due to economic sanctions placed on Russia, there is a great deal of uncertainty about Russian export prospects in the future [14]. Russian Black Sea ports remain open for the time being, and no significant interruption to agricultural production is predicted in the near future. However, the financial sanctions imposed on Russia have resulted in a significant devaluation, which, if sustained, may impede productivity and development while eventually raising agricultural output costs [23]. Furthermore, in April 2022, Russia vowed to limit agricultural and food exports to only ‘friendly’ countries in response to Western sanctions. The restriction would exacerbate the global food-supply shortfall [26]. A continuing war and sanctions would probably raise prices and weaken food security for hundreds of millions of people [15].

2.2. Indirect Impacts of the War on Food Security

The war has as well some indirect and cascading consequences. Firstly, prices for essential inputs, such as fertilizers, are reaching near-record highs [27]. Consequently, many farmers worldwide, such as in the USA, are replacing high-cost fertilizer-requiring crops, such as wheat and maize, with low fertilizer-requiring ones, such as soy. Since soybeans are used mainly in animal feed and biofuel, this might exacerbate the current supply shortages and raise the price of bread, cereals, and other critical food items [28]. Similarly, fertilizer shortages and high costs may have negative effects, particularly in developing countries where price repercussions may severely limit usage, and result in decreased yields during reduced global supply and record global prices [29].

Secondly, as seen during the 2007–2008 food crisis, many countries applied export restrictions to secure local food supply and mitigate inflation (India: wheat; Serbia: grains, and vegetable oils; Indonesia: palm oil, etc.), forcing other food exporters to limit exports to protect their populations as well, exacerbating the situation [30]. Since the beginning of the war, the number of countries enforcing food export restrictions, such as export bans and export licensing requirements, has increased from 3 to 26, covering 40 food items [31]. The entire volume of exports impacted by the restrictions accounts for around 15.68% of total calories traded globally, the same level seen during the 2007–2008 food crisis [31].

Export limits are especially significant in terms of calories for the following commodities: wheat (31% of total calories impacted), palm oil (29%), maize (12%), sunflower oil (11%), and soybean oil (6%). In terms of total trade in individual items, export restrictions have an impact on 36% of wheat exports, 55% of palm oil exports, 17% of maize exports, 78% of sunflower oil exports, and 6% of soybean oil exports [32]. However, while these measures may appeal locally, they have far-reaching implications for global food pricing and food security [30].

As seen during the 2007–2008 food crisis, instead of controlling price rises, export restrictions pushed up international market prices [33]. Indeed, rising protectionism is compounding the instability in global food markets caused by the war. These measures can potentially have disastrous unintended repercussions for vulnerable individuals in food-importing nations, raising prices and intensifying food insecurity concerns already exacerbated by the COVID-19 outbreak [31]. Export restrictions exacerbated shortages during the 2007–2008 food crisis, leading to food riots across Asia and Africa [34].

Thirdly, panic buying at both country and individual levels is another cascading impact of the war. Stockpiling and panic buying are significant components of crisis- and disaster-related consumer behavior that attracted substantial media attention during the COVID-19 pandemic [35]. Indeed, food becomes more important in people's lives during a crisis, and panic buying is a natural human reaction to a stressful scenario. As observed during the first months of the pandemic [36–39], in March 2022, several European countries saw a rise in panic buying due to the war. For example, in the United Kingdom, more than a third of the consumers hurried to stock up on critical products, such as pasta and cooking oils, while numerous retailers started to ration certain food items [40]. Likewise, residents in northern Italy stored pasta in large quantities, while trade experts in Germany reported panic buying of commodities [41]. Further, residents in Finland's border areas were hurrying to buy food in preparation for a possible war with Russia [42]. Furthermore, to ensure local food supply, some countries were stocking up food, such as China, a lesser-known driver of food prices increase. The Chinese government is hoarding food on a vast scale in order to avert shortages and minimize reliance on imports. According to the US Department of Agriculture (USDA) data, by mid-2022, China, which accounts for less than 20% of the world's population, is expected to have 69% of the globe's maize reserves, 60% of its rice, and 51% of its wheat. The forecasts imply rises of roughly 20% over the last decade, and the data plainly reveals that China continues to store grains, contributing to higher global food prices [43].

Fourthly, by slowing the post-COVID-19 economic recovery, the war may affect purchasing power at the country and individual level, affecting economic access to food. In fact, the war in Ukraine erupted at the worst possible time for the global economy, which was still reeling from the effects of the COVID-19 pandemic. The war exacerbated the dire global economic and social circumstances [44]. Before the war, post-pandemic recovery was predicted to continue in 2022 and 2023, backed by sustained global vaccine efforts, supportive macroeconomic policies, and favorable financial conditions, despite high inflation in several countries [9]. However, the war created a new negative shock for the world economy, affecting the global market of food, energy, and other commodities, fueling ongoing inflation, and prompting a global food crisis. In April 2022, the International Monetary Fund [45] predicted that global growth would fall from an expected 6.1% to 3.6% in 2022 and 2023. Additionally, food and fuel prices would increase by 3% in 2022 and 2.3% in 2023. This might have significant societal ramifications since rising food and energy costs will have a disproportionate impact on the poor and middle classes [20].

Fifthly, the rise in international prices has placed pressure on food-importing nations' foreign reserves and, as a result, their exchange rates. Most food import-dependent nations are already heavily indebted; before the crisis, developing countries spent an average of 16% of export profits on debt service [46]. For instance, as of April 2022, against the dollar, the Egyptian pound had depreciated by 17%, the Moroccan dirham by 4.5%, the Tunisian dinar by 3%, and the Lebanese pound by 25%. Currency depreciation is anticipated to negatively influence inflationary pressures on food and other commodities and services, reducing the buying power of consumers' earnings and adding to the load on governmental budgets. In February–March 2022, food costs had already risen in various countries. In Egypt, for example, food costs increased by an estimated 17% in February 2022 [20].

Additionally, many importing countries are more vulnerable than others and depend on Ukraine and Russia's food supplies. For instance, the Middle East and North Africa (MENA) region countries import more than 50% of their cereal needs and a large part of the wheat, maize, and barley from Ukraine and Russia. Lebanon, for example, obtains 80% of its wheat from Ukraine [19]. This might lead to increased food insecurity and poverty in countries where diets are dominated by government-subsidized bread, such as Egypt and Lebanon [47]. The war in Ukraine also reduces food supplies in the region at a time when governments have little budgetary flexibility to buffer the impact of increased food costs due to economic constraints caused by COVID-19 restrictions [10]. In many low- and middle-income countries (LMICs), governments' capacities to maintain their social safety-net programs and continually subsidize essential food products will be tested [48]. In addition, low-income families will be particularly affected by increased food prices since they spend most of their income on food [49]. For instance, in Egypt, the government spends around $3 billion a year on wheat imports, most of which goes toward a bread subsidy program, the Tamween ration card system, covering 73% of Egyptian families [50]. The recent spike in wheat prices has resulted in a significant increase in the expense of administering this program [49].

Furthermore, commodity speculation is another factor exacerbating these price shocks. However, 'extreme speculation' might cause bigger upward movements than would have been the case based only on supply-and-demand factors. For food, this means higher real-world prices that harm the world's poorest people, but for other commodities this means larger profits or losses for investors. In 2007–2008, a significant surge of speculative financial investment led to skyrocketing futures prices [46]. A Lighthouse Reports study discovered a massive flood of investor capital into specialized agricultural funds, most of it coming from speculators who have nothing to do with the physical production or distribution of wheat but saw a chance to make fast profits. According to the 'Hunger Profiteers' investigation, increased speculation in the commodities markets by investment corporations and funds has led to the price increase. For instance, by 11 April 2022, the top two US agricultural funds, Invesco's agriculture fund and Teucrium's wheat fund, had received a net investment of $1.2 billion, compared to $197 million for the whole year of 2021. By mid-April, they had contracts for wheat futures worth over half of the UK's annual flour consumption [51].

Finally, the war will delay many countries' sustainable transformation of food systems. Several countries are pushing Europe to postpone the transition to greener agriculture to increase agricultural output in response to the war. Indeed, the European Commission said in March 2022 that the publication of recommendations on sustainable farming and the environment would be delayed. With the effect of the Ukrainian war on food supplies, several nations are questioning the European Union's environmental effort [52]. Further, the EU's "Farm to Fork" policy, which seeks to cut pesticide usage in half, reduce fertilizer use by 20%, and commit a quarter of agricultural land to organic farming by the end of the decade, was set to be published in legislative texts in March 2022. It has been postponed indefinitely [53]. Due to high prices, in Brazil, some federal politicians are attempting to open protected indigenous territories for potash mining [54].

As a matter of fact, and as observed during the pandemic [55], the war may have an impact on the progress toward the UN Sustainable Development Goals (SDGs). Indeed, by creating a global food crisis, the war may jeopardize the SDGs' implementation, including SDG 1 (No Poverty) and SDG 2 (Zero hunger). Additionally, high energy costs have driven numerous governments to boost fossil fuel production, thus delaying the shift to renewable energy. For instance, fossil fuels are experiencing a wartime revival, with governments more concerned with lowering the price of oil and gas than with decreasing emissions quickly. In addition, governments are abandoning efforts to phase out coal use. They are scurrying for additional oil and devoting billions of dollars to the construction of liquefied natural gas facilities [56]. Furthermore, rising metal prices are increasing renewable energy costs, which depend on metals such as aluminum and battery-grade nickel [11]. This may jeopardize the implementation of SDG 12 (Responsible sustainable consumption and production).

3. The Impact of the Ukraine Crisis on the Global Agri-Food Markets

Following the dissolution of the Soviet Union in the early 1990s, agricultural productivity and output declined, and Russia and Ukraine became net food importers [57]. However, after intensive modernization and mechanization during the last three decades, Russian and Ukrainian agriculture outputs and food commodities exports have increased significantly, making the region the world's breadbasket. The two countries are now among the world's top producers of various agricultural products, mainly cereals and sunflower oil. Together, in 2020, they account for 72.7% of global trade in sunflower oil and seeds and 34.1% of global trade in wheat [58]. About 12% of the world's total caloric commerce is exported by Russia and Ukraine [27] (Figure 2).

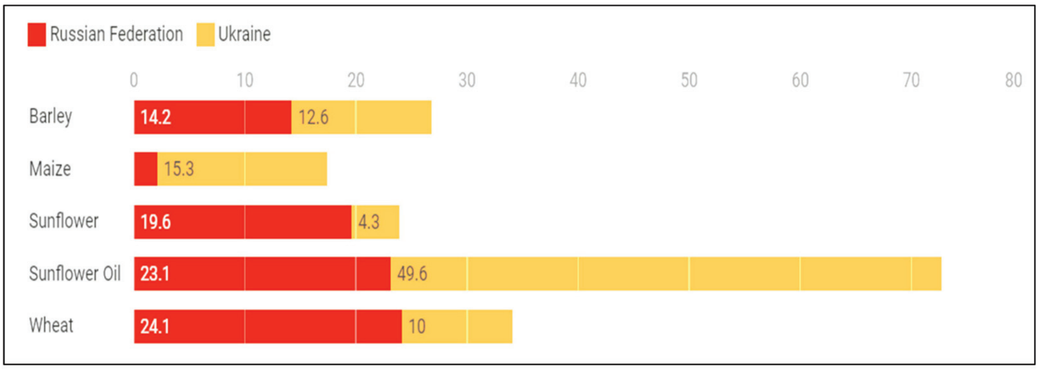

Figure 2. Shares of Russia and Ukraine in the global trade of selected commodities (2018–2020). Source: Glauber and Laborde [27].

3.1. Impact of the War on the Global Cereals Market

Regarding cereals, the contribution of Russia and Ukraine to the global supply is notably substantial for barley, wheat, and maize. Between 2016/17 and 2020/21, the two nations accounted for 19%, 14%, and 4% of the global production of these crops, respectively. In 2021, Russia and Ukraine were among the top three global wheat and maize exporters [14] (Figure 3).

Likewise, due to economic sanctions placed on Russia, there is a great deal of uncertainty about Russian export prospects in the future [14]. The early production outlook for 2022/23 winter crops is favorable in both countries. However, as explained above, the war may harm agricultural operations in Ukraine, prohibiting farmers from attending to their fields, and harvesting and selling their products [14].

Wheat occupies a central place in human nutrition. It is an essential food for more than 35% of the world's population, providing 20% of the daily protein and food calories. In North Africa and West Asia, wheat provides about 40–43% of the daily calories and proteins [59]. The present war may result in a sharp drop in wheat exports from Russia and Ukraine. The great uncertainty concerns the next campaign, which starts in July 2022. If shipments do not restart quickly, the silos will not be available to reap the summer harvests. The most dramatic situation would be when the continuation of the war would hamper the next Ukrainian harvest. Global stocks will not fill such supply disruptions for long. Moreover, there is hardly any untapped production potential globally in the short term. It is uncertain if other exporters can fill in the gap. Wheat supplies in Canada are already limited, and exports from the United States, Argentina, and other nations are likely constrained as the government attempts to assure local supply [19].

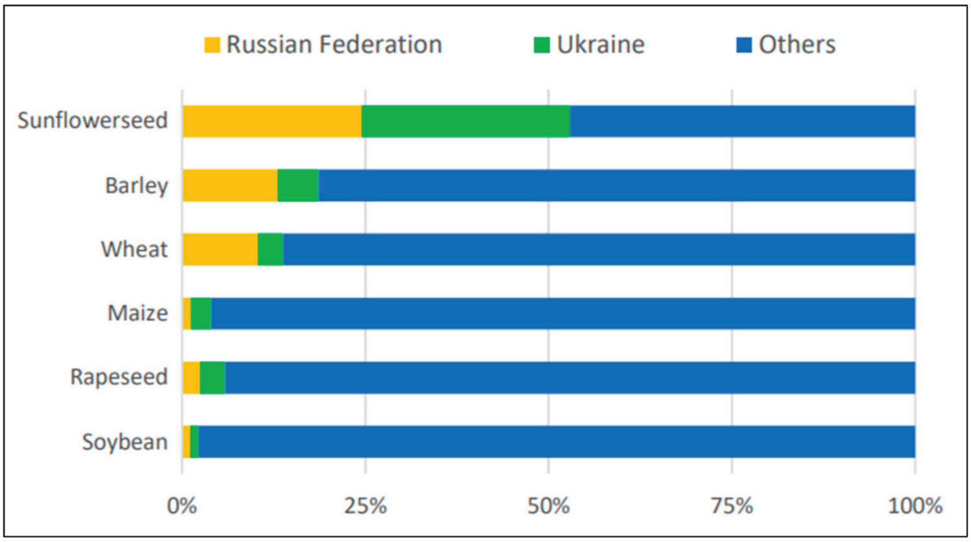

Figure 3. Share of Russia and Ukraine in global exports of selected crops. Source: FAO [19].

The impacts on the maize market depend mainly on Ukraine since Russia is a small producer. Ukraine is the world's fourth-largest maize exporter, accounting for around 15% of the global market. Following the droughts that had an impact on output in Brazil and Argentina, the market is tight, and the war jeopardizes the next crop and Ukraine's ability to export [15]. The first question for maize is about sowing in the spring of 2022 (April–May) for an autumn harvest. If the war prevents sowing, the world corn market, already very tight, will not be able to compensate for the lack of deliveries from Ukraine, with, in perspective, an additional increase in the cost of animal feed and difficulties for the food supply in Latin America. Furthermore, following supply concerns in maize and wheat, the war has raised feed demand for rice, driving rice prices into areas of extreme volatility. In the Asian rice market, domestic and international feed demand inflow has curtailed broken rice supplies [60].

Before the war, global food prices had already hit an all-time high. This was primarily due to market circumstances, but it was also owing to expensive energy, fertilizer, and other agricultural service costs. In February 2022, the FAO Food Price Index (FFPI) (the FAO Food Price Index (FFPI) measures the monthly change in international food commodity prices—it is made up of the average of five commodity price indices (viz. cereal, vegetable oil, dairy, meat, and sugar), weighted by the average export proportion of each category from 2014 to 2016) reached a new record high, 21% more than the previous year and 2.2% higher than the previous high in February 2011. In March 2022, the FFPI averaged 170.1 points, up 24.9 points (17.1%) compared to February 2022, marking its highest level on record since 1990 [19]. Since the beginning of the war, wheat and maize prices have risen by 35%, while overall food prices have increased by 5% globally [20]. On average, in April 2022, the FFPI fell by 1.2 points (0.8%) from its all-time high in March 2022 but was still 29.8% higher than its value in April 2021. While grain prices fell somewhat, vegetable oil prices took the biggest hit in April's Food and Feed Price Index (FFPI). Sugar, meat, and dairy products all saw modest rises in their pricing sub-indices [61].

The consequent supply shortages for importers may be particularly relevant for purchasers in the Near East and North Africa, and, given the significance of wheat as a dietary staple, some nations may increase imports now to secure supplies out of worry that wheat markets will tighten and prices will rise higher. This would add to the strain on global markets [19]. With agricultural prices on the rise, governments across the globe are attempting to secure local cereals supply. For instance, India suspended wheat exports on 14 May 2022, with immediate effects to ensure its national food security and domestic availability and manage inflation. Following the war in Ukraine, India sought to cover the global wheat supply shortfall and intends to export a record 10 million tonnes in 2022–2023 [62]. However, a record-breaking heatwave during India's warmest March on record has reduced this year's wheat harvest, potentially cutting production by up to 50% in some regions of the country [63]. India's export ban has been denounced by the G7 developed countries, who believe it would exacerbate the crisis [64]. Indeed, the impact of India's decision was immediate: prices on the European market skyrocketed on Monday, 16 May 2022. At the closure, the wheat price hit 438 euros/tonne [65]. Likewise, in April 2022, the Serbian government announced a limitation on the quantities of wheat, maize, flour, and cooking oil planned for export to mitigate the risks of market disruptions caused by rising demand on both the international and domestic markets [66].

3.2. Impacts of the War on the Global Vegetable Oil Market

Palm oil (58%), soybean oil (14%), sunflower oil (13%), and rapeseed (canola) oil (7%) together account for 92% of vegetable oils sold in global markets on average between 2019 and 2021 [67]. Due to several factors, such as protracted global supply tightness and robust demand, global vegetable oil supplies have tightened for the last two years, and, consequently, prices have been steadily rising. In 2021, the prices increased by 65% and 63% for rapeseed oil and sunflower oil, respectively [19]. Additionally, drought in South America has reduced soybean yields, notably in Brazil, a major producer. Malaysia's palm oil output fell in December 2021 owing to Typhoon Rai, severe labor shortages, and other challenges exacerbated by COVID-19-related restrictions on worker migration. In Canada, the major exporter of rapeseed oil, drought-affected rapeseed output fell 35% in 2021/22. Therefore, Canada's rapeseed exports are expected to drop by half and rapeseed oil exports by 20% [67].

The war prompted prices to rise in turbulent trade as the war disrupted Black Sea sunflower oil exports. Russia and Ukraine are significant exporters of sunflower oil, and the crisis has dramatically driven up vegetable oil prices. In the absence of other routes to the west through Romania or Poland, about half of last year's harvest's sunflower oil remained in Ukraine. Much of Ukraine's sunflower agricultural region sits east of the Dnieper River, where much of the fighting has since ceased. Due to Black Sea marine trade restrictions, Russian export quotas, and sanctions on corporate operations, Russian exports are now restricted. Sunflower oil has been the most immediately affected, with a more than 40% rise since the invasion. It accounts for around 13% of all vegetable oils sold worldwide, with Ukraine and Russia accounting for over 50% and 25% of all sunflower oil marketed globally, respectively. Because vegetable oils do not need much processing, high costs have already been passed on to consumers and retailers [67].

Consequently, in several countries, such as the United Kingdom, some consumers are being limited in their cooking oil purchases as shops and restaurants respond to rising prices. Indeed, grocery chains in Spain, Greece, Turkey, Belgium, and other countries have restricted cooking oil purchases [68]. The issue has also sparked trade policy reactions throughout the globe, further restricting supply and raising costs [67]. For instance, end of April 2022, Indonesia bans palm oil exports amid domestic price rises, putting more upward pressure on global cooking oil prices. The ban will see Indonesia restrict exports of all cooking oils and related raw materials to decrease local shortages and reign in price increases that potentially cause significant domestic unrest [69]. Meanwhile, the world's second-largest palm oil producer after Indonesia, Malaysia, is still suffering from a chronic labor shortage, having an impact on farmers' yields and output [70].

3.3. Impact of the War on the Global Fertilizer Market

Despite the efforts to reduce nutrient losses to the environment, fertilizers are still a crucial part of agricultural productivity [29]. In general, farmers must use three main kinds of mineral fertilizers to guarantee crop growth: nitrogen (N), phosphate (P), and potash (K). All three of these mineral fertilizers are marketed on a global scale, and their supply is geographically concentrated and controlled by a small number of miners (P and K) and a somewhat larger group of chemical businesses (N) [71].

Russia and Belarus are significant potash mining and production countries, and Russia is a considerable nitrogen supplier. In 2020, Russia was the world's top fertilizer exporter, with an estimated $7.6 billion in exports [72]. Around one-sixth of the world supply of potash fertilizers is exported by Russia, as is more than one-tenth of nitrogen fertilizer exports and around one-sixth of mixed fertilizer exports (containing two or more of nitrogen, potassium, and phosphate) [73]. In 2020, Belarus exported $2.96B in fertilizers, making it the sixth largest exporter globally. In the same year, Belarus was responsible for around 17.6% of the global potash production (K) [74]. Both Russia and Belarus are part of a cartelized potash market that accounts for one-third of worldwide exports and determines the price of potash on the global market (the other half consists of Canada and the USA) [73]. In addition, Russia is a large natural gas supplier, the primary raw material for nitrogen fertilizer. This is most significant to the EU and India, which rely heavily on imported natural gas for their domestic nitrogen production [71].

Before the war, the global fertilizer market was already under severe stress [75]. Surging energy costs, supply curtailments, and trade policies have pushed fertilizer prices up by 80% during 2021, reaching unseen levels since the 2008–2009 global financial crisis [11, 76]. Firstly, fertilizer prices had been rising hand-in-hand with energy prices throughout 2021. As nitrogen-based fertilizers are produced from natural gas (or coal in the case of China), the price of natural gas soared in 2021, pushing some fertilizer prices to their highest level since 2010 [75]. For instance, ammonia production in Europe, an essential input for nitrogen fertilizers, was severely curtailed due to soaring natural gas costs [76]. Several fertilizer companies in Europe were already battling to continue their operations due to rising gas costs, with two UK factories closing in 2021 [77]. For instance, in March 2022, the fertilizer giant Yara announced reducing its European ammonia and urea production capacity by 55% due to rising gas prices [29].

Secondly, additional constraints on supply arising from trade policy measures taken by individual countries put more pressure on the global market. For example, China, a major producer and supplier of phosphate-based fertilizers, has decided to restrict fertilizer exports from July 2021 through June 2022 to ensure domestic supply [73]. Further, following several countries' sanctions on Belarus in 2021, the global potash market faced more turbulence [76]. Later, following the war, on 8 April 2022, the European Union restricted importing fertilizers from Russia and Belarus as part of a larger package of economic sanctions [32].

The war in Ukraine has left the world not only short of important grains but also fertilizers, which could tighten food supplies. During the first quarter of 2022, the World Bank's Fertilizer Price Index climbed over 10% (q/q) to an all-time high in nominal terms [11]. International benchmark prices of fertilizers rose similarly throughout 2021, with many quotations reaching all-time highs. The most notable increases were registered for nitrogen fertilizer. Prices of urea, an essential N fertilizer, have risen by two and a half times over the past 12 months, with prices of phosphorous fertilizer rising in tandem over the same period, while those of potash (K-fertilizer) remained less affected.

Much of South and Central America, West Africa, and Europe—including Ukraine—rely heavily on Russia and Belarus for their fertilizer imports, especially potash. In addition, Russia dominates in exporting natural gas to fuel the production of nitrogenous fertilizers across Europe. The International Energy Agency (IEA) reports that Gazprom's gas exports to Europe decreased by roughly 25% in the last three months of 2021 compared to the same time in 2020 as tensions rose [73]. Roughly 20% of global trade in natural gas comes from Russia, while it contributes about 40% of EU imports. Natural gas prices might rise considerably more if sanctions halt trade. Additional fertilizer shortages may have global consequences, especially in developing countries where price repercussions might dramatically restrict usage and result in poor local harvests during lower global supplies and record global prices. Indeed, higher fertilizer prices make the world's food supply more expensive and less abundant, as farmers skimp on nutrients for their crops and get lower yields [71]. For instance, given Africa's still-limited fertilizer usage (an estimated average of 25 kg per hectare, a fraction of the worldwide average of 121 kg/ha), a decrease in fertilizer use would result in much lower production for the continent, possibly with significant ramifications for food security [29].

4. Conclusion: Towards More Sustainable and Resilient Food Systems

In the early hours of 24 February 2022, Russia started a full-scale military invasion of Ukraine that resulted in the deaths and injuries of civilians, as well as the destruction of key infrastructures. The war has also affected global trade, production, and consumption patterns, keeping commodity prices high until 2024 and threatening global food security. Analyzing the long-term and large-scale effects on global food security of conflict-related disruptions in the global food and fertilizer markets is crucial for understanding the overall impact on food security. The paper highlighted that the war resulted in immediate and far-reaching cascading consequences on global food security. Firstly, the war has both short- and long-term implications on Ukraine's ability to export agricultural products. Secondly, the war prevented farmers from working their fields, and conscription and population displacement caused labor shortages. This situation was exacerbated by limited access to crucial agricultural supplies, such as fertilizers. The war might disrupt the ongoing spring planting campaign and the approaching winter crop harvesting. The war has, as well, some indirect and cascading consequences. Firstly, fertilizer prices are reaching near-record highs, which may severely limit usage and decrease yields. Secondly, as seen during the 2007–2008 food crisis, many countries applied export restrictions, pushing up international market prices and worsening the crisis. Thirdly, panic buying at both country and individual levels is another cascading affect of the war. Finally, the war will delay the sustainable transformation of food systems in many countries. The war may affect the progress toward the SDGs, especially SDG 1 (No Poverty), SDG 2 (Zero hunger), and SDG 12 (Responsible consumption and production).

As the war continues, the potential scope of physical and economic disruptions to food and energy systems raises [73]. Indeed, with the war doubtful to be resolved shortly, its influence on global resource markets will grow, as will the possibility of highly significant 'ripple effects' or 'risk cascades' on economies and society across the globe. These effects may have swift and severe consequences in regions and industries far from the initial occurrence [73].

Unlike the previous global food-price crisis, driven by the 2007–2008 financial crash, the current upheaval comes after governments and households spent two years coping with the COVID-19 pandemic—the most significant economic shock since World War II. Consequently, humanitarian needs are unprecedented, with climate shocks, conflicts, COVID-19, and growing prices pushing millions closer to famine [78]. The war threatens to worsen the situation by pushing up food prices even further, causing shortages, and creating a global food crisis, especially in conflict-affected countries, such as Yemen, Sudan, Nigeria, and Ethiopia. Meanwhile, from an economic and food security perspective, some countries and regions, including several Middle Eastern, Northern and Sub-Saharan African, and South Asian countries, are more vulnerable than others [10]. Indeed, over 30 countries rely on Russia and Ukraine for at least 30% of their wheat imports, while at least 20 countries rely on those two countries for more than 50% of their wheat imports, making them very sensitive to price shocks and/or supply shortages [46].

However, despite the negative adverse consequences of the war, some opportunities may arise and lessen these consequences. Indeed, early indications show that increased soybean and other oilseed prices will encourage farmers to boost oilseed plantings in the United States and the European Union. Increased wheat acreage in Canada might help cover a part of the global supply gap [32]. Additionally, high fertilizer prices will motivate fertilizer makers to boost production. Likewise, global fertilizer merchants will adjust/restructure trade patterns to transfer the additional supply to the most crucial demand locations (mainly Latin America) [71].

However, for many experts, the failure to reform food systems has allowed the war in Ukraine to spark a third global food price crisis in 15 years. In fact, the consequences of the war on food security are being exacerbated by a variety of underlying rigidities, vulnerabilities, and inefficiencies in global food systems, such as food import dependence, inefficient and speculative grain markets, vicious cycles of conflicts, climate change, poverty, and food insecurity [46]. Consequently, specific urgent actions are required, such as lifting trade obstacles that impede nutrition access, maintaining or expanding social protection programs, safeguarding national nutrition budgets, and mobilizing greater resources for humanitarian aid [16]. Ultimately, governments, philanthropic organizations, the corporate sector, and civil society organizations must all work together to achieve a more resilient and sustainable food system that allows people to eat healthy food reasonably [16]. To prevent recurring global food crises, the international community must address the structural causes of hunger and malnutrition, as well as war, armed conflicts, and pervasive violence [79].

In a world of growing complexity and uncertainty, food systems are under increasing pressure to produce sufficient food for the global population, decrease the environmental impacts of production, and buffer against complex global change [80]. The war is both a warning about the operation of agri-food systems and a booster for their innovation [81]. Food systems are facing several challenges, and addressing them effectively necessitates the creation of research that crosses disciplines and innovates at their intersections to generate diverse solutions that address these challenges' social, economic, technical, and policy components [82]. Nonetheless, these and subsequent research will serve as a foundation for organizational and government readiness for future shocks, crises, and pandemics. Indeed, the lessons learned from the global response to the COVID-19 pandemic may be used to confront future shocks and contribute to food system transformation [83,84].

Meanwhile, increasing internal and external risks enhance food systems' shock vulnerability [85]. These shocks could also threaten food supply security [86–88] and disrupt many aspects of food systems, resulting in decreased productivity, market disruption, price volatility, and general system instability, disproportionately affecting the most vulnerable and food-insecure [89]. As highlighted by Hendrickson [90]: "The current economic and social organization of our food system presents social, ecological, and economic risks that threaten the long-term capability of humanity to provide its food needs." (p. 418). Therefore, it is essential to reduce these vulnerabilities and mitigate them by developing policies, technologies, practices, and partnerships that increase the resilience of food systems [80,88]. Further, policymakers in low- and middle-income countries (LMICs) must avoid imposing export limitations or price controls, which might amplify the rise in commodity prices. With increasing inflation, tighter financial conditions, and high debt levels restricting policy options, funding may be redirected toward targeted aid for vulnerable households [91].

In the context of the Russia–Ukraine war, the transition toward a healthy, equitable, and ecologically sustainable food system must be strengthened, not abandoned [92]. A new CGIAR report outlines seven key initiatives for global policymakers to minimize supply and price shocks and improve food systems' resilience to future crises [93]:

1. Invest in real-time analyses: real-time monitoring of food and input price volatility, together with country-specific evaluations of food security threats from price shocks and trade restrictions, provides insights into effective global and national policy responses;
2. Scrutinize market interventions: for instance, farmers might get subsidies or lower taxes on goods such as fertilizer and energy;
3. Do not worsen the situation: learning from the 2007–2008 food price crisis, governments should refrain from restricting exports, imposing sanctions that impede food and fertilizer commerce, stockpiling, or panic purchasing, and scrapping environmental initiatives;
4. Target short-term actions: short-term solutions that have proved effective in prior crises and seem relevant now include eliminating biofuel subsidies and mandates, extending social safety nets to the most disadvantaged, and fixing inefficiencies in current subsidies (such as bread subsidies in Egypt and Tunisia);

5. Make long-term investments in climate-friendly agriculture research: knowledge and innovation in agriculture not only contribute significantly to food security and sustainability, but they are also critical to attaining the several SDG 2 goals of eliminating hunger, achieving food security and improving nutrition, and promoting sustainable agriculture [94];
6. Capitalize on promising innovations and scale them up: satellite and remote sensing photos and data may help farmers optimize their use of inputs such as fertilizer, and scientists monitor the spread of pests and diseases; and
7. Invest in policy research: countries, multilateral organizations, and donors must dedicate resources not just to agricultural science but also to research on the optimal policies, programs, and interventions that might increase resilience.

Furthermore, we advocate for debt relief for poor and food-insecure nations, implementing policies that promote food sovereignty and lessen reliance and dependency on a small number of grain crops and exporting countries, and substituting traditional and locally adapted crops for wheat and maize. Finally, funding for agroecology, which relies less on external inputs (e.g., fertilizers, and pesticides) and, instead, valorizes local and endogenous knowledge and resources, as well as agroecological research, should be increased in order to make domestic food systems more resilient to future shocks and crises.

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Article

How Does Income Heterogeneity Affect Future Perspectives on Food Consumption? Empirical Evidence from Urban China

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Abstract: China is undergoing a rapid dietary transition as well as a changing income distribution. In this paper, we examine the impacts of income heterogeneity on the prediction of food consumption using a dataset that covered 22,210 urban households in China's 6 provinces. The two-stage Exact Affine Stone Index Implicit Marshallian Demand System (EASI demand system) model, which deals with the problem of censoring and endogeneity, is applied to estimate demand elasticity across income strata. Additionally, a dynamic simulation method considering income heterogeneity is conducted to predict future food consumption trends. The results reveal that income elasticity follows a decreasing trend with income growth. Furthermore, the results show that the consumption of major food items in the 15th period will increase by 7.9% to 42.0% over the base period. The growth potential of low-income groups is significantly higher than that of middle- and high-income groups. However, the prediction results may be overestimated if the differences in consumer behavior across income groups and the dynamic simulation procedure are not taken into account. Our study indicates that the consumption features of different income groups need to be included in food consumption forecasts. Moreover, the government should formulate food policies for different income groups to promote a sustainable food system transformation.

Keywords: food consumption; income heterogeneity; future perspective; China; EASI demand system model; dynamic simulation

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1. Introduction

The traditional food consumption structure in China that was centered on fiber-dominated foods has gradually shifted to a Western style of food consumption structure centered on animal food sources [1–3]. According to the National Bureau of Statistics of China (NBSC), in the last 20 years, the per capita consumption of grains and vegetables has dropped by 39.0% and 10.2%, respectively. Meanwhile, the per capita consumption of pork, beef and mutton, poultry, eggs, seafood, and milk increased by 7.9%, 121.1%, 244.1%, 86.3%, 109.0%, and 166.6%, respectively. The changing dietary patterns in China can be attributed to the fast economic growth which is accompanied by the rapid development of urbanization [4–6]. From 2001 to 2021, the per capita disposable income of Chinese residents increased from RMB 6824 to RMB 35,128, with a real growth rate of 6.1% annually, while the urbanization rate has increased from 36.2% to 64.7%. During the same period, the per capita Chinese food expenditure increased from RMB 1270 to RMB 7178, with a real growth rate of 15.0% annually.

However, changes in dietary structure may create potential health problems and environmental crises [7,8]. Excessive intake of fats and animal foods has led to over half of Chinese adults being overweight or obese, which may further increase the morbidity and mortality of chronic diseases and increase medical costs [9,10]. Additionally, dietary changes will increase greenhouse gas emissions and water demand, exacerbating climate change and putting significant pressure on resource management [11–13]. According to the FAOSTAT, China had the most GHG emissions (1.89 Gt CO_2 eq yr^{-1}) in terms of food system emissions in 2019, increased by 39.1% compared with the emission level in 2000 [14]. Furthermore, due to China's large population size, small changes in food consumption structure will cause dramatic fluctuations in total food demand [6,15].

It is vital to accurately predict the trends of future diets in China. These projections enable policy-makers to identify the future health, nutritional, and environmental impacts of projected dietary changes [16]. Accurate predictions on diet trends can provide helpful information for national and international organizations involved in designing food policy [17,18]. Demand elasticity analysis indicates that food consumption responds to changes in income or other determinants, and the estimated demand elasticity can be used to predict the trends of food consumption [5,19]. This method has been widely used in food consumption prediction, but much uncertainty still exists [4,20,21]. The uncertainty of elasticity prediction mainly comes from the estimation of elasticity value. Chen et al. (2016) conducted a meta-analysis of the demand elasticity of 19 types of food in 85 pieces of literature on food consumption in China [22]. Among them, there are significant differences between food items and items inside the same food item. The variations in estimated demand elasticities can be attributed to different models, data, and estimation methods [5]. Therefore, more robust prediction methods and datasets are needed to ensure the accuracy and robustness of the prediction results.

Income is a crucial factor affecting food consumption change [5,23]. Engel's and Bennett's laws demonstrate the impact of income changes on food consumption [4,24]. There is evidence that the dietary structure of Chinese citizens will continue to change with the growth of income in the future, but the exact routes of these changes are still unclear [25,26]. There is heterogeneity in the preferences and consumer behavior of different income groups. Different income groups have different income levels, income growth patterns, and sensitivities to food prices, which is directly reflected in the different elasticities of demand across different income strata [2,27]. This means that using the average elasticity of the entire population to carry out food consumption forecasts may lead to biased results. Therefore, it is very meaningful to conduct a simulation for capturing the possible food consumption trends with more accurate information on elasticities across detailed income strata.

The purpose of this paper is to analyze the impact of income heterogeneity on future perspectives on food consumption. Specifically, this paper estimates food demand elasticities across different income groups in urban China using the EASI demand system model and analyzes the response of food consumption to income changes. Then, this paper predicts the future trends of food consumption in distinct scenarios using a dynamic simulation approach with segment income groups.

Two main contributions are made in this article to the literature. First, this paper uses the more advantageous EASI demand system model and microdata with significant sample sizes to estimate the food demand elasticity of different income groups. This study provides a quantitative basis for analyzing the characteristics of food consumption behavior across income groups. The study also provides parameter support for developing other food-consumption-related research. Second, this paper improves the application of the prediction method in the field of food consumption. The method fully considers the heterogeneity and the dynamic mechanism across income groups and corrects the estimation bias caused by the use of average population elasticity and static simulation. This research provides implications for the formulation of relevant food policies.

The structure of this paper is as follows. Section 2 presents the methodology and the data. In Section 3, the empirical results and simulation results are presented. Section 4 is the discussion, and Section 5 is the conclusion.

2. Materials and Methods

2.1. Study Design

There are two steps to conducting the analysis in this study. The first step is to estimate the income elasticity and price elasticity under the conditions of no income group, five income groups, and one hundred income groups using the two-stage EASI demand system model. The level of detail of the division is considered in the income groups. The second step is to use the dynamic prediction method embedded in income group differences to simulate the changing trend of food consumption. In the prediction process, the differential elasticity information of different income groups is used, and the static simulation mechanism is optimized into a dynamic process.

2.2. Two-Stage EASI Demand System Model

Assuming that preferences are weakly separable, a two-stage budgeting procedure is used to characterize consumer preferences for foods in urban China [19]. Consumers allocate their total expenditures between food and other goods and services in the first stage. In the second stage, consumers allocate their expenditures to thirteen food categories. Finally, the income elasticity and unconditional price elasticity are calculated by the parameters estimated at each stage [28].

2.2.1. First Stage: Engel Model

In the first stage, this study adopts the Engel model [21,29,30]. Following the previous work, this study uses the extended Engel model, in which the core explanatory variables include the logarithm of total expenditure, the square of the logarithm of total expenditure, and the food price index. The model also controls for other commodity prices and demographic variables [31,32].

$$W_f = \alpha_0 + \beta_1 lnX + \beta_2 (lnX)^2 + \beta_3 lnP_{food} + \beta_4 lnP_{other} + \sum_{k=1}^{n} \lambda_k Z_k + \mu \quad (1)$$

where W_f represents the proportion of the total expenditure on the thirteen categories of food defined in this study in the total household expenditure; lnX is the natural logarithm of the total household expenditure; $(lnX)^2$ represents the square of the logarithm of the total household expenditure; Z_k represents the kth demographic variable; μ represents the random disturbance term; α_0, β_1, β_2, β_3, β_4, and λ_k are all parameters to be estimated; and lnP_{food} and lnP_{other} represent the food price index and the price of other commodities, respectively, represented by the Stone price index.

2.2.2. Second Stage: EASI Demand System Model

In the second stage, the EASI demand system model was applied, which can effectively capture the effect of income and price on food consumption. The EASI model not only shares all of the desirable properties of the Quadratic Almost Ideal Demand System (QUAIDS) model but also provides additional benefits. First, it is not subject to the three rank limitations of Gorman and allows the Engel curves to take arbitrary shapes [33]. Second, the EASI error term can be interpreted as unobserved consumer heterogeneity, while the QUAIDS residual does not have this interpretation. Third, the EASI model adds the interaction terms of total expenditure, price, and demographic variables, which have certain advantages and are extensible [34]. The EASI model has recently been widely used in food consumption research [6,35,36].

The EASI model is derived from the cost function based on consumer behavior theory. Consumers with observable characteristics (vector $\mathbf{z}$) and unobservable characteristics (vector $\boldsymbol{\varepsilon}$), given a commodity price (vector $\mathbf{p}$), choose the proportion of budgeted expenditures w for each type of food to achieve a certain level of utility u so that the total cost $C(\mathbf{p}, u, \mathbf{z}, \boldsymbol{\varepsilon})$ is minimized. According to Lewbel and Pendakur, the natural logarithm of the cost function $C(\mathbf{p}, u, \mathbf{z}, \boldsymbol{\varepsilon})$ of the EASI model can be expressed as

$$lnC(\mathbf{p}, u, \mathbf{z}, \boldsymbol{\varepsilon}) = u + (\mathbf{lnp})' \left[\left(\sum_{r=0}^{R} \boldsymbol{\alpha}_{\mathbf{r}} u^r \right) + \mathbf{Cz} + \mathbf{Dz}u \right] + \frac{1}{2} \sum_{l=0}^{L} z_l (\mathbf{lnp})' \mathbf{A}_l (\mathbf{lnp}) + \frac{1}{2} (\mathbf{lnp})' \mathbf{B} (\mathbf{lnp}) u + (\mathbf{lnp})' \boldsymbol{\varepsilon} \quad (2)$$

where $\mathbf{lnp} = (lnp_1, \ldots, lnp_J)'$ represents the J-order vector of the logarithm of food prices; $\mathbf{z} = (z_1, \ldots, z_l)'$ represents the L-order observable influence on consumer preference; $\boldsymbol{\varepsilon} = (\varepsilon_1, \ldots, \varepsilon_J)'$ represents the unobservable features of the J-order affecting consumption preferences and satisfies $\mathbf{1}_I' \boldsymbol{\varepsilon} = 0$; $\mathbf{1}_I$ is a J-order column vector with all elements equal to 1; u is the utility level; $\boldsymbol{\alpha}_{\mathbf{r}}$ is a J-order parameter column vector satisfying $\mathbf{1}_J' \boldsymbol{\alpha}_{\mathbf{0}} = 1$ and $\mathbf{1}_J' \boldsymbol{\alpha}_{\mathbf{r}} = 0$ $(r \neq 0)$; R represents the rank of the demand system, which is an integer and $1 \leq R \leq J - 2$; J is the total number of commodities in the demand system; $\mathbf{A}_l$(l = 1,. . ., L) and $\mathbf{B}$ are both parametric symmetric matrices of order $J \times J$, satisfying $\mathbf{1}_J' \mathbf{A}_l = \mathbf{1}_J' \mathbf{B} = 0_J'$ and when l = 0, z_0 = 1; and both $\mathbf{C}$ and $\mathbf{D}$ are $J \times L$ order parameter matrices, satisfying $\mathbf{1}_J' \mathbf{C} = \mathbf{1}_J' \mathbf{D} = \mathbf{0}_L'$.

The Marshallian demand share (vector $\mathbf{w}$) can be expressed as:

$$\mathbf{w} = \left(\sum_{r=0}^{R} \boldsymbol{\alpha}_r y^r \right) + \mathbf{Cz} + \mathbf{Dz}y + \sum_{l=0}^{L} z_l \mathbf{A}_l (\mathbf{lnp}) + \mathbf{B}(\mathbf{lnp}) y + \boldsymbol{\varepsilon} \quad (3)$$

$$y = \frac{lnx - (\mathbf{lnp})' \mathbf{w} + \frac{1}{2} \sum_{l=0}^{L} z_l (\mathbf{lnp})' \mathbf{A}_l (\mathbf{lnp})}{1 - \frac{1}{2} (\mathbf{lnp})' \mathbf{B} (\mathbf{lnp})} \quad (4)$$

This y has many of the properties of log real expenditures. It equals a cardinalization of utility u, it is affine in nominal expenditures x, and it equals x in the base period when all prices equal one. Like any money-metric utility measure, y is just a mathematically convenient representation of utility. Therefore, the demand system composed of the above two functional expressions is called the Exact Affine Stone Index Implicit Marshallian Demand System.

2.2.3. Censoring Problem

If some households do not purchase all food items, the problem of censoring occurs. Because the data used in this analysis were collected using household surveys, it is common to observe zero values in the consumption of a particular food. In empirical studies, zero consumption has important econometric and economic implications, and statistical estimation procedures that do not account for these zero observations in the dependent variable have biased and inconsistent parameter estimates [37]. To address the problem of censoring in a reasonable way, this study applies the two-step consistent estimation developed by Shonkwiler and Yen (1999) in the second stage [38].

2.2.4. Endogeneity

In the demand system model with expenditure share as the explained variable, the relationship between expenditure share, expenditure, and food price will cause endogeneity. This study uses the generalized method of moments (GMM) to estimate the two-stage models. To verify whether the endogeneity problem can be effectively dealt with after the above methods are applied, this study uses the Dubin–Wu–Hausman (DWH) test [3,30,39].

2.2.5. Elasticity

Combining the condition expenditure elasticity and Marshall price elasticity in the two stages, building on the work of Carpentier and Guyomard (2001) [28], the unconditional expenditure elasticity (income elasticity) e_i^U and unconditional Marshall price elasticity e_{ij}^U of the two-stage EASI demand system model are calculated as:

$$e_i^U = e_i \times e_{food} \quad (5)$$

$$e_{ij}^{U} = e_{ij} + w_j \left[\frac{1}{e_j} + e_{food}^{p} \right] e_i e_j + e_i e_{food} w_j W_f \left(e_j - 1 \right) \quad (6)$$

where e_{food} is the total food expenditure elasticity with respect to income in the first stage; e_i is the conditional expenditure elasticity of food *i*; e_{ij} is the conditional Marshall price elasticity of food *i* with respect to the price of food *j*; e_{food}^{p} is the Marshallian self-price elasticity of total food consumption in the first stage; and W_f is the expenditure share of the food group in total expenditure.

2.3. Dynamic Prediction Method

Compared with the traditional static simulation method, this method fully considers the heterogeneity and the dynamic mechanism across income groups and corrects the estimation bias caused by the use of average population elasticity and static simulation.

Prior to carrying out the simulation analysis, referring to Zheng and Henneberry (2010), Ren et al. (2018), and Li et al. (2021) [21,29,40], four basic assumptions are set. First, it is assumed that the consumer preferences of each income group will not change in the whole simulation process; that is, the income elasticity, price elasticity, income growth rate, and price change rate of a specific income group are fixed. Second, it is assumed that household structure also impacts food consumption. Since the household adult equivalence scale captures precise household structural characteristics, the household-level data in the sample are converted into standard human per capita food consumption through the household adult equivalence scale [41,42]. Third, the impact of factors other than income, price, and family structure on food consumption is not considered. Fourth, the total population is assumed to be constant, but the population of each income group is dynamic.

Based on the above assumptions, the per capita food consumption in period *t* + 1 can be expressed as:

$$q_{i,t+1} = \sum_m \left\{ \left[e_{m,\,i} \left(\frac{\Delta Y_t}{Y_t} \right)_m + \sum_j e_{m,\,ij} \left(\frac{\Delta P_{j,t}}{P_{j,t}} \right) + 1 \right] \cdot q_{m,i,t} E H_{m,t} \right\} / E H_t \quad (7)$$

where *t* = 0, . . . , 14; *i* and *j* represent thirteen food items; $q_{i,t+1}$ represents the per capita consumption of food *i* in period *t* + 1; $q_{m,i,t}$ is the per capita consumption of food *i* in period *t* by the residents of income Group *m*; *E* is the adult-equivalent household population; $H_{m,t}$ represents the number of households in income Group m in period *t*; H_t is the total number of households in the sample in period *t*, $H_t = \sum_{m=1}^{n} H_{m,t}$; *n* is the number of divided income groups; $e_{m,\,i}$ represents the income elasticity of food *i* for residents of income Group *m*; $e_{m,\,ij}$ represents the unconditional Marshall price elasticity for residents in income Group *m*; $(\Delta Y_t / Y_t)_m$ represents the income growth rate of residents in income Group *m* in period *t*; and $\Delta P_{j,t} / P_{j,t}$ is the rate of change in the price of food *j* in period *t*.

Specifically, the threshold value between the income groups is determined when dividing the income groups. If the consumer crosses the threshold between adjacent income groups after the current period's income increase, the consumer will enter the adjacent higher income group during the following period's simulation. Meanwhile, consumers will use the demand elasticity, income growth rate, and price change rate of their current income group in the simulation. Figure 1 displays an overview of the dynamics on food consumption of representative consumer *k*.

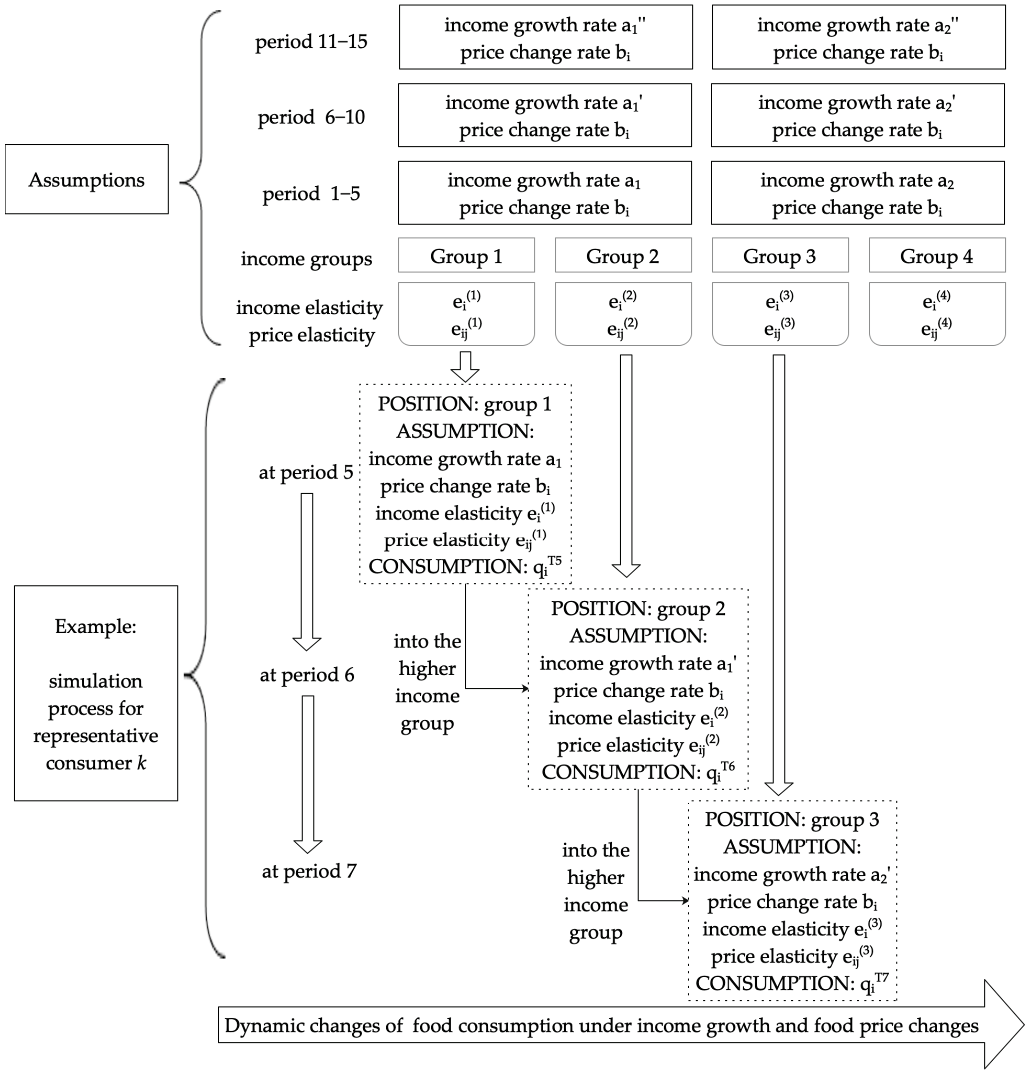

Figure 1. Dynamic simulation process for a representative consumer *k*. Notes: The $'$ and $''$ in this figure are just to indicate that the income growth rate is different in period 1–5, period 6–10 and period 11–15.

Taking the time of sample data as the base period, the changes in food consumption in simulation period 15 are extrapolated given the demand elasticity, income growth rate, and food price change rate. Among them, the demand elasticity of different income groups comes from the estimation results of the EASI model. Moreover, the income growth rate of different income groups is calculated based on data from 2009 to 2018 sourced from the National Bureau of Statistics. In simulation periods 1–5, the income growth rates of the low-income group, lower-middle-income group, middle-income group, upper-middle-income group, and high-income group are 6.66%, 6.94%, 7.28%, 7.44%, and 6.91%, respectively. Furthermore, the extrapolated income growth rate for the 6–10 period and 11–15 period will be reduced and raised by one percentage point, respectively. Additionally, based on the uncertainty and complexity of food price change, this study sets the scenario assumption of the price change rate based on previous research. The price change rates of rice, wheat, oils, pork, beef, mutton, poultry, eggs, dairy, seafood, vegetables, fruits, and other grains are 1.521, 1.015, 1.871, 0.283, 0.516, 0.216, 0.469, 1.099, 0.955, 0.985, −0.064, −0.064, and 1.268, respectively.

2.4. Data and Variables

2.4.1. Data Collection

The data used in this study come from the urban household survey conducted by the National Bureau of Statistics of China. The NBSC household survey data reflect the regional differences through 22,210 urban households from Hebei Province (region: north), Jilin Province (northeast), Henan Province (central), Guangdong Province (south), Sichuan Province (southwest), and Xinjiang Uygur Autonomous Region (west). The advantage of this extensive dataset is that the chosen households in the survey recorded their food consumption and expenditure characteristics using a diary for over a year, which accurately captured the consumption behavior of Chinese households. The data are widely used in Chinese food consumption and related empirical studies [2,43–45]. Therefore, the dataset used in this study is of high quality and can more realistically reflect the dietary features across different income strata in China.

The standard for dividing the income groups in this study is to sort all sample families from low to high according to the level of household disposable income and divide them into five equal parts on average. Specifically, ranking all households in descending order of income, the low-income group refers to households in the lowest 20% income bracket, the high-income group refers to those in the highest 20%, and the lower-middle-income group, middle-income group, and upper-middle-income group refer to the remaining portion of the sample [5,46]. The division standard of 100 equal income groups is the same.

2.4.2. Major Variables and Statistical Analysis

The food system of this study includes thirteen food items, namely, rice, wheat, oils, pork, beef, mutton, poultry, eggs, dairy, seafood, vegetables, fruits, and other grains. In the first stage, the budget share of food expenditure in the total expenditure is the dependent variable, while the shares of each food expenditure in total food expenditure are the dependent variable of the EASI model in the second stage. The proportion of various food expenditures in food expenditures ranges from 1.53% to 20.26% (Table 1).

Table 1. Summary statistics for major variables.

Variables	Mean	S.D.	Variables	Mean	S.D.
Budget share (%)			Social economic variables		
Rice in food expenditure	6.61	3.17	Rice price (kg/RMB)	3.34	0.37
Wheat in food expenditure	2.29	3.07	Wheat price (kg/RMB)	0.67	0.50
Oils in food expenditure	7.07	3.89	Oils price (kg/RMB)	5.34	2.49
Pork in food expenditure	20.26	7.83	Pork price (kg/RMB)	12.46	1.59
Beef in food expenditure	3.01	2.68	Beef price (kg/RMB)	16.60	3.32
Mutton in food expenditure	2.02	3.50	Mutton price (kg/RMB)	19.15	4.12
Poultry in food expenditure	10.22	5.29	Poultry price (kg/RMB)	9.27	9.09
Eggs in food expenditure	4.56	2.60	Eggs price (kg/RMB)	5.92	0.79
Diary in food expenditure	7.24	4.87	Diary price (kg/RMB)	3.06	1.49
Seafood in food expenditure	6.86	4.91	Seafood price (kg/RMB)	5.53	2.74
Vegetables in food expenditure	18.36	5.25	Vegetables price (kg/RMB)	2.55	0.47
Fruits in food expenditure	9.99	4.69	Fruits price (kg/RMB)	1.90	0.79
Other grains in food expenditure	1.53	1.12	Other grains price (kg/RMB)	2.28	0.78
Food in total expenditure	20.55	10.59	Food expenditure (RMB)	6351.73	3504.36
Demographic variables			Region and time dummy variables		
Family size	2.93	0.92	Guangdong (Yes = 1; No = 0)	0.28	0.45
Seniors aged 65 and above (Yes = 1; No = 0)	0.35	0.48	Sichuan(Yes = 1; No = 0)	0.23	0.42
Children aged 14 and below (Yes = 1; No = 0)	0.21	0.41	Jilin (Yes = 1; No = 0)	0.04	0.21
Proportion of FAFH (%)	5.11	5.21	Hebei (Yes = 1; No = 0)	0.17	0.38
Local urban household registration (Yes = 1; No = 0)	0.94	0.24	Henan (Yes = 1; No = 0)	0.22	0.41
High school (Yes = 1; No = 0)	0.34	0.47	Xinjiang (Reference)	0.06	0.25
Age (years old)	47.72	12.27	Year 2007 (Reference)	0.20	0.40
Han nationality (Yes = 1; No = 0)	0.98	0.15	Year 2008 (Yes = 1; No = 0)	0.38	0.49
Town size (small = 1; middle = 2; big = 3)	1.87	0.53	Year 2009 (Yes = 1; No = 0)	0.42	0.49

Notes: Education, age, and ethnicity refer to the meal planner's feature.

Among the explanatory variables, income or expenditure is an essential determinant of food consumption. The average annual food expenditure of the sample households is RMB 6351.73, accounting for 20.55% of the total household consumption expenditure. The literature suggests that the Engel curve forms of various foods are not linear or even quadratic, and there may be higher-order Engel curve forms in practice [33]. Therefore, the Engel curve is set as a cubic type (fourth-order rank demand system) in the EASI model and is tested by the significance of the model coefficient $\boldsymbol{\alpha}_r$.

To examine the differences in the food consumption status of residents in different income groups, this study uses a one-way analysis of variance (ANOVA) to carry out statistical inference. That is, through the F statistic and its significance level, it can be judged whether there is a difference in the overall mean represented by the mean food consumption of residents in different income groups (Table A1). There are significant differences in the consumption of various foods among different income groups at the 1% statistical significance level. In general, the consumption of most foods increases with income levels. This illustrates the importance of considering income group differences when estimating demand elasticity and simulation analysis.

In addition to other control variables except for income, this study also considers food prices and nine demographic variables and controls for time and region effects through year and province dummy variables (Table 1). First, since the dataset does not contain food price variables, the unit value obtained by dividing the expenditure by the consumption quantity is used [27,30,47]. Second, this study added three variables to reflect the impact of household structure on food consumption, including family size, the dummy of whether seniors are aged 65 and above, and the dummy of whether they have children aged 14 and below. Third, this study also added the education, age, and nationality of household food consumption decision-makers. Finally, this study incorporates household registration, characteristics of food consumption when away from home (FAFH), and the level of urbanization [48].

3. Results

3.1. Model Estimation Results

In the first stage, three Engel models were estimated by the least squares method (OLS) and the generalized method of moments (GMM) (Table A2). In all three models, the coefficients of the log of expenditures were significant at the 1% statistical significance level. However, the coefficients of the log of expenditures for Model 1 and Model 2 are negative because neither model considers the nonlinear effect of expenditures, which is not as expected. In contrast, Model 3 considers the nonlinear effects of expenditure while controlling for food prices and other goods prices. Although the coefficient of the log of expenditure in the OLS estimation result is still negative, after using the GMM method to deal with the endogeneity problem, the sign of the coefficient becomes positive. Additionally, the coefficient of the square term of the log of expenditure is also significant at the 1% statistical significance level, as expected. Furthermore, the food price index variables of Model 2 and Model 3 are both significant at the 1% level, but the sign of the coefficient is positive, consistent with the results of Ren et al. (2018) [40]. Considering that Model 3 uses the GMM estimation method to deal with the endogeneity effectively and includes the expenditure square term and the price index, this study uses the estimation results of Model 3 to calculate the elasticity.

In the second stage, the GMM method is used to estimate the EASI demand system model dealing with the problem of censoring and endogeneity. The estimated parameters are very complex, so this study only explains the statistical significance level of critical parameters, including expenditure and prices (Table A3). The estimation results show that 36 parameters of 48 expenditure items (α_{i0}, α_{i1}, α_{i2}, and α_{i3}, $i = 1, \ldots, 12$) are significant at the 1% statistical significance level. Among them, 9 of the 12 parameters of the cubic term of expenditure (α_{i3}, $i = 1, \ldots, 12$) were significant at the 1% statistical significance level. These results prove that the Engel curves of most foods satisfy the cubic characteristics, and the rank of the demand system is higher than the third order. It can be seen that it is correct to select the EASI requirement system model in the second stage. Meanwhile, 9 parameters of the 12 own-price items ($A_{0,ii}$, $i = 1, \ldots, 12$) are significant at the 1% statistical significance level and 1 at the 5% statistical significance level. Of the other 66 cross-price parameters ($A_{0,ij}$, $i = 1, \ldots, 12$, $j = 1, \ldots, 12$, $i \neq j$), 37 parameters were statistically significant, at least at 1%.

The Dubin–Wu–Hausman test results showed that the values of the DWH statistic in the two stages were 35,976.9 and 4443.2, respectively, rejecting the null hypothesis at the 1% statistical significance level and proving that the endogeneity problem was effectively dealt with. Furthermore, the values of order one to order three of the Hessian matrix are 0.0654, 0.0018, and 0.0001, respectively. The values of the remaining k-order main subformulas are all 0, and the results are all non-negative values. Therefore, the EASI demand system model established in this study satisfies the demand property of negativity.

In summary, the parameters estimated by the two-stage EASI demand system model in this study are robust to a certain extent. Next, the income and price elasticity of food demand are estimated based on the estimated parameters.

3.2. Elasticity Estimation Results

For the whole sample, the results of the food demand elasticity estimated by the two-stage EASI model show that the income elasticity of various types of food for urban residents ranges from 0.392 to 0.743 ($p < 0.01$), and the unconditional Marshall own-price elasticity ranges from -1.558 to -0.664 ($p < 0.01$) (Table 2). The three food items with the most flexible income elasticity are beef, mutton, and seafood. The three food items with the most flexible own-price elasticity are wheat, rice, and poultry. The result indicates that these food items are most sensitive to income growth and price changes. Additionally, the conditional Marshall (uncompensated) price elasticity and conditional expenditure elasticity are provided in Table S1. The conditional Hicksian (compensated) price elasticity is provided in Table S2.

This study further calculates the food demand elasticity for different income groups. The most significant finding is that, with the increase in income, the income elasticity displays a gradually decreasing trend (Figure 2), but the own-price elasticity shows a differentiated trend (Figure 3). Among the income elasticity of the five income groups, the income elasticity of the low-income group is 0.565 to 1.020, while the income elasticity of the high-income group is narrowed to 0.162 to 0.239. The empirical results are consistent with the literature, which proves Engel's law [20,45,49]. It should be noted that the distribution pattern of the income elasticity of various foods remained unchanged. Among the income elasticity of the low-income group, the income elasticity of beef is the most elastic, and the income elasticity of other grains is the least elastic. Meanwhile, the change characteristics of income and own-price elasticity with income growth of the 100 income groups are consistent with the five income groups (Figures A1 and A2). The unconditional Marshall (uncompensated) price elasticity and the income elasticity of five income groups are provided in Tables S3–S7.

Table 2. Unconditional Marshall (uncompensated) price elasticity and income elasticity.

	Rice	Wheat	Oils	Pork	Beef	Mutton	Poultry	Eggs	Diary	Seafood	Vegetables	Fruits	Other Grains
Unconditional price elasticity													
Rice	−1.049 ***	0.012 ***	−0.002 ***	0.017 ***	−0.003 ***	0.021 ***	0.020 ***	−0.075 ***	−0.004 ***	−0.036 ***	−0.081 ***	0.021 ***	0.428 ***
Wheat	0.027 ***	−1.189 ***	−0.024 ***	0.044 ***	0.038 ***	0.036 ***	0.059 ***	−0.078 ***	−0.010 ***	0.006 ***	0.148 ***	0.010 ***	0.190 ***
Oils	−0.019 ***	−0.004 ***	−0.955 ***	0.043 ***	−0.008 ***	0.005 ***	0.016 ***	−0.010 ***	0.020 ***	−0.005 ***	0.009 ***	0.025 ***	0.060 ***
Pork	0.041 ***	0.012 ***	0.014 ***	−0.764 ***	−0.002 ***	−0.020 ***	0.016 ***	−0.033 ***	−0.005 ***	−0.014 ***	−0.051 ***	−0.019 ***	0.019 ***
Beef	0.225 ***	0.010 ***	0.032 ***	0.032 ***	−0.792 ***	−0.017 ***	0.063 ***	0.072 ***	−0.025 ***	0.058 ***	0.090 ***	0.037 ***	−0.911 ***
Mutton	−0.005 ***	0.019 ***	0.047 ***	−0.154 ***	−0.003 **	−0.775 ***	0.044 ***	0.145 ***	−0.019 ***	0.052 ***	0.041 ***	0.059 ***	−0.491 ***
Poultry	0.026 ***	0.015 ***	0.011 ***	0.032 ***	0.013 ***	0.007 ***	−0.982 ***	0.007 ***	0.002 ***	0.011 ***	0.038 ***	0.019 ***	−0.010 ***
Eggs	−0.108 ***	0.006 ***	−0.021 ***	−0.141 ***	−0.044 ***	−0.009 ***	0.018 ***	−0.664 ***	−0.008 ***	−0.024 ***	−0.112 ***	0.010 ***	0.442 ***
Diary	−0.027 ***	−0.005 ***	0.011 ***	0.092 ***	−0.018 ***	−0.017 ***	0.005 ***	0.193 ***	−0.845 ***	0.032 ***	0.113 ***	0.074 ***	−0.455 ***
Seafood	−0.023 ***	0.010 ***	−0.007 ***	−0.045 ***	−0.008 ***	0.001 **	0.015 ***	−0.018 ***	−0.002 ***	−0.854 ***	−0.049 ***	0.041 ***	0.007 ***
Vegetables	−0.035 ***	0.005 ***	0.004 ***	−0.054 ***	−0.025 ***	−0.005 ***	0.022 ***	−0.028 ***	−0.004 ***	−0.017 ***	−0.707 ***	−0.009 ***	0.106 ***
Fruits	0.034 ***	0.004 ***	0.018 ***	−0.037 ***	−0.024 ***	0.004 ***	0.020 ***	0.004 ***	0.023 ***	0.030 ***	−0.016 ***	−0.870 ***	0.048 ***
Other grains	1.854 ***	0.285 ***	0.278 ***	0.257 ***	−1.792 ***	−0.649 ***	−0.066 ***	1.319 ***	−2.154 ***	0.035 ***	1.279 ***	0.318 ***	−1.558 ***
Income elasticity	0.483 ***	0.491 ***	0.545 ***	0.533 ***	0.743 ***	0.687 ***	0.536 ***	0.433 ***	0.560 ***	0.616 ***	0.493 ***	0.503 ***	0.392 ***

Notes: ** $p < 0.05$, *** $p < 0.01$.

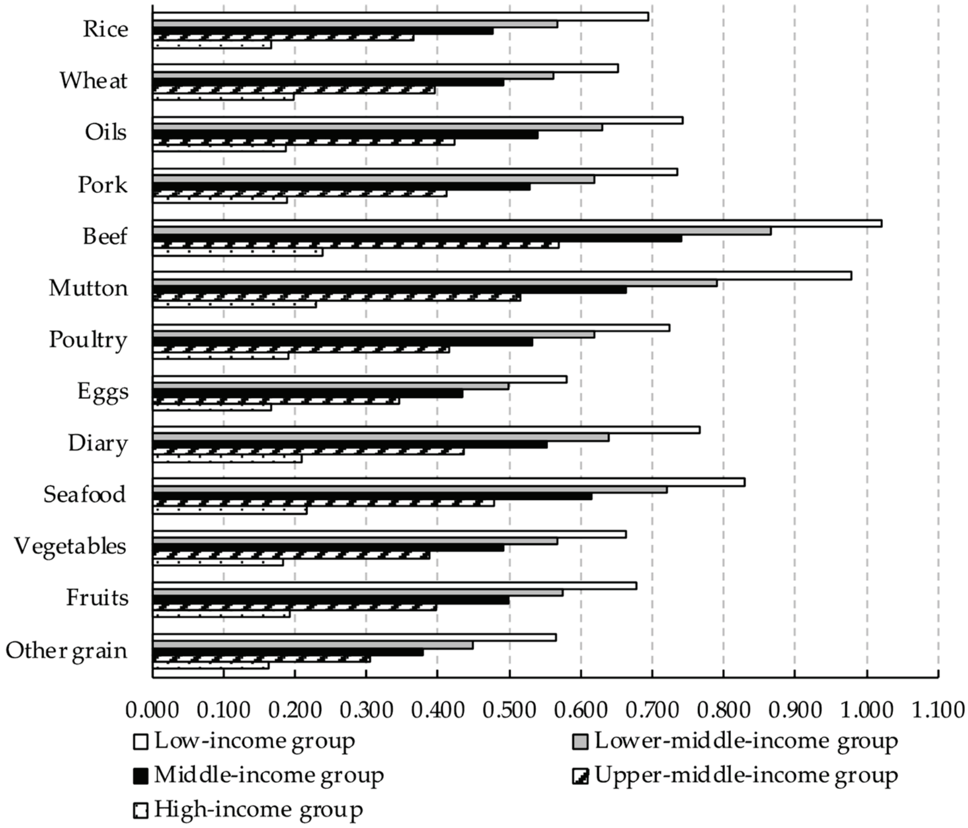

Figure 2. Income elasticity for different income groups estimated by the two-stage EASI demand system model.

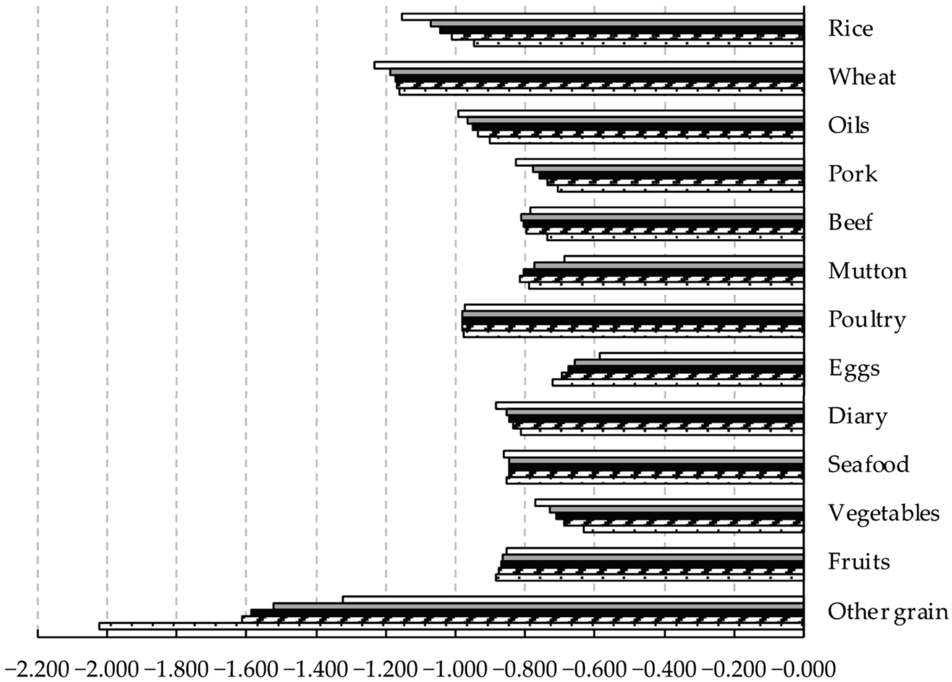

Figure 3. Own-price elasticity for different income groups estimated by the two-stage EASI demand system model.

3.3. Simulation Results

3.3.1. Food Consumption Perspectives

Income growth and price changes will continue to increase the per capita food consumption of Chinese urban residents (Figure 4). The consumption of all food items in the 10th period will increase by 9.8% to 33.1% from the base period. Meanwhile, food consumption in the 15th period will increase by 7.9% to 42.0% over the base period. Among these periods, all foods show steady growth except rice, oil, and dairy, which follow a trend of growth followed by decline. The consumption of meat and fruits and vegetables grows faster than that of grains and other animal foods. In the 15th period, the increase in per capita food consumption in descending order is mutton, fruits, vegetables, beef, pork, poultry, wheat, eggs, other grains, seafood, dairy, rice, and oil. Specifically, the consumption of rice and oil increases first and then decreases, while the consumption of wheat and other grains continues to expand. In meat products, the consumption of pork, beef, mutton, and poultry shows a rapid growth trend, and the growth rate is ranked from high to low as mutton, beef, pork, and poultry. Meanwhile, the consumption of eggs, dairy, and seafood increases steadily. Among them, diary shows an increasing trend before decreasing. Additionally, the consumption of vegetables and fruits has risen rapidly, surpassing some animal products, and the growth rate of fruits is faster than that of vegetables.

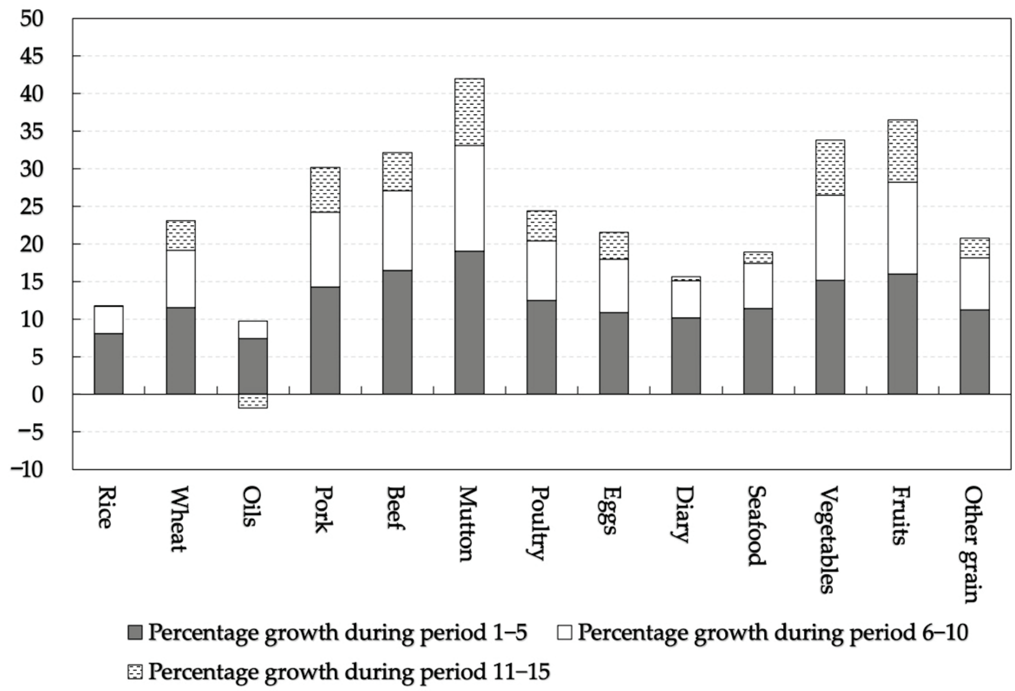

Figure 4. Percentage growth in food consumption after 15 periods. Notes: The change in food consumption is the percentage change from the sample base period.

3.3.2. Impact of Income Heterogeneity on Food Prediction

There are differences in the growth patterns of food consumption across income groups. The simulation results of the low-income, lower-middle-income, middle-income, upper-middle-income, and high-income groups are shown in Figure A3. On the one hand, the food consumption of the low-income, lower-middle-income, and middle-income groups will follow an increasing trend with income growth and price changes. Among them, the per capita consumption of the thirteen foods for residents in the low-income group will increase by 34.9% to 84.7% during the extrapolated 15-year period. The per capita consumption of the thirteen foods in the lower-middle-income group and the middle-income group will increase in the range of 19.6% to 58.3% and 6.5% to 38.4%, respectively, during the extrapolated 15-year period. On the other hand, the food consumption in the upper-middle-income group and the high-income group will show a pattern of either growth or decrease. Among them, in the simulation results of the upper-middle-income group, except for oils, which decrease by 5.3% in the 15th period compared with the base period, the per capita consumption of the other 12 foods will increase by 1.2% to 20.8% in the extrapolated 15th period. In the simulation results for the high-income group, mutton and fruit are the only two food items that show positive growth, with a growing range of 0.2% to 0.9%. The per capita consumption of the other ten food items will be lower than the base period levels in period 15, with a declining range of 1.5% to 20.7%.

Furthermore, this study analyzes the impact of the number of income groups and the dynamic procedure on the simulation results (Table 3). The Baseline Scenario, Scenario 1, and Scenario 2 have 100, 5, and 1 income groups, respectively. In other words, the Baseline scenario and Scenario 1 examine the impact of income heterogeneity on food consumption forecasting, while Scenario 2 continues to use the overall sample parameters for forecasting. Scenario 3 shows the simulation results of the traditional static procedure, which is used to compare and analyze the impact of the simulation method on the prediction results. The simulation results for the different scenarios show that the results are overestimated if the differences in consumer behavior between income groups are not considered. Additionally, the more detailed the division into income groups, the smaller the overestimation bias. The average percentage growth in per capita consumption of the 13 food items in the Baseline scenario, Scenario 1, and Scenario 2 are 24.5%, 28.1%, and 48.2% in period 15, respectively. However, if a dynamic procedure across income groups is not used in the simulation methodology, the prediction results will also be overestimated.

Table 3. Percentage growth in food consumption after period 15 under different scenarios.

Items	Baseline Scenario	Scenario 1	Scenario 2	Scenario 3
Income groups	100 groups	5 groups	1 group	100 groups
Income heterogeneity	Yes	Yes	No	Yes
Dynamic procedure	Yes	Yes	Yes	No
Rice	11.8	14.8	30.1	26.5
Wheat	23.1	23.9	33.9	35.1
Oils	7.9	10.3	26.2	23.5
Pork	30.2	34.8	57.4	50.8
Beef	32.1	36.3	66.9	59.1
Mutton	42.0	44.3	70.7	67.6
Poultry	24.4	29.5	52.8	44.3
Eggs	21.6	24.2	38.0	35.7
Diary	15.6	19.5	39.0	33.9
Seafood	18.9	24.7	51.5	41.2
Vegetables	33.8	37.4	56.8	53.3
Fruits	36.5	40.9	62.5	57.4
Other grains	20.7	24.8	41.1	39.8
Average	24.5	28.1	48.2	43.7

Notes: The change in food consumption is the percentage change from the sample base period.

3.4. Robustness Check

To ensure the robustness of the simulation results, this study conducted a sensitivity analysis for the critical parameter for simulated food consumption changes based on the Baseline scenario (Table 4). When the value of all income and price elasticities decreases by 20% in sensitive Scenario 1, the mean value of the percentage growth in food consumption in the 15th period decreases by 5.7 percentage points. Meanwhile, when the value of all income and price elasticities increases by 20% in sensitive Scenario 2, the mean value of the percentage growth in food consumption in period 15 increases by 6.1 percentage points. The sensitivity analysis demonstrates the robustness of the simulation results.

Table 4. Sensitivity analysis of demand elasticity.

Items	Baseline Scenario with Original Elasticity	Sensitive Scenario 1 with All Elasticity Reduced by 20%		Sensitive Scenario 2 with All Elasticity Increased by 20%	
	Percentage Growth (%)	Percentage Growth (%)	Deviation	Percentage Growth (%)	Deviation
Rice	11.8	9.1	−2.7	14.6	2.8
Wheat	23.1	18.0	−5.1	28.4	5.3
Oils	7.9	6.0	−1.9	10.0	2.1
Pork	30.2	23.2	−7.0	37.7	7.5
Beef	32.1	24.5	−7.6	40.5	8.4
Mutton	42.0	32.1	−9.9	52.8	10.8
Poultry	24.4	18.8	−5.6	30.5	6.1
Eggs	21.6	16.7	−4.9	26.6	5.0
Diary	15.6	12.0	−3.6	19.5	3.9
Seafood	18.9	14.5	−4.4	23.8	4.9
Vegetables	33.8	26.0	−7.8	42.2	8.4
Fruits	36.5	28.0	−8.5	45.6	9.1
Other grains	20.7	15.9	−4.8	25.9	5.2
Average	24.5	18.8	−5.7	30.6	6.1

Notes: The change in food consumption is the percentage change from the sample base period.

4. Discussion

Recently, investigators have examined the impact of income on food consumption and estimated income elasticity based on the EASI model [6,35]. However, there is a general paucity of empirical research that seeks to identify the predictions of food consumption systematically considering the dynamic impacts of income difference. Therefore, this study makes a major contribution to research on food consumption in urban China by demonstrating the dynamic impact of income heterogeneity based on an extensive dataset and the EASI demand system. China's food consumption will continue to grow in the future. Nevertheless, different categories of food will have different growth patterns. Excluding differences in consumption behavior between income groups would significantly overestimate the predicted results for food consumption. Inaccurate demand forecasts could mislead agricultural production. Meanwhile, the inequality of income distribution in China is changing dramatically. China's Gini coefficient, a measure of the unequal distribution of population income, was 0.490 in 2009 and 0.468 in 2020, reflecting significant income disparity in China. Therefore, in addition to the significant changes in the income distribution of Chinese residents, the effects of income heterogeneity persist over time and profoundly affect the dietary transition of Chinese residents. The impact of income heterogeneity on food consumption cannot be ignored.

Considering the predicted results of grains and oil, it can be seen that the consumption of rice and wheat does not show a continuous downward trend. However, rice consumption declined after a steady increase, and wheat consumption continued to grow. The growth in demand for wheat may originate from the westernization and diversification of the dietary patterns of Chinese residents in different regions [50,51]. Furthermore, the challenges posed by the growth in grain consumption demand to China's food security requires attention. Meanwhile, the trend in the consumption of oils and other grains may be related to the improved health perceptions of the population. According to the latest version of the *Chinese Dietary Guidelines (2022)*, reducing fat intake and eating more mixed grains are beneficial for health management [52].

The predicted results for animal source foods show that eggs, as the most widely consumed source of daily protein intake by Chinese residents, will show a rigid growth trend in consumption demand. Additionally, beef, mutton, dairy, and seafood are high-quality products and essential sources of high-quality protein in the diet [2]. The growth in demand for these four food items illustrates the growing diversified dietary needs of the

Chinese population, which indicates that the Chinese dietary transition will continue to shift from the traditional fiber-dominated food system to a Western-style meat-dominated diet [1,4,10]. Furthermore, the increase in greenhouse gas emissions brought by increasing meat consumption and its negative impact on the global environment cannot be ignored.

Furthermore, the predicted expansion of consumption for vegetables and fruits proves that the Chinese population is gradually pursuing a healthier diet. This rising consumption of fruits and vegetables is because vegetables and fruits are rich in vitamins, minerals, and dietary fiber and are low in energy, which has important effects such as reducing the risk of chronic diseases such as cardiovascular diseases and cancer [52–54]. With the further improvement of Chinese residents' income level and health concepts, as well as the decrease in fruit and vegetable prices due to the scale effect and technological progress, healthy and nutritious food with low calories, low fat, and high fiber will become not only a fashion label but also a general lifestyle. Fruits and vegetables will play an increasingly important role in the future dietary structure of Chinese residents.

Several important policy implications are derived from the study. First, since income heterogeneity significantly impacts the prediction results of food consumption, the differences in consumer behavior of different income groups should be fully incorporated into the early warning and prediction research of food consumption. Second, since the food consumption growth potential of low-income groups is significantly higher than that of middle- and high-income groups, joint measures should be taken from the production and import sides to ensure the primary food supply of low-income groups and improve the diet quality of middle- and high-income groups. Third, considering future trends, the structure of food consumption in China will continue to be transformed and upgraded, which will bring about unbalanced nutritional intake and negative environmental impacts. In this context, exploring the transformation path of the food system has become an essential topic in the development of human society [9]. It is an important policy tool to guide residents to transition to new sustainable dietary patterns by strengthening publicity and other options [16,55].

5. Conclusions

In summary, based on nationwide data and the two-stage EASI demand system model, this paper provides insights into the impacts of income heterogeneity on the demand elasticity and prediction of food consumption in urban China. We found that income elasticity shows a decreasing trend with income growth. Furthermore, the consumption of major food items will continue to expand in the future. Nevertheless, there are different growth patterns across income groups. The most obvious finding to emerge from the analysis is that the income elasticity of food consumption displays a gradually decreasing trend with the increase in income, and food consumption of lower income groups increased more than higher income groups during the extrapolated 15-year period. Therefore, the empirical results as well as the simulation results both indicate that food consumption growth potential of low-income groups is significantly higher than that of middle- and high-income groups. However, the prediction results will be overestimated if the differences in consumer behavior across income groups and the dynamic simulation procedure are not taken into account. These findings may further indicate that the consumer characteristics of different income groups need to be included in food consumption forecasts. Moreover, the government should formulate food policies for different income groups to promote a sustainable transformation of the food system. Specifically, on the one hand, it is necessary to meet the food intake of low-income groups by improving the total food supply capacity and emergency food distribution. Food subsidies can be appropriately given to vulnerable groups on the verge of returning to poverty. On the other hand, the transition to healthy diets for middle-income groups should be promoted through dietary guidelines and advertising. In addition, it is recommended that the government should guide urban high-income consumers to further consider the low-carbon attributes of food while ensuring a healthy diet. For example, the food carbon footprint can be reduced by reducing red meat consumption and increasing local vegetable intake.

Supplementary Materials: The following supporting information can be downloaded: https://www.mdpi.com/article/10.3390/foods11172597/s1, Table S1: Conditional Marshall price elasticity and conditional expenditure elasticity (full sample); Table S2: Conditional Hicksian price elasticity (full sample); Table S3: Unconditional Marshall price elasticity and income elasticity (low-income group); Table S4: Unconditional Marshall price elasticity and income elasticity (lower-middle-income group); Table S5: Unconditional Marshall price elasticity and income elasticity (middle-income group); Table S6: Unconditional Marshall price elasticity and income elasticity (upper-middle-income group); Table S7: Unconditional Marshall price elasticity and income elasticity (high-income group).

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Appendix A

Table A1. Average food consumption by income group (kg/year).

Food Items	Low-Income Group	Lower-Middle-Income Group	Middle-Income Group	Upper-Middle-Income Group	High-Income Group	F-Statistic
Rice	91.80 (65.10)	109.60 (75.28)	116.77 (84.60)	122.11 (86.95)	143.86 (91.07)	242.40 ***
Wheat	41.99 (59.94)	46.68 (59.80)	46.88 (61.09)	41.21 (55.65)	25.71 (46.10)	103.45 ***
Oils	26.01 (16.72)	30.29 (17.80)	31.60 (19.41)	31.42 (19.49)	31.81 (20.34)	74.06 ***
Pork	44.70 (31.11)	55.92 (36.66)	61.95 (41.92)	66.05 (43.59)	83.90 (48.88)	552.00 ***
Beef	4.58 (5.10)	6.40 (6.26)	7.01 (6.46)	7.75 (6.96)	8.70 (7.14)	258.02 ***
Mutton	2.84 (5.80)	3.98 (6.75)	4.39 (7.20)	4.47 (6.93)	3.44 (5.43)	49.79 ***
Poultry	21.40 (17.22)	28.41 (22.01)	31.66 (25.07)	35.61 (27.86)	49.30 (32.72)	732.64 ***
Eggs	25.86 (17.25)	32.76 (19.09)	34.51 (19.25)	35.44 (19.88)	33.65 (18.45)	182.75 ***
Diary	45.11 (41.26)	61.86 (49.17)	68.75 (52.22)	75.02 (54.08)	78.87 (56.81)	302.40 ***
Seafood	18.03 (16.83)	24.90 (22.09)	29.67 (27.40)	34.46 (31.38)	48.57 (35.82)	773.34 ***
Vegetables	301.04 (149.93)	368.95 (152.54)	391.33 (161.81)	401.08 (168.25)	409.78 (175.54)	324.62 ***
Fruits	104.85 (72.65)	139.33 (81.59)	151.56 (84.70)	162.82 (87.43)	176.32 (88.48)	476.29 ***
Other grains	27.69 (24.15)	30.67 (24.30)	30.63 (23.92)	30.65 (23.79)	28.95 (21.57)	14.64 ***

Notes: Standard deviations in parentheses; *** $p < 0.01$.

Table A2. Estimated results of the first-stage Engel model.

Variable	Model 1		Model 2		Model 3	
	OLS	GMM	OLS	GMM	OLS	GMM
log expenditure	−0.104 ***	−0.096 ***	−0.104 ***	−0.094 ***	−0.109 ***	0.187 ***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.017)	(0.030)
Square of log expenditure					0.0003	−0.014 ***
					(0.001)	(0.001)
Food price index			0.043 ***	0.043 ***	0.043 ***	0.041 ***
			(0.002)	(0.002)	(0.002)	(0.002)
Other good price index			0.008 ***	0.007 ***	0.008 ***	0.007 ***
			(0.001)	(0.002)	(0.001)	(0.002)
Family size	0.011 ***	0.010 ***	0.011 ***	0.010 ***	0.011 ***	0.010 ***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Seniors aged 65 and above	0.003 **	0.003 ***	0.004 ***	0.004 ***	0.004 ***	0.005 ***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Children aged 14 and below	0.014 ***	0.015 ***	0.013 ***	0.014 ***	0.013 ***	0.014 ***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Proportion of FAFH	−0.003 ***	−0.003 ***	−0.003 ***	−0.003 ***	−0.003 ***	−0.003 ***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Local urban household registration	0.007 ***	0.006 ***	0.005 **	0.004 **	0.005 **	0.004 *
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Education in high school	−0.014 ***	−0.017 ***	−0.014 ***	−0.017 ***	−0.014 ***	−0.016 ***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Age of meal planner	0.001 ***	0.001 ***	0.001 ***	0.001 ***	0.001 ***	0.001 ***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Han nationality of meal planner	0.002	0.004	0.003	0.004	0.003	0.003
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Town size	0.000	0.000	−0.001	0.000	−0.001	−0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Guangdong	0.086 ***	0.084 ***	0.073 ***	0.071 ***	0.073 ***	0.075 ***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Sichuan	0.045 ***	0.047 ***	0.038 ***	0.039 ***	0.038 ***	0.040 ***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Jilin	0.003	0.004	0.002	0.002	0.002	0.004
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Hebei	−0.010 ***	−0.009 ***	−0.001	−0.002	−0.001	−0.003
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Henan	−0.028 ***	−0.027 ***	−0.027 ***	−0.026 ***	−0.027 ***	−0.027 ***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Year 2008	0.015 ***	0.015 ***	0.002	0.004 **	0.002	0.005 **
	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)
Year 2009	0.022 ***	0.021 ***	0.007 **	0.008 ***	0.007 **	0.009 ***
	(0.001)	(0.001)	(0.003)	(0.003)	(0.003)	(0.003)
Constant	1.171 ***	1.091 ***	1.082 ***	0.994 ***	1.110 ***	−0.437 ***
	(0.011)	(0.015)	(0.013)	(0.015)	(0.091)	(0.155)

Notes: Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A3. Estimated results of expenditure and price parameters for the second stage of the EASI demand system model.

	Coef.	S.E.		Coef.	S.E.		Coef.	S.E.		Coef.	S.E.		Coef.	S.E.		Coef.	S.E.
α_{10}	−0.195	0.261	α_{61}	−0.301 ***	0.058	α_{112}	−0.082 ***	0.018	$A_{0,25}$	0.021 ***	0.005	$A_{0,47}$	−0.029 ***	0.007	$A_{0,77}$	0.014 ***	0.005
α_{11}	0.034	0.099	α_{62}	0.047 ***	0.008	α_{113}	0.004 ***	0.001	$A_{0,26}$	0.001	0.005	$A_{0,48}$	0.002	0.017	$A_{0,78}$	−0.004	0.003
α_{12}	0.005	0.013	α_{63}	−0.002 ***	0.000	α_{120}	−1.528 ***	0.255	$A_{0,27}$	−0.001	0.003	$A_{0,49}$	0.008	0.012	$A_{0,79}$	−0.002	0.005
α_{13}	−0.001	0.001	α_{70}	1.073 ***	0.194	α_{121}	0.739 ***	0.109	$A_{0,28}$	0.000	0.004	$A_{0,410}$	0.044 ***	0.012	$A_{0,710}$	0.001	0.004
α_{20}	−0.648	0.160	α_{71}	−0.429 ***	0.084	α_{122}	−0.109 ***	0.016	$A_{0,29}$	0.007	0.005	$A_{0,411}$	0.139 ***	0.028	$A_{0,711}$	−0.017 ***	0.005
α_{21}	0.244 ***	0.068	α_{72}	0.062 ***	0.012	α_{123}	0.005 ***	0.001	$A_{0,210}$	−0.033 ***	0.005	$A_{0,412}$	−0.031 * *	0.015	$A_{0,712}$	−0.008 *	0.005
α_{22}	−0.032 ***	0.010	α_{73}	−0.003 ***	0.001	$A_{0,11}$	−0.167 ***	0.034	$A_{0,211}$	0.037 ***	0.007	$A_{0,55}$	0.045 ***	0.011	$A_{0,88}$	0.081 ***	0.018
α_{23}	0.002 ***	0.000	α_{80}	−0.635 ***	0.133	$A_{0,12}$	−0.011 *	0.006	$A_{0,212}$	0.017 ***	0.005	$A_{0,56}$	−0.033 ***	0.009	$A_{0,89}$	−0.011 **	0.004
α_{30}	0.800 ***	0.232	α_{81}	0.307 ***	0.055	$A_{0,13}$	−0.015 *	0.008	$A_{0,33}$	−0.039 ***	0.011	$A_{0,57}$	0.019 ***	0.004	$A_{0,810}$	−0.024 ***	0.005
α_{31}	−0.341 ***	0.096	α_{82}	−0.048 ***	0.008	$A_{0,14}$	0.110 ***	0.026	$A_{0,34}$	0.051 ***	0.014	$A_{0,58}$	−0.006	0.009	$A_{0,811}$	−0.032 **	0.013
α_{32}	0.052 ***	0.014	α_{83}	0.002 ***	0.000	$A_{0,15}$	0.026 **	0.013	$A_{0,35}$	−0.005	0.007	$A_{0,59}$	0.003	0.006	$A_{0,812}$	−0.008	0.006
α_{33}	−0.003 ***	0.001	α_{90}	−0.301	0.288	$A_{0,16}$	−0.012	0.012	$A_{0,36}$	0.004	0.008	$A_{0,510}$	−0.018 ***	0.006	$A_{0,99}$	−0.004	0.011
α_{40}	0.367	0.304	α_{91}	0.157	0.124	$A_{0,17}$	0.019 ***	0.004	$A_{0,37}$	0.011 ***	0.004	$A_{0,511}$	0.000	0.013	$A_{0,910}$	0.017 **	0.007
α_{41}	−0.172	0.131	α_{92}	−0.023	0.018	$A_{0,18}$	−0.058 ***	0.018	$A_{0,38}$	−0.021 ***	0.005	$A_{0,512}$	−0.021 ***	0.007	$A_{0,911}$	−0.043 ***	0.010
α_{42}	0.024	0.019	α_{93}	0.001	0.001	$A_{0,19}$	0.012	0.007	$A_{0,39}$	0.029 ***	0.007	$A_{0,66}$	0.059 ***	0.011	$A_{0,912}$	0.016 *	0.008
α_{43}	−0.001	0.001	α_{100}	1.091 ***	0.231	$A_{0,110}$	0.023 ***	0.008	$A_{0,310}$	−0.004	0.006	$A_{0,67}$	0.014 ***	0.004	$A_{0,1010}$	−0.025 ***	0.009
α_{50}	1.267 ***	0.192	α_{101}	−0.425 ***	0.102	$A_{0,111}$	−0.018	0.020	$A_{0,311}$	−0.031 ***	0.011	$A_{0,68}$	0.001	0.007	$A_{0,1011}$	−0.034 ***	0.010
α_{51}	−0.559 ***	0.085	α_{102}	0.058 ***	0.015	$A_{0,112}$	0.043 ***	0.011	$A_{0,312}$	0.017 **	0.008	$A_{0,69}$	−0.007	0.007	$A_{0,1012}$	0.018 **	0.008
α_{52}	0.081 ***	0.012	α_{103}	−0.003 ***	0.001	$A_{0,22}$	−0.048 ***	0.004	$A_{0,44}$	−0.148 ***	0.046	$A_{0,610}$	−0.004	0.007	$A_{0,1111}$	−0.067 **	0.030
α_{53}	−0.004 ***	0.001	α_{110}	−0.808 ***	0.293	$A_{0,23}$	−0.012 **	0.005	$A_{0,45}$	0.014	0.018	$A_{0,611}$	0.006	0.013	$A_{0,1112}$	−0.073 ***	0.012
α_{60}	0.641 ***	0.142	α_{111}	0.526 ***	0.125	$A_{0,24}$	0.011	0.009	$A_{0,46}$	0.013	0.018	$A_{0,612}$	0.005	0.008	$A_{0,1212}$	0.019	0.013

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. α is an element of vector α_r and A is an element of vector A_l which are parameters of EASI demand system model.

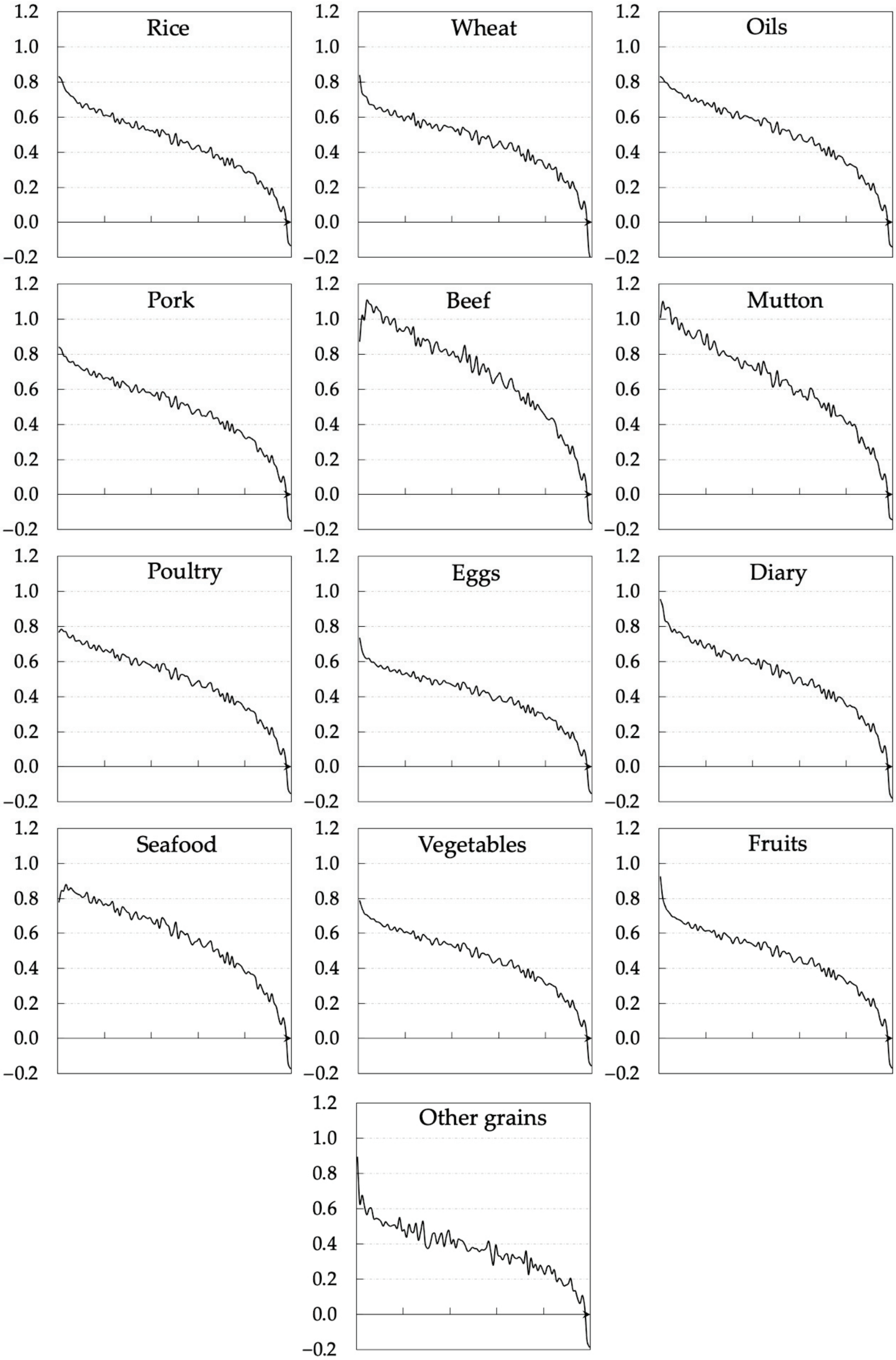

Figure A1. Income elasticity for 100 income groups. Notes: The horizontal axis of each subgraph represents an increase in income from left to right.

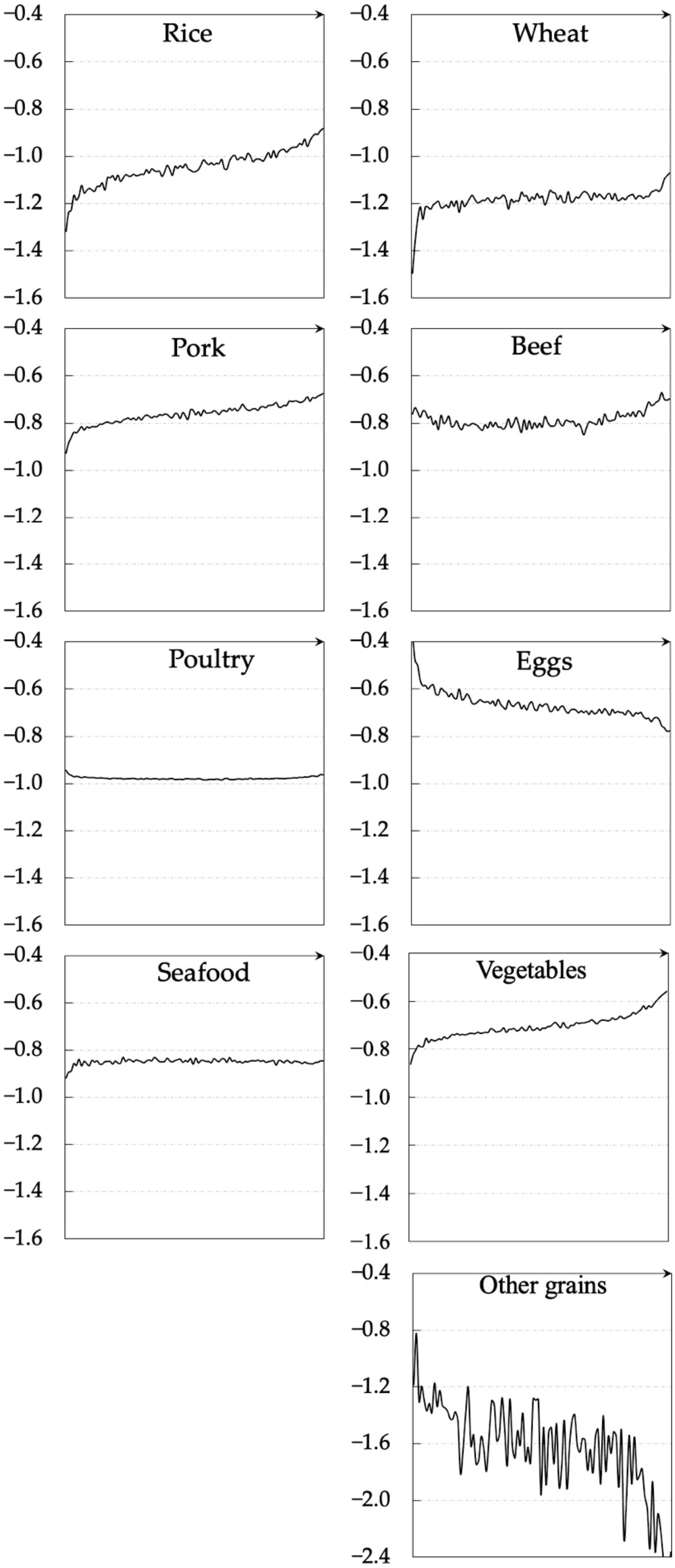

Figure A2. Own-price elasticity for 100 income groups. Notes: The horizontal axis of each subgraph represents an increase in income from left to right.

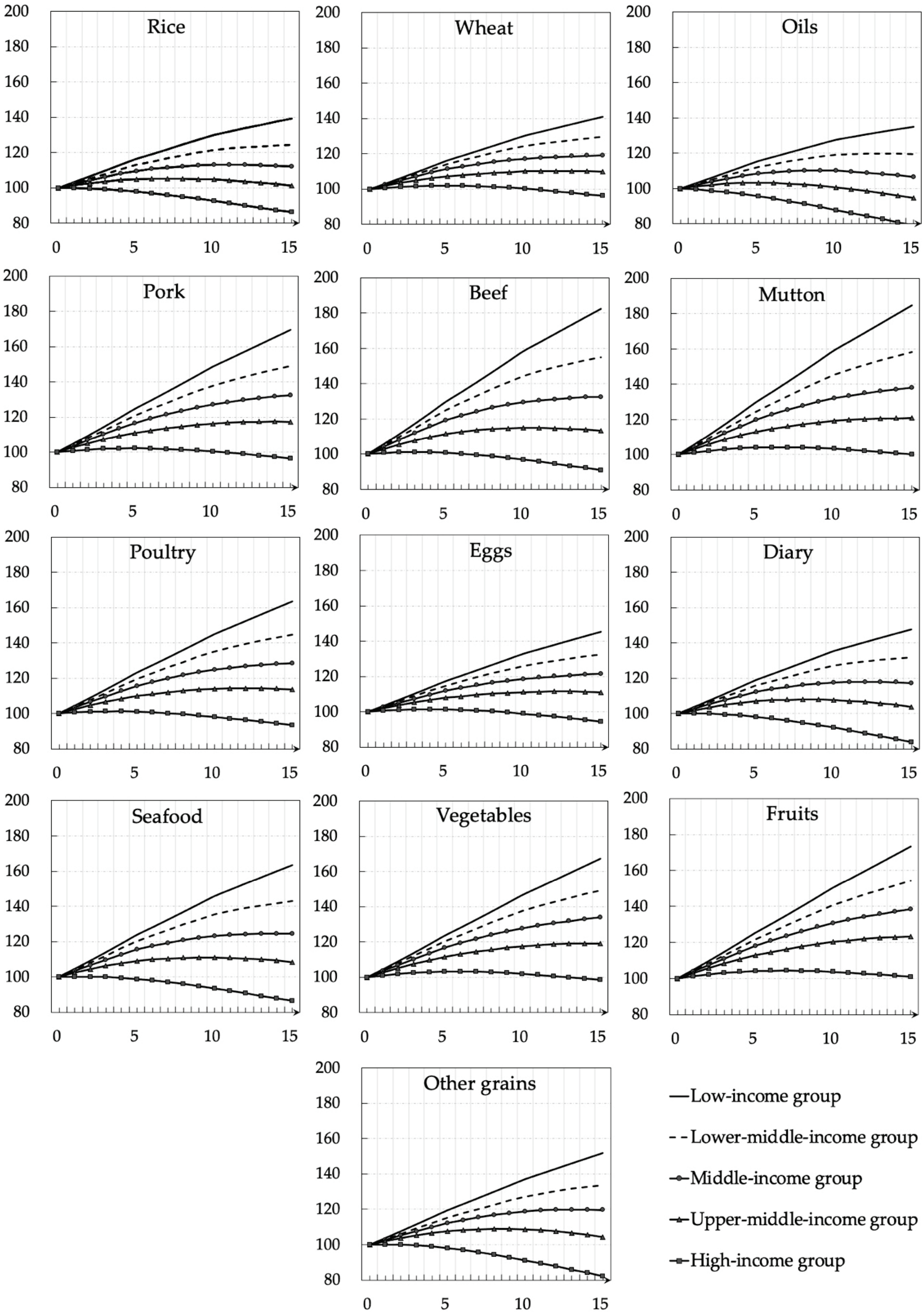

Figure A3. Simulation results of changes in food consumption for different income groups. Notes: The horizontal axis of each subgraph represents the predicting period from period 0 to period 15.

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foods

Article

Quantitative Analysis of Food Safety Policy—Based on Text Mining Methods

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Abstract: Recently, food safety and cold chain food have been closely related to the epidemic. The party and the state have intensified efforts to solve food safety problems and prevent possible epidemic risks. China has issued a series of policies and plans to strengthen food safety supervision to improve the food safety policy system. To our knowledge, little work has studied policy problems of food safety with in-depth quantitative analysis for an extended period. In accordance with the different national policies and regulations for food safety, this paper fills the gap by analyzing the policies and comparing the central and local policies issued in China from 2007–2022. In addition, the Latent Dirichlet Allocation (LDA) topic model and K-Means clustering model are constructed to analyze the content of food safety policies and identify hot topics. Finally, a quantitative analysis of China's food safety policies is made from four aspects: the number of policy release years, the distribution area, the range of action, and the affiliated institutions. The results show that: (a) there is a partial surge in food safety policies issued in 2007, 2011, and 2017; (b) the local food safety policy has a high inheritance to the central policy content, and the trends of annual publication number are highly consistent; (c) the innovation of different policy contents in the region have their own characteristics; (d) the proportion of compulsory and capacity policies is much more significant than that of other types of policies. This paper provides some novel insights into food safety policies.

Keywords: food safety policy; central and local government; text mining; cluster analysis; LDA

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1. Introduction

Although the food safety situation in China continues to improve, there are still some difficulties and challenges in food safety supervision. In 2021, the Beijing Municipal and District Market Supervision Bureau carried out special food safety supervision and spot check work for catering enterprises such as viral food restaurants, chain restaurants, and food courts (BeijingDaily, 2021) [1]. As the most effective method for regulating food safety issues, the central and local governments have issued a series of policy measures to strengthen food safety supervision.

On 28 September 2021, the International Conference on Food Safety and Health, co-organized by the Chinese Society for Food Science and Technology and the International Union of Food Science and Technology, was held in Beijing (Xinhuanet, 2022) [2]. The conference's topic was "New Needs and Challenges for Food Safety and Health in the Post-Epidemic Era", which addressed the latest issues in the food sector at home and abroad. The White Paper on Food Safety Best Practices focuses on four main topics and includes best practices provided by leading companies, which demonstrates that China is paying more and more attention to food safety management. Based on the relevant policies of the food industry in China from 2007 to 2022, it can be found that the policies issued by the central government concentrate on strengthening supervision and unifying norms of the industry. Each city actively implements the national development strategy in terms of local policies. According to the actual situation and existing local development problems, relevant policies and measures are formulated to improve the access threshold of the food industry, avoid inferior products disturbing the market order, and promote the healthy development of the food industry.

Text mining enables people to quickly discover useful information from a large amount of redundant information and reveal the connections between various information. Based on the text mining approach, this paper analyzes and compares the characteristics of central and local food safety policy development, explores the shortcomings of the existing food safety policy system, and makes suggestions to improve the food safety policy system.

2. Literature Review

2.1. Text Mining on Policies and Topic Model

As an emerging field in text mining, policy text mining has been studied by an increasing number of scholars in this area in recent years. Han et al. (2019) used text mining, potential semantic analysis, and other technologies to extract policy elements with the relevant policies of state-owned capital layout and reorganization. The non-interventionist approach avoids the validity flaws caused by the subjective bias of researchers and provides more objective policy recommendations for policymakers from a neutral perspective [3]. Miao et al. (2021) used text mining technology to construct a policy evaluation model using logistics policies from three Chinese provinces. They scored the logistics policy texts using the Policy Modeling Consistency (PMC) model to visually reflect the focus of logistics policy documents in different provinces [4]. Park et al. (2022) analyzed 103,428 Google Maps reviews from major U.S. hub airports to identify representative topics of passenger concern and to further investigate spatial drivers and policy compliance in an epidemic environment [5]. Gao et al. (2021) combined text mining and machine learning methods to propose a modular policy evaluation system, which includes data acquisition, data processing, index evaluation construction, and score evaluation. Compared with the traditional policy evaluation method, it has higher accuracy, objectivity, and efficiency, which is helpful for the government's policy implementation [6].

The LDA model, as a topic model for semantic extraction of text information, is widely used in text classification, text clustering, abstract extraction, and sentiment analysis (Zhu et al. 2017) [7]. Jiang et al. (2012) used the CUDA toolkit provided by NVDIA to optimize the traditional LDA program, which significantly accelerated the program's speed when processing documents [8]. Jeon and Kim (2015) proposed a spatial class LDA model for image classification, which significantly improves image classification accuracy [9]. Wei (2017) fused LDA with fuzzy k-nearest neighbors and proposed a fully fuzzy LDA method to enhance the recognition performance of the model [10]. Shi et al. (2017) proposed an augmented LDA model using high-quality word vectors. As a result, the cumulative accuracy of the model under various metrics increased by 5.3% on average [11]. In addition, text clustering is an important research direction in the field of text mining. It has important application value in the organization and browsing of large-scale text sets and the automatic generation of text set classification (Shi and Han 2010) [12]. As one of the classical clustering algorithms based on partition, the K-means algorithm is widely used in text clustering (Yuan et al. 2019) [13]. Li et al. (2017) proposed a distributed improved K-means algorithm based on Hadoop, which overcomes the problem that traditional algorithms are easy to fall into local optimal solution due to the uncertainty of the initial center point [14]. Yang et al. (2016) proposed an improved K-means clustering algorithm based on Adaptive Cuckoo Search, which improves the search accuracy and convergence speed [15].

2.2. Research on Food Safety

2.2.1. Related Technologies Used in the Field of Food

The use of modern scientific techniques to ensure food safety and guarantee the quality of food and drugs has attracted the attention of many researchers. Wu and Sun (2013) found that hyperspectral imaging is a non-destructive and rapid method for food quality and safety analysis and assessment [16]. Bai and Liu (2015) introduced the applications of nanotechnology and nanomaterials in food processing, food packaging, food machinery, food testing, and food traceability [17]. Jespersen et al. (2016) measured the food safety culture in the food manufacturing industry through the food safety maturity model to determine the focus of strengthening the food safety culture [18]. Nyarugwe et al. (2020) believed that understanding national values and food safety governance methods would influence food safety culture in different ways, which is expected to develop the best methods for companies operating to improve food safety performance [19]. Fan et al. (2020) studied the progress of carbon precursor utilization of food waste and its application in food safety testing and concluded that food waste has the potential to prepare carbon quantum dots (CQDs) [20]. Tao et al. (2019) proposed a hierarchical multi-domain blockchain (HMDBC) network structure and secondary inspection mechanism to improve the traditional food regulatory system with problems such as a lack of industry chain and data fragmentation [21]. Thangalakshmi et al. (2021) introduced 3D food printing technology and experimented with the best proportional composition of raw materials for 3D printability [22].

2.2.2. Research on Food Logistics

Food logistics have been widely studied, including controlling food risks in the supply chain and the food early warning system. Ng and Yang (2009) proposed using the mass media's public wisdom to improve the existing food supply chain framework [23]. Zhang (2014) proposed a framework for a food safety early warning system based on consumer feedback, which can effectively avoid the outbreak of widespread food safety events and reduce food safety risks in China [24]. Zheng et al. (2021) proposed a food safety traceability system based on RFID two-dimensional code technology and big data storage technology, which can trace the whole process of food production information and is conducive to epidemic prevention and control [25]. Henrichs (2021) used an adaptive system in the food supply chain to reduce food waste and improve food safety [26]. Anand and Saxena (2022) believed that food safety and quality issues are critical during the COVID-19 pandemic and explored the application of IOT devices for safe-packaged food and frozen food to improve food standards [27].

2.2.3. Food Safety Policy

There is a stream of research on food safety-related policies. Basha (2014) suggested that policymakers should develop appropriate marketing strategies to promote organic food as a healthier and safer food for society [28]. Simone et al. (2019) explored whether food safety policies affect the support, risk control, and time preferences of respondents and found that good news and bad news affect preferences and welfare measures [29]. Li et al. (2021) systematically analyzed the food safety-related literature and policies and identified the factors influencing food safety problems in China. They divide the evolution of China's pollution-based food safety policies into four stages [30]. However, most scholars study food safety policies from a qualitative perspective, and few conduct quantitative analysis. Ni (2017) used the quantitative method of policy text to study the structure and characteristics of China's food safety policy under the current regulatory system [31].

In all, most of the research on food safety is on the technical aspects and risk control. However, few articles systematically review food safety policies and analyze the policies' role in the regulatory system. In addition, few papers on food safety policy grooming suffer from a possible lack of comprehensiveness in selecting, collecting, and organizing policy texts. Based on the LDA topic model and K-Means clustering model, this paper analyzed the food safety policies issued by the central and local governments, respectively, from a quantitative perspective that included the number of policy release years, the distribution area, the range of action, and the affiliated institutions.

The remainder of this paper is structured as follows: Section 3 introduces operations such as data acquisition and preprocessing and develops a preliminary understanding of the topics of policy texts. Section 4 uses the LDA and K-Means model for topic recognition of policy texts, and the results are compared and analyzed. Section 5 quantifies food safety policies from four perspectives and provides a specific analysis. Finally, Section 6 summarizes the research results. The flowchart in Figure 1 shows the methodology that we have followed in this research.

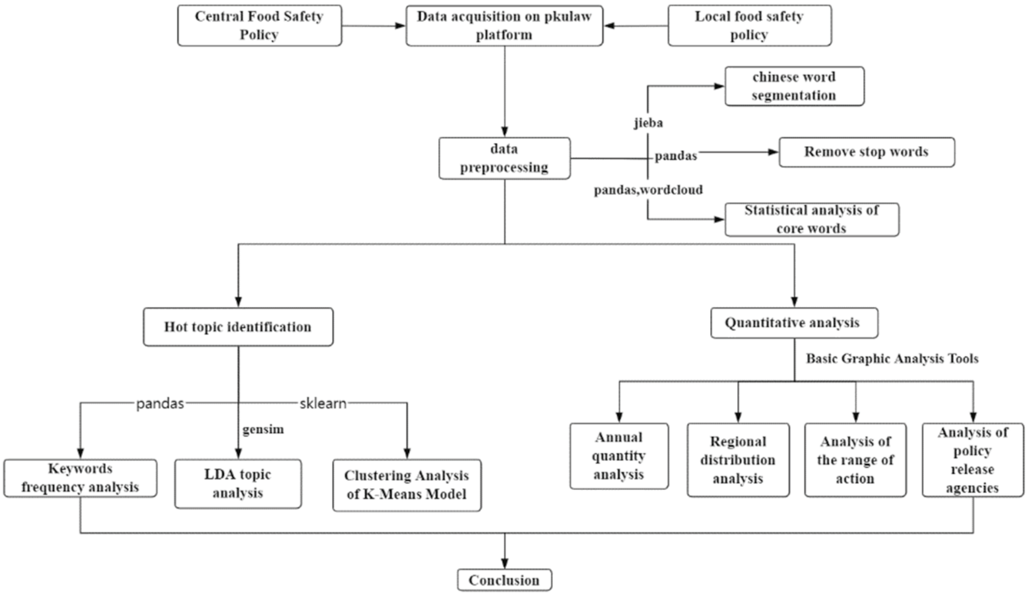

Figure 1. The methodological approach followed in this study.

3. Data Processing and Statistical Analysis of Core Words

3.1. Data Collection for Food Safety Policy

In the PKULAW dataset, the central and local food safety policies issued in China from 2007 to 2022 are crawled, including title, release department, release date, timeliness, effectiveness level, legal category, and policy-specific content. The vacancy value is eliminated for all of the obtained policy documents, and the duplicate removal operation is carried out. Although only the document number of the central food safety policy is collected, one of the local food safety policies is not collected. Therefore, Python has been mainly been used to de-duplicate documents with the same title. The data in each document are arranged according to the release date of the policy, while a total of 10,180 target data are obtained.

3.2. Statistical Analysis of Core Words

After word segmentation and stop words, the effective keywords and the frequency of the target data obtained by the central and local food safety policies are analyzed. The top 20 high-frequency keywords of the central and local food safety policies are: food and drug, agricultural products, additives, catering, health, product quality, safety accidents, school canteens, diet, raw materials, quarantine, safety hazards, family-planning commission, food poisoning, pesticides, disinfection, shelf life, infants, butcher, and dairy products. It has been found that the food safety policies issued by the central government are highly consistent with those issued by the local government, who focus on agricultural products and additives.

Agricultural products are one of the most widely consumed food in China, which require increasingly high quality. Currently, China's agriculture has fully entered the global economic competition stage, which pays increasing attention to the safety control of agricultural products that are conducive to increasing market competitiveness. As an essential part of the modern food industry, food additives have greatly promoted the development of the food industry. However, controlling the production, procurement, storage, and other aspects is also very important. Irrational use of additives can cause significant harm to the human body. Therefore, both the central and local governments regard the standardization of the production and use of food additives as a focus on food safety. However, the central government policies are mostly macros, such as laws and regulations, guidance, and planning outlines. Policies formulated by local ministries are more relevant to their own practicality, primarily because of announcements and notifications.

4. Hot Topic Identification

4.1. Keyword Analysis of Food Safety Policies

From 2007 to 2021, the central government issued four policy documents. This paper divides the time between the four policy documents into one stage, so the four documents are separated into three stages. Because the policies issued in 2022 have not yet been fully collected, the number is small; therefore, the policies of 2022 and 2021 are merged. Based on the central release of food safety planning at different times, the three stages of food safety development are determined.

4.1.1. Keywords Frequency Analysis of Central Food Safety Policy

According to China's food safety policy course, the central food safety policy research is divided into three phases. The first phase is between the "Eleventh Five-Year Plan" and the "Twelfth Five-Year Plan", which corresponds to the period from 2007 to 2012. The second phase is between the "Twelfth Five-Year Plan" and the "Thirteenth Five-Year Plan", which corresponds to the period from 2013 to 2017. Finally, the third phase is between the "Thirteenth Five-Year Plan" and the "Fourteenth Five-Year Plan", which corresponds to the period from 2018 to 2022. The research direction of food safety in these three stages is studied, and the course of China's food safety policy is shown in Figure 2.

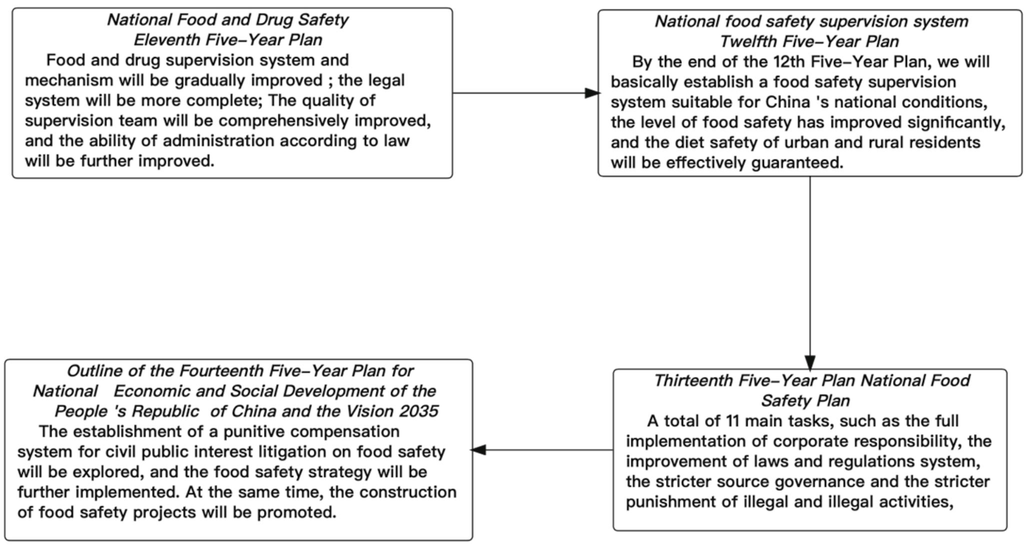

Figure 2. The Policy development process of the food safety industry.

Table 1 shows the central food safety policy's annual keywords and corresponding word frequency information. There are three main keyword topics for food safety in China: the first is the main upper regulatory authority for food safety, which includes the National Medical Products Administration (NMPA) and the China Entry-Exit Inspection and Quarantine (CIQ); the second is high-risk food safety products, which mainly includes healthcare food, infant milk powder, tableware, and alcohol; finally, the third is the main object of food safety and places such as food markets, canteens, and sellers.

Table 1. Annual keywords of national food safety policy.

2007–2012		2013–2017		2018–2022	
Keywords	**Word Frequency**	**Keywords**	**Word Frequency**	**Keywords**	**Word Frequency**
Additive	259	National Food Safety Standards	449	Additive	287
NMPA	216	Additive	315	National Food Safety Standards	205
National Food Safety Standards	191	Food and Drug	311	Infant	59
School Canteen	140	Recipes	122	Expiration Date	57
Product Quality	136	Healthcare Food	122	Tableware	33
Safety Accidents	121	Milk Powder	72	Sellers	29
Healthcare Food	113	Expiration Date	43	Date of Manufacture	27
Food Market	69	Level Measurement of Residue	31	Canteen	25
CIQ	59	Alcohol Products	28	Responsible Person	23
Enforcement Inspection	53	Date of Manufacture	27	Failure Rate	23

4.1.2. Keywords Frequency Analysis of Local Food Safety Policies

Table 2 shows the local food safety policy's annual keywords and corresponding word frequency information. Comparing the keywords in the food safety policies issued by the central and local governments shows a high degree of consistency between the policies. This may be because the local government should first formulate policies around the general framework of policies formulated by the central government and then adjust the policies to suit the economic and social development of the region and consider the specific local conditions. The keywords' frequencies show that local governments are determined to maintain stability and build a strong defense line by focusing on aquatic products, canteens, and food and drug products. At the same time, they comprehensively investigate hidden dangers, strictly control the use of various additives and fake and shoddy products, and deepen special rectification. At the National Conference on Food Safety in the Market Supervision System held on 27 April 2022, the government also deployed the next phase of the "guard the bottom line, investigate hidden dangers, ensure safety" special work to ensure the overall stability of food safety was in accordance with the sound development trend.

Table 2. Annual keywords of local food safety policy.

2008–2012		2013–2017		2018–2022	
Keywords	**Word Frequency**	**Keywords**	**Word Frequency**	**Keywords**	**Word Frequency**
Additive	3051	Food and Drug	4767	Safety Accidents	1405
Safety Accidents	2400	Safety Accidents	2632	Food and Drug	845
Canteen	1495	Additive	1228	Canteen	654
Food and Drug	1297	Highlights of food safety work arrangements	918	Education Bureau	308
Physical Health	914	Life Safety	705	Meals	255
Healthcare Food	805	Food Poisoning	701	Source	255
Safety Hazards	756	Safety Hazards	689	Life Safety	253
Aquatic Products	689	Aquatic Products	669	Foodborne	251
Life Safety	634	Source	645	National Food Safety Standards	245
counterfeit and shoddy goods	632	Healthcare Food	582	prewarning	221
Clenbuterol	622	Infant	553	Food Market	202

4.2. LDA Topic Analysis

Table 3 shows that the first three topics are food itself. The government has formulated corresponding legal norms for using raw materials and additives and has carried out publicity and education for various enterprises to ensure food safety from the source. The last three topics are aimed at all aspects of food and drug production, such as logistics, distribution, and upper supervision. In all, it can be seen that the government has put forward corresponding policies for the whole food distribution process to properly regulate the food industry market environment. The characteristics of each Topic combined with the actual development of China's food safety industry and the implementation of China's policies are analyzed as follows.

(1) Food additives. In order to strengthen the management of food additives, China has introduced a series of national food safety standards and has established a relatively perfect national food safety standard system for food additives. In the whole system, a total of 600 food additive food safety national standards are formulated, which can meet the industry supervision and demand in China. Furthermore, some of the standards in the system have been advanced, such as the "Food safety national standards Food Additives Gum base and its ingredients". Similarly, China has improved the legal system, revised the standards system, carried out a series of sampling and risk monitoring, and conducted other means of continuously strengthening the supervision of food additives. All these measures show that China has carried out the omnidirectional management of food additives, which can effectively guarantee food safety.

(2) Source tracing. As an effective means to ensure food safety, traceability has always been highly valued by governments, industry organizations, and enterprises. In 2004, the Shandong Institute of Standardization carried out research on the tracking and traceability of the agricultural products supply chain, established the "food safety traceability system" with Chinese characteristics, realized the traceability management of all aspects of product production and circulation, and recorded the product quality-related information from production to packaging. In addition, the additional information data in the process of product circulation is recorded to ensure full traceability of products from production to sales. Although China has effectively promoted the improvement of the traceability system construction, it is still difficult to implement effective tracking and traceability, control, and recall when food safety problems occur. Combined with the current situation of epidemic prevention and control, China continues to do a good job on imported cold chain food "physical defense" work, which strengthens the inspection and control of food related to the epidemic and resolutely puts an end to food safety problems.

(3) Regulation and early warning. As food safety incidents continue to occur frequently, China puts forward various normative measures, such as the "food safety operation norms of catering services" issued by the State Administration for Market Regulation in 2018. In addition, since food safety is a systemic project that includes all aspects, from cultivation to distribution, different aspects face different problems. For these issues, China has established a food safety early warning mechanism to socially supervise and manage food safety to protect workers' and consumers' lives and health. However, scholars have more research on food safety supervision and less research on food safety early warning mechanisms and early warning management.

(4) Food logistics. The Food supply chain in China has problems such as high logistics costs, perishable products, and a low degree of informatization. Zhejiang Province and Beijing have implemented the "Network catering service catering safety management specification" and "Takeaway seal" as local legislation in response to consumers' concerns about the disconnection between safety and health protection in the last mile of takeaway distribution. As the development of food logistics is inevitable, the operation mechanism of the logistics supply chain needs to be improved, and the upper and lower sources of the production chain should be combined. At the same time, the application of cold chain technology should be promoted, and the operation and management system of the cold chain should be optimized to solve the problems

of food diversity and fast demand that are closely related to food logistics, which can improve the competitiveness of China's food enterprises.

(5) Campus security. Campus food safety issues are closely related to the health of adolescents. However, in recent years, incidents in provinces and cities have occurred from time to time. For example, in 2021, students in middle schools in Henan Province detected excessive Escherichia coli in their lunches. In 2018, an international school in Shanghai provided mildew and expired food to children. Therefore, campus catering food safety should not be ignored. How to encourage students to eat healthy and nutritiously is a big concern. Relevant departments in various regions have continued to carry out campus food safety protection actions against this problem and strictly abide by the bottom line of campus food safety. The market supervision department should further improve supervision efficiency, strictly control the risk of campus food safety, and protect the safety of teachers and students.

(6) Upper supervision. Food safety is related to people's health and is a major event related to the national economy and people's livelihood. The "14th Five-Year Plan" proposes to strengthen biosafety protection and improve the level of safety and security of people's health products and services such as food and drugs. With the goal of being "scientific, unified, authoritative, and efficient", China has continuously deepened the food safety supervision system reform. From decentralized supervision to unified supervision of food safety, and from food safety supervision to food safety governance, China's food safety supervision has entered a new stage.

Table 3. Hot words with 6 Topics for LDA.

Topics	Topic 1	Topic 2	Topic 3	Topic 4	Topic 5	Topic 6
	Food Additives	**Source Tracing**	**Regulation and Early Warning**	**Food Logistics**	**Campus Assurance**	**Upper-Level Supervision**
8 words with a high frequency of occurrence	Additive	Source	Safety Accident	Diet	School Canteen	Health Bureau
	Health Food	Place of origin	Life Safety	Chain Stores	Students	Department of Health
	Raw Materials	Grain	The Law	Delivery	Education Bureau	Foodborne
	Agricultural Products	Cold Chain	Early Warning	Ordering	Kindergarten	Infectious Diseases
	Dairy Product	Agricultural Products	Security Events	Disinfection	Schools	Product Quality
	Quarantine	Food Market	Publicity and Education	Restaurants	Dining	Ministry of Health
	Poultry	Grain Bureau	Food and Drug	Selection	Raw materials	Quality Control
	Recipes	Wholesale Market	Quality	Catering Utensils	Food Poisoning	Quarantine Bureau

4.3. Cluster Analysis of Food Safety Policies

The central policy provides official keywords in the PKULAW database, which refines a document's core information. The central food safety policy data is replaced with the officially given keywords. When searching for policy information, the Peking University magic database will give official keywords to each policy to summarize the main content of the policy. It is believed that the keywords of the official policy content have a good effect on the analysis of hot spots in the policy. Therefore, the keywords of the official food safety policy issued by the central government are combined with the main content of the food safety policy issued by the local government to form a new data set. K-Means clustering is applied to the new data set to further analyze the hot spots of food safety policy in China.

By constructing the K-Means model, the obtained target data are classified into four categories. The categories related to the Department of health, supervisors, safety control, supervision institutions, rights, and interests are classified into the category of supervision and rights protection. The categories related to counterfeit and inferior, market supply, quarantine, and quality are classified into the category of market regulation. The categories related to catering, ordering, business licenses, and vendors are classified into catering licenses. The categories related to food, drug, and product safety are classified into food safety products.

Table 4 shows that the market regulation policy accounts for 73.91%, which is far greater than the other types of policies. This policy demonstrates that the government pays more attention to the quality and safety of food and improves the food safety levels in China by controlling the production and sales of counterfeit and inferior products, which prevents food safety incidents and ensures the output and quality of food. In addition, with the impact of COVID-19, there has been a significant increase in the correlation between the epidemic, food safety, and cold-chain food. In response to the food safety issues of epidemic prevention and control, the government has also increased the supervision and regulation of imported cold chain food.

Table 4. The keywords and percentages in the categories of cluster analysis.

Category	Keywords	Percentage (%)
Supervision and Rights Protection	Department of Health; Supervisor; Sanitary Authority; Supervision Institutions; Food Poisoning; Security Control; Rights and Interests; Food Industry	8.59
Market Regulation	Counterfeit and Inferior; Security Incident; Market Supply; Disinfection; Quarantine; Quality Grain; Epidemic; Cold Chain	73.91
Catering License	Catering; Ordering; Vendors; Business license School Canteen; Quality Supervision; Physical Health; Early Warning	11.14
Food Safety Products	Food and Drug; Product Safety; Pilot work; Diet; Quality and Technical Supervision Bureau; Publicity and Education; Pharmaceuticals	6.36

Comparing the results of the K-Means model with the ones of the LDA topic model, it is found that there are two more topics in LDA than in K-Means, and the policy division of LDA is more detailed. However, they both show that China's food safety policy focuses on market regulation and early warning. Especially during the epidemic, both models' results reflect China's current regulatory focus on quarantine and supervision of imported cold chain foods. With the current epidemic prevention and control situation, the third-party testing agencies, the use of intelligent Internet and food safety rapid inspection means to prevent food safety problems under normal epidemic prevention and control, and the strict implementation of traceability platform management requirements to ensure the traceability of food raw material procurement is advocated. The "Fourteenth Five-Year Plan" for the development of cold chain logistics released by the state in December 2021 calls for an increase in the construction of cold chain logistics supervision warehouses and vigorously promotes the development of cold chain logistics to guarantee quality and safety, which shows that the results of the two models match the current food safety situation.

5. Quantitative Analysis of Food Safety Policies

5.1. Annual Quantitative Analysis of Policy Texts

5.1.1. Annual Quantity Analysis of the Central Policy

The food safety policy can be divided into central policy and local policy. Due to the small number of central policies in 2022 and the difficulty in availability, Figure 3 shows the annual central policies between 2007 and 2021. It is found that the policies issued by the three nodes in 2007, 2011, and 2017 have surged partially, which may be related to the release of the "Eleventh Five-Year Plan", "Twelfth Five-Year Plan", and "Thirteen Five-Year Plan", respectively, in the three years. The number of food safety policies issued by the central authorities in other years has been relatively stable. There are few policies in 2019 and 2020. These policies demonstrate that the task of food safety governance is complicated, the government is very concerned about this, and the attitude is firm to build and improve the food safety governance system with great determination.

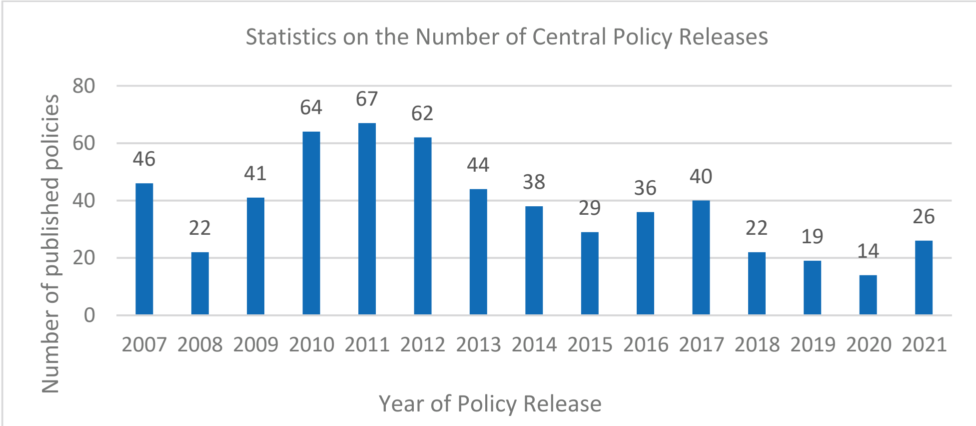

Figure 3. Annual quantitative analysis of the central policy (2007–2021).

5.1.2. Annual Quantity Analysis of the Local Policy

From the comparison between Figures 3 and 4, it is found that the number trend of food safety policies issued by the central and local governments is very similar, which indicates that the central and local governments not only maintain a high degree of correlation between policy content, but also ensure a high degree of consistency of policy release time.

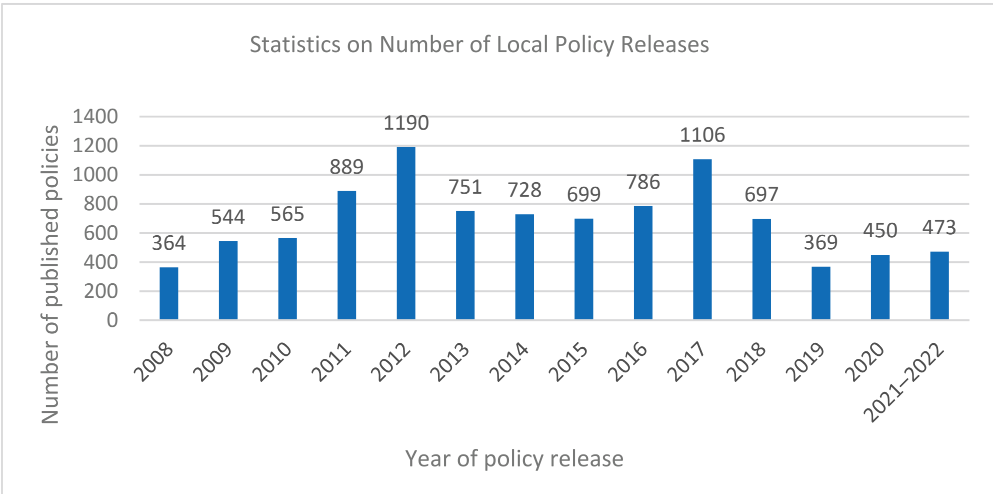

Figure 4. Annual quantitative analysis of the local policy (2008–2022).

5.2. Regional Distribution Analysis of Policy Texts

5.2.1. Regional Distribution Analysis of Central Policy

From 2007 to 2021, the central government issued 570 policies, which was significantly less than the local food safety policies. However, the policies issued by the central government are more macro. The central government should ensure enough authority to achieve unified leadership but also make local governments have certain autonomy and creativity so that their enthusiasms are fully played. Specifically, before the 18th National Congress of the Communist Party of China, the food safety strategy is "To rely on the domestic resources and achieve basic self-sufficiency in grain". After the 18th National Congress of the Communist Party of China, the central government made major adjustments to the strategic policy of food safety, namely "domestic grain production, guaranteed food production capacity, moderate imports, and technological support", and formed a food security guarantee mechanism.

5.2.2. Regional Distribution Analysis of Local Policy

From 2008 to 2022, the number of policies issued by the local government was 9611, which is very large. Almost all provinces and cities issue local food safety policies. Figure 5 shows the top 20 provinces and cities with the most significant number of policies issued. It is found that China's food safety policies are unevenly distributed. More policies are issued in the south, especially in Guangxi and Jiangsu Province, which are significantly higher than other provinces and cities, while Beijing has only issued 251, which accounts for approximately 2.6%.

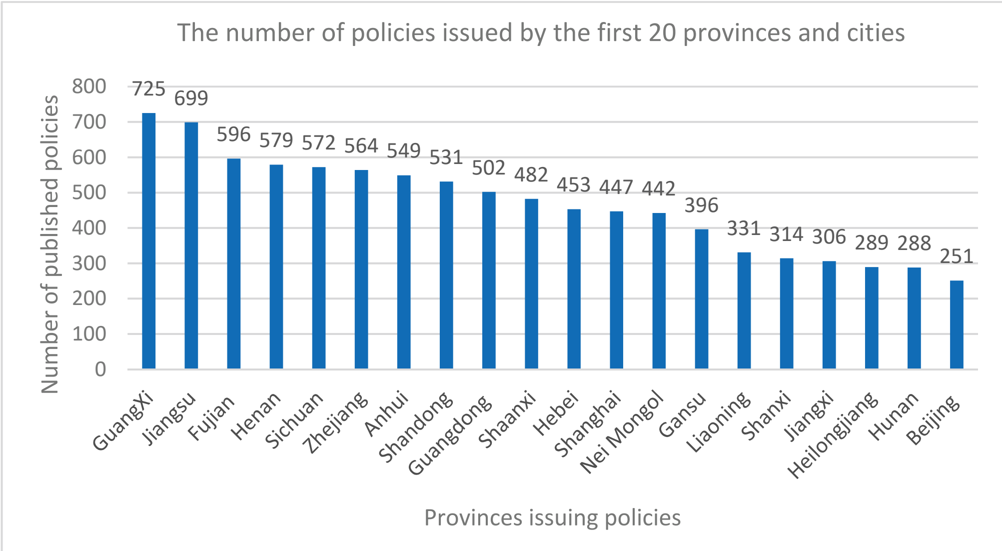

Figure 5. Regional distribution of food safety policies in China (2008–2022).

5.3. Analysis of the Range of Action of Policy Texts

Although China's food safety has shown a stable and good situation, the foundation of food safety is still weak, and problems occur from time to time, such as "melamine milk", "fake mutton", and "fast-grown chicken". These problems have illustrated China's severe food safety situation, and there is still a gap compared with the people's expectations. Given the aforementioned situation, China has taken a series of measures to ensure food safety: the Food Safety Law was promulgated in 2009, the Food Safety Commission of the State Council was set up in 2010, the China National Center for Food Safety Risk Assessment was established in 2011, the Decision of the State Council on Strengthening Food Safety was issued in 2012, and the National Medical Products Administration was established in 2013. In recent years, the regulatory authorities have successively promulgated laws and regulations such as the Measures for the Administration of Food Production License and Food Operation Approval Administration Measures, as well as industrial policies such as Opinions on Deepening Reform and Strengthening Food Safety Work, as well as Guidance on Promoting Healthy Development of Food Industry. These measures control food safety in China. This subsection will provide a specific classification of the food safety policies issued in China according to the different policy roles, which mainly includes Mandatory, Value, Capability, Awards and Punishments, and Innovation. Since the division of such policies requires careful manual reading of the policy text and the division can only be made after understanding the main content, which is time-consuming, this paper divides the range of action of the 570 policies issued by the central government. It is found that the coverage of China's food safety policy is comprehensive, and all aspects of the food industry are involved, which promotes the healthy development of China's food industry.

Table 5 shows the statistics of the number and proportion of the range of action of policy texts. It is found that the market supervision departments are guided by food safety issues, and that they have increased the intensity of spot checks on safety indicators, industries, formats, regions, and related enterprises that have more problems in daily supervision, complaint reporting, law enforcement, punishment and disposal, and risk warning. Specifically, the policy that accounts for the largest proportion is the establishment and implementation of standards in the capability category, which is 16.14%. That is, with the continuous improvement of living standards, people not only pursue food and clothing but also pay more attention to eating safely, healthily, and comfortably. Food safety standards play a vital role in this process. Currently, China's food safety standards can cover the sales market and the main food categories consumed by people, and the coverage can reach more than 90%. The second is the regulatory system, which accounts for 11.58%. The regulatory system mainly refers to the reform of the food regulatory system, the implementation of superior work, and some comprehensive policies involving multiple dimensions. This part covers a wide range of dimensions. It aims to promote the improvement of the food safety supervision system and comprehensively enhance the ability of food safety supervision, which is of great significance to maintaining people's health and life safety. The remaining awards and punishments policies, value policies, and innovation policies accounted for less than the mandatory and capability policies, especially the awards and punishments policies, which only accounted for far less than other categories at only 2.11%. This shows that the policy role is unevenly distributed in types. The government should strengthen policy support for these weaknesses, establish positive and negative models and technological innovation, strengthen the comprehensive coordination of food safety, and play a positive role in ensuring public food safety.

Table 5. Statistics on the number and proportion of various policies.

First Dimension	Secondary Dimension	Number of Policies	Single Percentage %	Subtotal of Various Policies	Total Percentage %
mandatory-type	Administrative Permits	7	1.23	192	33.68
	Supervision and Sampling	45	7.89		
	Inspection and Quarantine	16	2.81		
	Law Enforcement Investigation	18	3.15		
	Regulatory System	66	11.58		
	Special Rectification	40	7.02		
capability-type	Personnel Team Construction	10	1.75	207	36.32
	Establishment and Implementation of Standards	92	16.14		
	Construction of Grassroots Institutions and Testing Institutions	10	1.75		
	Territory Management and Assessment	20	3.51		
	Emergency Plan	28	4.91		
	Signal the Potential Risks	27	4.74		
	Construction of Traceability System	4	0.71		
	Informatization Construction	16	2.81		
value-type	Create a Demonstration	16	2.81	61	10.70
	Propaganda and Guidance	31	5.44		
	Technological Innovation	14	2.46		
awards and punishments-type	Give Recognition	7	1.23	12	2.11
	Punishment Disposal	5	0.88		
innovation-type	Construction of Expert Team	19	3.33	98	17.19
	Joint Supervision	30	5.26		
	Credit Management	3	0.53		
	Openly Soliciting or Giving Opinions	46	8.07		
Total		570			100

5.4. Analysis of Policy Release Agencies

The main functions and areas of responsibility of the department are different. The focus of policy formulation is not consistent. For instance, the Ministry of Health is mainly responsible for the formulation of national standards. The Administration of Quality Supervision, Inspection, and Quarantine (AQSIQ) is mainly responsible for the import and export of food, all kinds of food supervision and sampling inspection, and risk monitoring policy formulation. The State Council is mainly responsible for grasping the direction of macro policies. The National Medical Products Administration focuses on strengthening some daily social supervision and spot checks before major festivals and activities.

Table 6 shows the statistics of the release departments of the central food safety policies. Since there are many departments involved in policy releases, this paper merges departments that are not the main release policies into the last line to facilitate readability. This table shows that the National Medical Products Administration (NMPA), the Ministry of Health, the National Health and Family Planning Commission, and the Food Safety Commission of the State Council are the four departments that issue the most policies, accounting for 34.74%, 12.63%, 9.12%, and 6.49%, respectively. Other agencies will also formulate some targeted food safety policies to improve the entire policy system according to the different needs of different regions or industries. For example, according to the problems in the field of pension services, the Ministry of Civil Affairs issued policies requiring the implementation of a food safety management "president responsibility system" and required producers and operators to strictly perform the main responsibility of product safety. The Ministry of Transport issued policies to accelerate the development of cold chain logistics to improve cold chain flow equipment and facilities and encourage the innovative development of cold chain logistics enterprises.

Table 6. Statistics of release departments of central policies.

Department	Number of Published Policies	Proportion %
NMPA	198	34.74
Ministry of Health	72	12.63
National Health and Family Planning Commission	52	9.12
The Food Safety Commission of the State Council	37	6.49
AQSIQ	36	6.32
State Administration for Market Regulation	36	6.32
The State Administration for Industry and Commerce	28	4.91
Ministry of Commerce	23	4.04
National Health Commission	20	3.51
Certification and Accreditation Administration	10	1.75
Ministry of Education	8	1.40
Others	50	8.77
Total	570	100

6. Conclusions

This paper constructs the LDA and K-Means model to analyze food safety policy texts from 2007 to 2022. The annual number and regional distribution of policies are analyzed from the perspectives of the central and local governments, which emphasizes the types of roles and publishing agencies of central policies. The hot topics of policy release, annual high-frequency keywords and annual change trend, distribution trend, and policy organization distribution are obtained. Our conclusions are as follows:

The focuses of food safety policies issued by the central and local governments and the trends of annual publication numbers are highly consistent. Food safety policy focuses on the supervision of food additives, the construction of a food traceability system, food safety norms and early warning, food logistics, and campus security. According to the trend of food safety development, the focuses of policies are different each year. The peak period of policy release is around 2010–2012, which matches the period of the 11th Five-Year Plan for

National Food and Drug Safety issued by the central government. The number of policies issued annually in other years is relatively stable, which demonstrates that the state has a strong attitude towards food safety supervision and that the whole system of food safety supervision is constantly improving.

The local food safety policy has a high inheritance to the central policy content, and the innovation of different regional policy contents have their own characteristics. Specifically, the regional distribution of China's food safety policies is not balanced, and the policies issued in the south are more than those in the north, especially in the Guangxi, Jiangsu, and Fujian provinces. This disparity may be related to the local economic conditions and the development level of the food safety industry. Similarly, various provinces and cities are actively promoting the development of the local food safety industry in response to the country's call. Food safety supervision also presents the national, provincial, municipal, and county "four levels" phenomenon, and each level has its concentration. Currently, China's food safety is guaranteed, but there are still some problems and a certain gap in the expectations of the people. Although food safety issues cannot be "zero risk", government regulation can be "zero tolerance".

According to the classification of food safety policies issued by the central government, it can be found that the proportion of mandatory and capability policies is much larger than other types of policies, which shows that the current focus is still on the supervision of sampling and supervision system construction. In the future, the food safety industry should improve continuously strengthening the supervision and sampling of enterprises and units, investigate food safety hazards, prevent and control all kinds of explicit and invisible risks, and carry out special rectification of outstanding problems of food safety. In addition, it needs to ensure the healthy growth of students, focus on the supervision of school food safety and continue to strengthen supervision. Finally, it is necessary to crack down on illegal activities and focus on the governance of products with poor quality in accordance with the law.

The research in this paper can be improved in other ways as follows:

The data acquisition. The raw data can be selected according to the different departments of the release policy by year. We suggest to record the policy's document number during the retrieval process for subsequent deduplication and text analysis.

The division method of the range of action of the policy. It is better to use a more objective, accurate, and fast division method instead of manual division to ensure that the locally-issued policies, as well as the centrally-issued policies, are divided.

The analysis of policy-affiliated institutions. Besides the analysis of the single policy release department, the joint policy release department should be analyzed and compared.

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foods

Article

Cost of Recommended Diet (CoRD) and Its Affordability in Bangladesh

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Abstract: The cost of diet has been recognized as a major determinant of overall diet quality and nutritional outcomes. We aimed to estimate the minimum cost and affordability of the recommended diet based on the updated food-based dietary guidelines (FBDG) in Bangladesh. To compute the cost of the recommended diet (CoRD), we collected retail prices of foods corresponding to each of the food groups in the latest Bangladeshi FBDG. For affordability, the household size and daily food expenditure data were used from the most recent Household Income and Expenditure survey (HIES). The CoRD was calculated based on the average number of servings recommended for each food group; the CoRD was adjusted by a deflation factor and divided by the household's daily food expenditure to estimate affordability. We found that the CoRD was $0.87 (83 BDT) per person per day at the national level. Nationally, about 43% of households could not afford the CoRD, with rural areas bearing a disproportionate share of the burden. We also found households to overspend on starchy staples while underspending on protein-rich foods, fruits, and dairy. These findings highlight the need for immediate implementation of interventions to improve the affordability of the CoRD and redesign policy instruments to create a sustainable food system.

Keywords: affordability; Bangladesh; cost of recommended diets; food-based dietary guidelines

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1. Introduction

The cost of recommended diets (CoRD) is an estimate of the basic minimum cost needed to follow the food-based dietary guidelines (FBDG). The cost of diet has increasingly been recognized as a major determinant of the quality of overall diets and nutrition outcomes. The relatively higher cost of healthy foods leads to reduced consumption of nutrients, resulting in compromised diets and micronutrient inadequacy. In fact, Dizon and Anna considered food cost as a major and presumably one of the limiting factors to accessing safe and healthy diets [1]. The latest report of the State of Food Security and Nutrition in the World (SOFI) estimated that globally 3 billion people are unable to afford a healthy diet [2]. Findings of the recent studies also highlighted that affording the cost of healthy and nutritious foods has remained an overarching goal for a significant portion of the world's population, particularly for the poorest people [3–5]. Additionally, with the economic shock and instability caused by the COVID-19 pandemic, food prices have increased, making it more difficult to afford healthy diets, especially for people from low- and middle-income countries. As a result, achieving the Sustainable Development Goal 2 (SDG 2) targets of zero hunger, food security, and improved nutrition by 2030 is becoming a far-reaching dream [2].

Bangladesh, the world's eighth most populous country, has made remarkable progress from its earlier estimates in economic growth, food production, health, and nutrition [6]. The country with a gross national per capita income of $1470 is scheduled to graduate from its current status to a developing country in 2026 [7]. The poverty rate has also appreciably dropped to 20.5% in 2019 from 24.3% in 2016 [8]. Despite all these gains, Bangladeshi diets continue to be dominated by rice, with less emphasis on non-cereals and a variety of other nutrient-rich foods. This scenario reflects the fact that 34% of infants and young children in Bangladesh have a minimum adequate diversity in their diets [9]. Latest estimates from food consumption surveys have shown that a diet composed of different foods in Bangladesh is far below in diet quality according to the definition of a "Healthy Diet" by World Health Organization (WHO) [10]. Moreover, the recent measures to mitigate the COVID-19 pandemic have further exacerbated household dietary quality in that 61% of families in Bangladesh reported consuming less diversified diets than their pre-pandemic diets [11].

To eradicate all forms of malnutrition and achieve food and nutrition security, there is a need to create a sustainable, resilient food system for healthy diets that meet the needs of the population in terms of energy and macro- and micro-nutrients. However, attaining food and nutrition security is not about just meeting energy and nutrient needs. It also entails the consumption of balanced and healthy diets, as promoted in the FBDG. FBDG are guidelines that are formed considering the dietary pattern, food habits, and culture of a population and incorporate recommendations that address major diet-related public health issues [12]. Such guidelines not only include the basic nutrient needs but go beyond and represent diets in a manner that provides overall health protection in order to eradicate all forms of malnutrition. The inability to afford sufficient, safe and nutritious foods is a critical driver of the lack of access to such recommended diets. As a result, it is critical to understand whether a country's existing food systems can translate dietary guidelines into affordable consumption of recommended diets.

Existing literature on the cost and affordability of diets in Bangladesh is almost exclusively based on the Save the Children UK-developed cost-of-the-diet (CoD) methodology, which calculates the least cost of meeting essential nutrient requirements by typical households in a specific geographic location. In 2006, the CoD approach was first piloted in a village in the Rangpur district [13]. Subsequently, this analysis was conducted for the fish cultivation livelihood zone in Khulna [14] and beneficiary households of the Suchana program in the districts of Sylhet and Moulvibazar [15]. This methodology was also used by the World Food Programme in its Fill the Nutrient Gap (FNG) analyses in Bangladesh [16]. CoD or other similar analyses [17] are based on meeting only the bare minimum of critical nutrient requirements. However, they are useful for nutrition assistance/relief programs in planning diets for the poor or other specific vulnerable groups such as children [18]. In contrast to CoD, the Cost of Recommended Diet (CoRD) goes beyond essential nutrients to incorporate the cost of foods from different food groups as recommended in the FBDG. While the CoRD may suffer the limitation of not fully reflecting the food culture and consumption behavior of a particular population, this method is obviously superior to CoD when the goal is to promote overall protection and promotion of the health of the Bangladeshi population. This is because the CoRD is based on calculating the cost of meeting the FBDG recommendations, which include diversified foods with varying functionalities.

The method of calculating the cost of meeting recommendations in the FBDG, alias the Cost of Recommended Diet (CoRD), was pioneered in Ghana [19] and later applied in Africa [20], India [21], and Myanmar [22]. More recently, the CoRD has been assessed using a regional FBDG generated using national dietary guidelines of South Asian countries [1,23]. Although Bangladesh was included in the analysis, the CoRD and affordability estimates for Bangladesh were not truly based on Bangladesh-specific FBDG, which differs from other FBDGs from South Asian countries in terms of food groupings and amounts of foods in food groups. For example, Bangladeshi FBDG has nine food groups compared to only six in the regional (South Asian) FBDG. Also, the maximum recommended amount of vegetable and fruit groups are set at much higher, and that of the starchy staple at much lower amounts than the maximum recommended amount in the regional FBDG [1]. More importantly, the analysis relied on almost a decade-old FBDG [24] instead of the most recent one, revised and updated in 2020. Furthermore, it used households-reported price data collected back in 2014–2015 that do not fully reflect the food prices in the current context.

Similarly, the recent report of the World Bank published in March 2021 also estimated the cost and affordability of a healthy diet in Bangladesh by following the outdated FBDG of 2013 [25]. With these considerations, this study aimed to generate the CoRD estimates using FBDG specifically developed for the Bangladeshi population (i.e., FBDG 2020) and retail food prices collected through a market survey. It also aimed to estimate the affordability of the CoRD with respect to household food expenditures from the Household Income and Expenditure Survey (HIES) of 2016 [26].

2. Methods

2.1. Food Selection

Figure 1 presents the overall methodology we followed. Calculating the CoRD required a list of food items that are frequently consumed and available in the food markets throughout Bangladesh. Foods listed in the Food Composition Table for Bangladesh (FCTB) were used as our initial food list, as it contains 386 Bangladeshi food items with their nutrient composition [27,28]. Later, to reflect the current consumption pattern, the food list was updated based on recent nutrition-related surveys, namely the Bangladesh Integrated Household Survey, 2015 (BIHS, 2015), Institute of Nutrition and Food Science Survey, 2017–2018 (INFS, 2017–2018), and Household Income and Expenditure Survey, 2016 (HIES, 2016). Subsequently, a comprehensive food list containing 124 food items was finalized. The food items were then categorized into nine food groups by separating leafy and non-leafy vegetables into distinct groups. To address the regional variation of food availability across 8 divisions of Bangladesh, food items exclusively available to regional markets were incorporated into the regional food list while calculating the CoRD of that respective division.

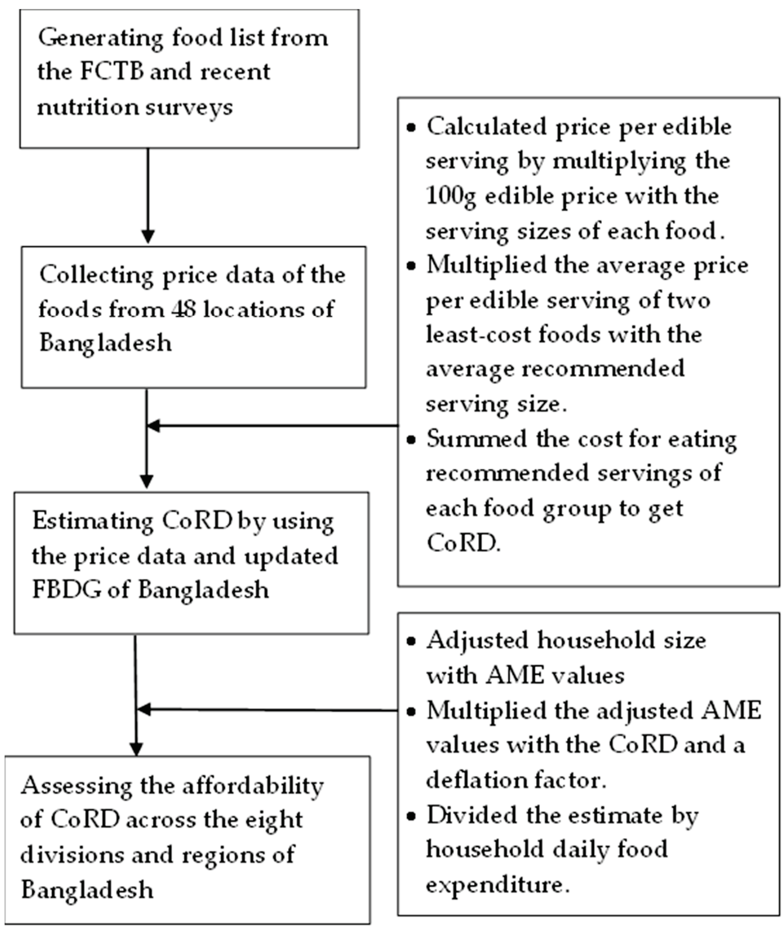


Figure 1. Flowchart of the overall methodology.

2.2. Market Survey on the Price of Food Items

Food prices were collected through a market survey conducted in the last week of January 2021 to 5 February 2021. For collecting price data from eight divisions of Bangladesh, a list of all food markets listed on the Department of Agricultural Marketing (DAM) website was made. The list was then stratified by division (i.e., 8 strata for 8 divisions). Six locations from each division, including 3 urban and 3 rural areas, were randomly chosen to make the final market list comprising 48 markets surveyed.

A two-day training session was conducted to discuss the aims of the market survey and the method of collecting price data for each specific food item. The data enumerators who had previous experience doing market surveys and were familiar with the local language of the assessment area were recruited from each location. The enumerators were provided with pictures of the listed food items to reduce the odds of systematic errors. Before starting the data collection process, formal permission was obtained from the market leaders and local traders to avoid unsolicited circumstances.

The price of food items was collected from four retailers in each market subject to the availability of the food item and retailers in the markets. If any food was not available on the day of data collection, the latest market price of that food item was taken. The 100 g price of every food item from each of the four retailers was recorded, and their average was considered as the food price of that market. The division-specific price of a food item was computed by averaging the prices from 6 locations (e.g., urban and rural areas) of that division. Finally, the average of the prices collected from 48 locations was considered the national-level price of each food item.

It was made sure that the data collectors avoided rush hours, and the prices were collected without causing any disturbance to the traders. As the data collection was conducted amid the pandemic, all our data collectors wore masks and followed hygiene protocols.

2.3. Food-Based Dietary Guidelines

In a joint initiative by the Food Planning and Monitoring Unit (FPMU), the Ministry of Food, and the Ministry of Health and Family Welfare of the Government of Bangladesh (GoB), the older 2013 version of FBDG was updated in 2020. This updated FBDG (Figure 2), which provides more quantitative information and specific serving recommendations (Table 1), was used in this study.

Table 1. Serving size estimates based on the food-based dietary guidelines of Bangladesh.

Food Groups		Serving Size (g)	Recommended Number of Servings		Number of Servings Used (Average of the Number of Servings)
			Min	Max	
Cereals		30	9	15	12
Pulses		30	1	2	1.5
Vegetables	Non-leafy vegetables	150	2	4	3
	Leafy vegetables	150	1	2	1.5
Fruits		100	1	3	2.0
Meat, fish, and egg		100	1	4	2.5
Milk and milk products		150	1	2	1.5
Fats and oils		5	3	6	4.5
Sugar		5	5	5	5

The FBDG for Bangladesh is presented in the form of a pyramid of eight food groups such as (1) Cereals; (2) Pulses; (3) Vegetables; (4) Fruits; (5) Meat, fish, and egg; (6) Milk and milk products; (7) Fats and oils; and (8) Sugar. It provides a description of a healthy diet that includes specific serving sizes and the minimum and maximum number of servings from each food group to be eaten in a day for a healthy adult. The FBDG pyramid places leafy and non-leafy vegetables in the same group; however, it instructs that at least one serving of green leafy vegetables should be consumed every day. Thus, we separated leafy and non-leafy vegetables into 2 distinct food groups to make sure we met this condition. Foods under the categories of spices, beverages (except milk), and sweets in the FCTB were excluded while calculating the CoRD, as these are not mentioned in the FBDG of Bangladesh.

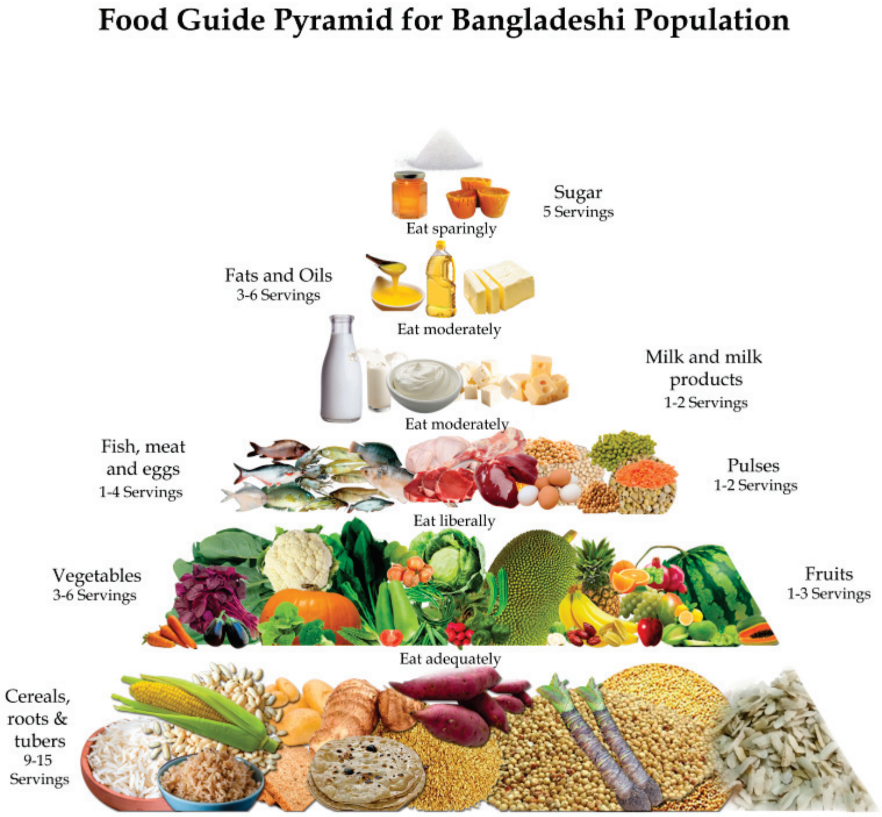


Figure 2. Food-based dietary guidelines of Bangladesh, 2020 (prepared by FPMU, GoB).

2.4. Calculating the Cost of Recommended Diet (CoRD)

The calculation of the CoRD consisted of several steps. Firstly, the foods were categorized into specific food groups according to the FBDG. In the case of multiple varieties of the same food, their average price was taken. For example, the average price of *red wheat flour* and *white wheat flour* was taken as the price of *wheat*. The weights of all the food items were standardized into grams. Items that are normally measured in non-standardized units were also converted into grams, such as a dozen eggs and a dozen bananas.

In the second step, the price of the food items as purchased was converted into the price per 100 g edible portion by dividing the "as purchased price" by the edible coefficient. The edible co-efficient value of each food was taken from the FCTB. Next, the price of 100 g of edible food was multiplied by the serving size for each food group recommended in the FBDG of Bangladesh to estimate the price per edible serving.

$$Price\ per\ edible\ serving = Price\ per\ 100\ \mathrm{g}\ edible\ portion\ of\ food \times Recommended\ servings\ of\ food\ group$$

In the third step, we took the average price per edible serving of the 2 lowest-cost items from each food group (see Table S1 in the Supplementary File) and multiplied it by the average of the upper and lower bound of the number of servings recommended for that group. We chose the lowest-cost items as our objective was to calculate the minimum cost of meeting the recommended diet, and more than 1 lowest-cost item was chosen as the dietary guideline promotes diversity within food groups.

Finally, the costs for meeting the recommendations for each food group were summed to calculate the CoRD.

$$CoRD = \Sigma\ Average\ price\ per\ edible\ serving\ of\ least\ cost\ items \times Average\ recommended\ servings$$

2.5. Measuring Affordability

To assess affordability, the proportion of households in the whole country and in each division that could not afford the CoRD was calculated. Data on household size and daily food expenditure of every household were taken from the 16th round of the HIES (i.e., survey data collected by the Bangladesh Bureau of Statistics from April 2016 to March 2017). Briefly, this survey included 46,080 households from 2304 primary sampling units following a two-stage stratified cluster sampling design. Further details on the planning and implementation of the survey are available elsewhere [26]. As the CoRD was calculated for an adult individual, the reported household size was adjusted with adult male equivalent (AME) values. By multiplying the cost by AME-adjusted household size, the CoRD was determined for every household. As the cost of diets was computed using the food prices of 2021 while the expenditure data were from 2016, the CoRDs were multiplied by a deflation factor. We estimated the deflation factor to be 1.269, 1.271, and 1.264 for national, urban, and rural areas, respectively. Then the deflation-adjusted cost was divided by every household's daily food expenditure, and the results were expressed in ratios. Ratios above 1 indicated a diet to be unaffordable as the cost exceeded the average food expenditures of a household.

$$Unaffordability\ (\%) = \frac{Adjusted\ household\ size \times CoRD \times Deflation\ factor}{Household\ daily\ food\ expenditure}$$

3. Results

3.1. Cost of Recommended Diet

The CoRD was $0.87 per day for an adult person at the national level. The regional variation in the CoRD was clearly observed across the eight divisions, with the highest ($0.93) being in the Sylhet division and the lowest in the Barisal division ($0.64). Recommended diets were more expensive in urban areas for all divisions except Barisal. The residents of Dhaka, the capital and most densely populated region, needed to spend $0.83 on average (Table 2).

Table 2. The cost of recommended diet (CoRD) in Bangladesh by region and residence.

Locations	Areas	CoRD $ (BDT) * (BDT)
Dhaka	Urban	0.93 (88.4)
	Rural	0.81 (77.3)
	Whole division	0.83 (79.8)
Chattagram	Urban	0.94 (89.2)
	Rural	0.75 (70.6)
	Whole division	0.89 (84.9)
Mymensingh	Urban	0.92 (87.1)
	Rural	0.80 (76.3)
	Whole division	0.85 (80.5)
Barisal	Urban	0.64 (61.3)
	Rural	0.78 (74.5)
	Whole division	0.74 (70.6)
Rajshahi	Urban	0.81 (77.7)
	Rural	0.73 (69.1)
	Whole division	0.79 (75.6)

Table 2. *Cont.*

Locations	Areas	CoRD $ (BDT) * (BDT)
Khulna	Urban	0.94 (89.5)
	Rural	0.92 (88.0)
	Whole division	0.84 (81.4)
Sylhet	Urban	0.98 (92.5)
	Rural	0.88 (83.3)
	Whole division	0.93 (88.9)
Rangpur	Urban	0.81 (77.6)
	Rural	0.68 (64.1)
	Whole division	0.79 (75.9)
National	Urban	0.90 (85.4)
	Rural	0.84 (80.7)
	Whole country	0.87 (83.0)

* 1$ = 94.7 BDT.

3.2. Percentage Share of the CoRD and Actual Expenditure

The food expenditure of the Bangladeshi people was dominated mainly by starchy staples rather than protein-rich animal-source foods, dairy products, fruits, and vegetables. According to the expenditure data of HIES, 2016 survey, households spend the lion's share of their food expenditure on starchy staples (38%), whereas it needs to spend only 21 percent to meet their daily requirements of cereals according to the FBDG. In contrast to staples, households spend only 35 percent of their expenses on protein and 3 percent on dairy products, but to meet the recommended servings, they need to pay 43% and 16%, respectively. On the other hand, they spend 200 percent more on fats and oils compared to what is required for a recommended diet (Figure 3).

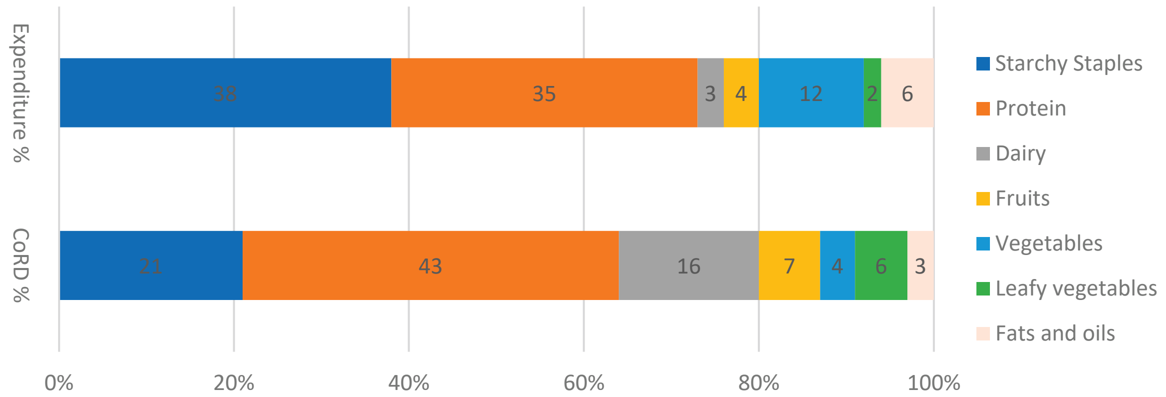
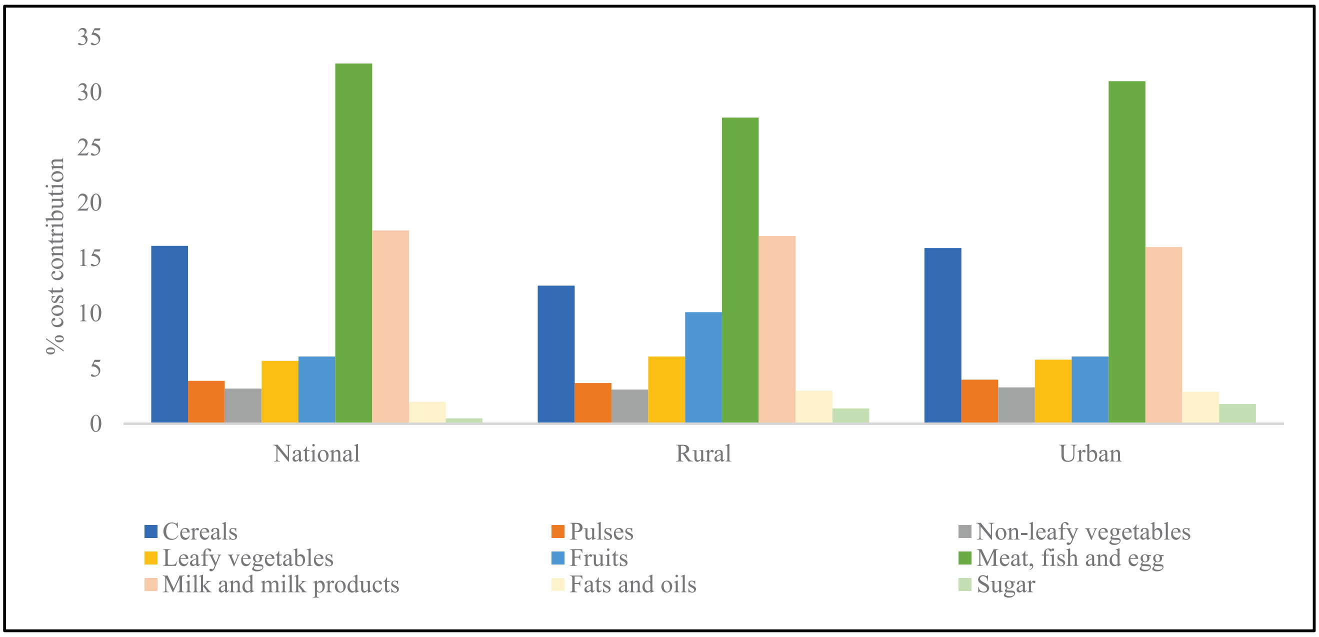


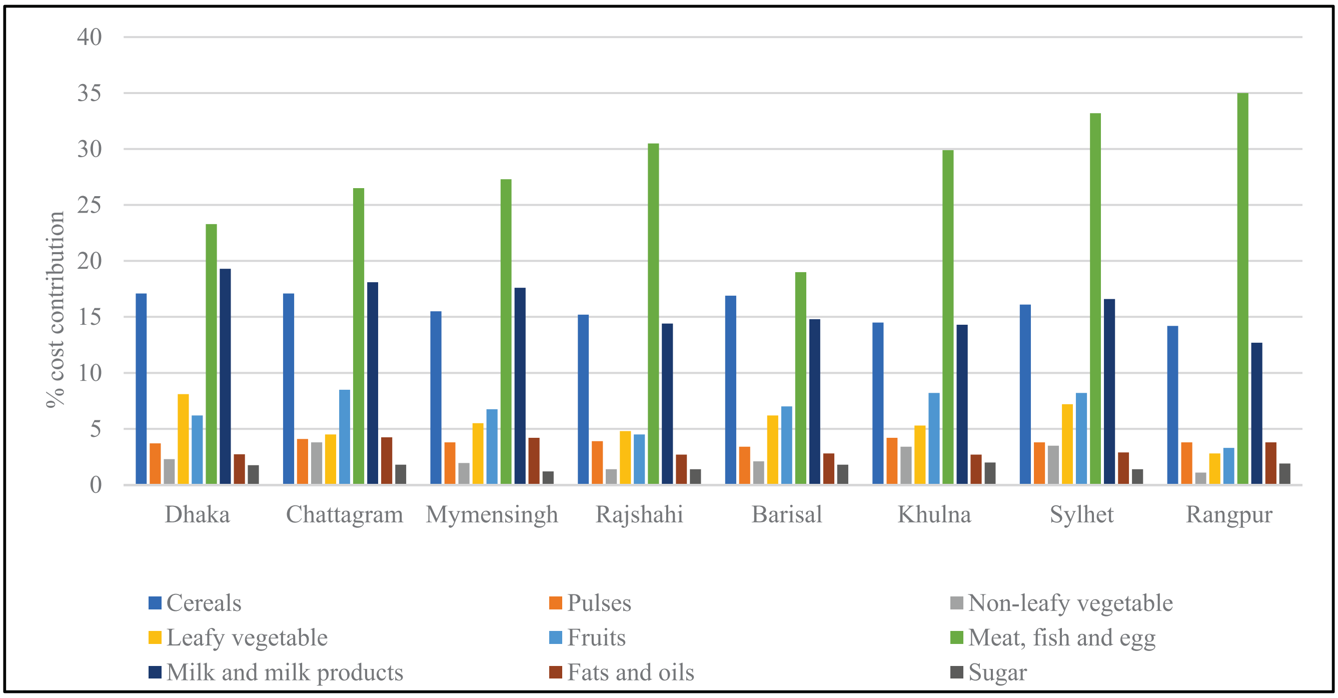
Figure 3. Percentage share of the cost of recommended diet and household food expenditure.

3.3. Cost Share of Each Food Group in Recommended Diet

Figure 4 represents the cost contribution of each food group according to FBDG in comprising the total cost of a recommended diet. To the total cost, "meat, fish and egg" and "milk and milk products" contribute the major share nationally and in urban and rural areas. This means that to meet the FBDG of Bangladesh, an individual would need to spend more on meat, fish, and egg, along with milk and milk products. The cost of meeting the recommended number of servings of all food groups except leafy vegetables, sugar, and fruits was higher in rural areas than in urban areas (Figure 4, Panel A).



Panel A: Percent cost contribution of food groups by residence



Panel B: Percent cost contribution of food groups by region

Figure 4. Percent cost contribution of food groups in the recommended diet by residence and region.

Panel B in Figure 4 presents the percent cost contributions of the food groups across eight divisions where meat, fish, and eggs drive up the cost of a healthy diet in all divisions, especially in Rangpur. Followed by meat, fish, egg, milk and milk products are the food group that costs more in Dhaka, Chattagram, Mymensingh and Sylhet divisions. The cost of meeting recommended amount of cereals is the highest in Barisal and the lowest in Rangpur. To attain the CoRD, one must pay relatively more for fruits and leafy vegetables in Dhaka, whereas an individual from Rangpur would have to pay the least. The results indicate that not only does the cost of the diets vary with geographical location, but also the cost of each food and food group differs simultaneously.

3.4. Affordability of the CoRD

As the cost of diets varied with the region and residential area, the affordability of the diets also differed across divisions and areas (Table 3). Nationally about 41.3% (95% CI: 40.8–41.7%) households could not afford the CoRD. The burden of unaffordability was significantly greater in rural (42%) than in urban (39%) areas. The analysis revealed that the highest percentage of households who could not afford recommended diets were from the Khulna division, which was 65.5% (95% CI: 64.5–66.7%), and the fewest in the Chattagram division, which was 25.5% (95% CI: 24.5–26.4%). We also analyzed the district-wise proportion of households unable to afford a recommended diet (see Table S2 in the Supplementary File).

Table 3. Percent of households unable to afford the recommended diet.

		Unaffordability of CoRD	
		% Households	**95% Confidence Interval**
By administrative unit	National	41.3	40.8–41.7
	Barisal	35.6	34.1–37.0
	Chattagram	25.5	24.5–26.4
	Dhaka	30.4	29.5–31.4
	Khulna	65.6	64.5–66.7
	Mymensingh	47.3	45.5–49.2
	Rajshahi	45.6	44.4–46.9
	Rangpur	47.5	46.2–48.8
	Sylhet	40.3	38.4–42.1
By residence	Rural	42.5	41.8–42.9
	Urban	39.0	37.9–39.5

Likewise, in administrative units and residences, the affordability also altered with geographical locations. Figure 5 shows the percentage of households unable to afford the CoRD in 64 districts of Bangladesh. The percentage of households lacking affordability was divided into five categories ranging from 9.3% to 75.5%. As the percentage of households unable to afford the CoRD increased, the color of the areas got darker. This indicates that the geographical areas with the darkest color were the districts where the freight of unaffordability was the highest. The Choropleth map shows that unaffordability was the highest in the Southwest part, followed by the Northwest part of Bangladesh.

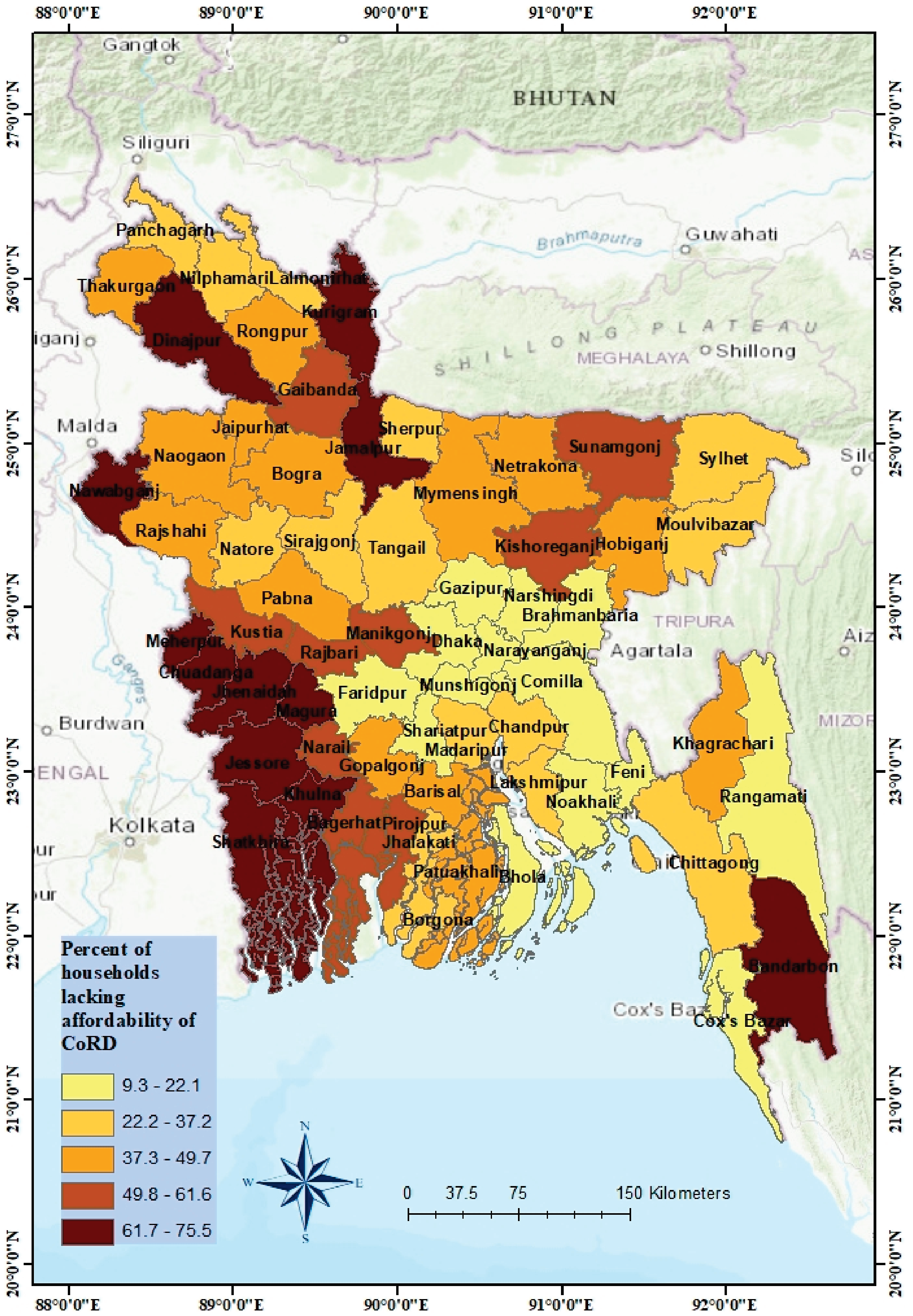


Figure 5. Variation in affordability of CoRD across all districts of Bangladesh.

4. Discussion

This study aimed to estimate the minimum cost for meeting the FBDG recommended diet (CoRD) of Bangladesh and its affordability. We found that to afford the CoRD, a person must pay $0.87 (83 BDT) per day at the national level, and affordability varied significantly with both residence (e.g., rural and urban) and regions across the eight divisions. The study also showed the percentage an average household spends on individual food groups compared to what they should be paying to meet the FBDG recommended amount. According to the affordability analysis, the prevalence of unaffordability was higher in rural areas compared to urban areas, and the burden of unaffordability was the highest among households in the Khulna division.

The cost of the diets fluctuated largely across regions. These differences may occur likely due to disparities in the prices of foods, especially nutritious foods, as they are often highly perishable and less tradable. A study by Headey and Alderman reported that prices of foods are sensitive to factors such as local food productivity and the efficiency of food value chains [29]. Fluctuations in the cost of diets have also been observed in several previous studies in Bangladesh. For example, to determine the cost of a nutritious diet in the Rangpur division, Save the Children in the year 2007 estimated that the daily cost of meeting a nutritious diet for a family was $0.75 (71 BDT) in the lean season [13]. Later in 2019, the World Food Program (WFP), using the data on food prices and household food expenditure from HIES of 2016, reported the cost of a nutrient-adequate diet was $1.83 (174 BDT) [16]. A more recent study by World Bank and another study by Dizon and Herforth found that to meet the requirements of a healthy diet, and one must pay $0.61 per (58 BDT) day [1,25]. These findings significantly differed from the CoRD we estimated at the national level. Differences in these costs may be attributed to several reasons. One major reason is that this study used the updated FBDG of 2020, which provides more robust information on serving sizes and amounts than the previous FBDG of 2015 and 2013. Moreover, the food prices were collected during the COVID-19 pandemic, which may have influenced the estimates of the CoRD. As per the United Nations report, the prices of food unexpectedly increased during the lockdown, specifically in the rural areas where food supplies had been greatly hampered [30]. Additionally, in this study, the food list used to calculate the CoRD contained 124 food items, whereas the previous studies used a food list from HIES containing only 82 food items.

At the national level, the results showed that 4 out of 10 households were unable to afford the CoRD, and the unaffordability was prominent in the Southwest districts of Bangladesh. Apart from the Southwest part, some districts of the Northwest also had a higher burden of unaffordability compared to the other parts of the country. These variations may attribute to differences in food prices and the purchasing ability of the population. In the report by the World Bank named "Food for improved nutrition in Bangladesh," the authors stated geographical differences as one of the factors for unaffordability [31]. The report showed that due to the higher diet cost, the people of the Northwest and Southeast parts of Bangladesh spend less on food than the CoRD. Seasonality was another influencing factor, as, during the lean season (July to August), people have less money and face difficulty affording the CoRD than any other period of the year. Unaffordability also varied with the residence as it was higher among the households in rural areas than the urban ones. One reason might be the households of rural areas earn less than those of urban areas and thus exercise less purchasing power. Another reason may be the inadequate storage and processing facilities; the prices of perishable foods are likely to increase in rural areas. Apart from the influence of price, higher unaffordability in rural areas may also be due to the different expenditure patterns of rural households. Often households in rural areas raise consumer crops and livestock for their own consumption, causing them to spend less on foods from markets.

One of the major findings of this study was that among all the food groups, staples possessed the largest share of household expenditure (38%). The households significantly underspent on protein-rich animal-source foods, fruits, leafy vegetables and dairy products, whereas they spent 180% and 200% more on cereals and oils, respectively. The most likely explanation behind this is the drastic rise in the cost of diet when protein-rich animal-source foods (meat, fish, and eggs) and dairy are added to the food basket compared to cereals, pulses, and oil. The implication is that it is costlier to meet the recommendations for dairy and protein-rich animal-source foods, and thus households choose to under-consume them. The high prices of these food groups are also observed in literature of South Asia, where they presented animal foods and dairy products as the costliest food groups and less affordable ones [18,21,25,31]. According to the State of Food Security and Nutrition in the World report (SOFI), low productivity, lack of fair-trade policies, inefficient supply chains, and insufficient local storage capacities are the critical factors to rocketing the prices of nutritious foods [2].

The study results have several implications for making recommended diets less costly and affordable. To reduce the cost of recommended diets, the government should focus on agricultural policies and public food procurement policies to increase the productivity and diversity of foods. In parallel, the government would need to strengthen the market infrastructure and supply chains to allow the flow of diverse nutritious foods into markets, especially dairy, fruits, vegetables and protein-rich animal-source foods. It should also encourage local small and medium entrepreneurs (SMEs) to make investments and innovations to increase the production of indigenous food items to ensure affordable food prices for the poor. A robust nutrition education and behavior change communication (BCC) program through various channels should be undertaken to bring about changes in rice-based food habits and make people aware of nutrient-rich yet relatively cheap food items. To increase affordability, the government should enhance the coverage of existing social protection programs (e.g., open market sales, employment generation programs, and cash for work) to protect the population’s purchasing power.

Though this study gives valuable insights into the cost and affordability of recommended diets, some limitations exist. Firstly, the CoRD method does not consider the local taste and food preferences; rather, it selects the two cheapest foods from each food group. However, this study only estimated the CoRD, which may not fully reflect the food culture and consumption behavior of Bangladeshi consumers. Future works on the CoRD in Bangladesh should take local tastes and food preferences into consideration [22]. For example, a food item, even with the cheapest price, may be discarded when ranking the foods within each food group if that food is known not to be a part of the regular diet of a specific population. Secondly, as we collected price data at a single time, the study could not evaluate the seasonal variations in the cost of the diets. Future studies may employ a longitudinal design to collect price data across the seasons and determine whether significant variability in affordability exists throughout the year. On the other hand, the strength of the study is that it used the actual market price of the foods. Though there are several other sources for food prices, such as the Bangladesh Bureau of Statistics (BBS) and household income and expenditure surveys, the study did not use them due to several shortcomings. For example, the consumer price index (CPI) data of BBS-collected price data for a limited number of food items, and the data were not easily accessible. The household survey data are less frequently collected, often after 5–6 years, and do not give the actual or latest price trend. Thus, using the latest food prices and FBDG of 2020 made the estimate of cost more accurate and reliable in the context of the present time. Future studies may collect food price data on a large scale with more food items at different times of the year to address seasonality. In addition, age and sex-specific dietary guidelines can be designed to assess the cost of meeting recommended diet by age, sex, and reproductive status, rather than focusing on only the adult population.

5. Conclusions

The cost of meeting recommended diet remains unaffordable to a large proportion of households in Bangladesh. Due to the higher prices of nutritious foods such as fruits, dairy, and animal foods, the cost of recommended diet rises in all regions. Food price increases compromise diet quality and result in the underconsumption of nutrient-dense foods and the overconsumption of starchy staples. To make diets more affordable, appropriate agricultural policies must be implemented to reduce food price volatility and increase the availability of nutritious foods in the local markets. Food and nutritional assistance can be provided as a part of social security programs in conjunction with behavior change communication to improve access to and consumption of recommended diets.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/foods12040790/s1, Table S1: List of two least cost items under each food group; Table S2: District-wise estimates of proportion of households unable to afford CoRD.

Author Contributions: Conceptualization, S.I., A.N., M.R.A. and N.S.; Methodology, S.I. and A.N.; Software, S.I. and A.N.; Validation, S.I., A.N. and N.S.; Formal Analysis, S.I. and A.N.; Resources, N.S. and M.R.A.; Data Curation, S.I. and A.N.; Writing—Original Draft Preparation, A.N. and S.I.; Writing—Review & Editing, A.N., S.I., N.S. and M.R.A.; Visualization, S.I., N.S. and M.R.A.; Supervision, N.S. and M.R.A.; Project Administration, N.S.; Funding Acquisition, N.S. and M.R.A. All authors have read and agreed to the published version of the manuscript.

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Potential Forage Hybrid Markets for Enhancing Sustainability and Food Security in East Africa

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Abstract: The cattle sector is strategic for both the economic development and food security of Africa, but the low availability and quality of forage puts the most vulnerable population at risk. Hybrid forages are an alternative for enhancing both food security and sustainability of the sector but adoption levels are still low in Africa, which is related to various factors such as the availability of seeds. This document analyzes potential markets for new interspecific hybrids of *Urochloa* and potential hybrids of *Megathyrsus maximus*, adapted to the environmental conditions of eastern and partially western Africa, applying a four-step methodology based on estimating (i) required forage amounts for each country according to its dairy herd, (ii) potential hectares for forage cultivation based on (i), (iii) hectares that can be covered by the two hybrids of interest according to a Target Population of Environment approach, and (iv) potential market values for each country and hybrid. The results show a potential market of 414,388 ha for new interspecific hybrids of *Urochloa* and 528,409 ha for potential hybrids of *Megathyrsus maximus*, with approximate annual values of 73.5 and 101.1 million dollars, respectively. Ethiopia, Tanzania, and Kenya hold a market share of 70% for *Urochloa*, and South Sudan, Ethiopia, and Tanzania a 67% market share for *Megathyrsus maximus*. The results will help different actors in decision-making, i.e., regarding private sector investments in forage seed commercialization or public sector incentives supporting adoption processes, and thus contribute to increasing food security and sustainability in the region.

Keywords: potential markets; improved forages; food systems; food security; forage hybrids; nutrition

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1. Introduction

The cattle sector in East Africa is strategic in the fight against hunger and poverty. It provides employment and, at least partially, the livelihood for about 70% of the rural inhabitants in the dry areas of West and East Africa, i.e., for about 110 to 120 million people [1–3]. Dryland cattle farmers have on average 1.2–2 Tropical Livestock Units (TLU) per capita, which makes them vulnerable to deteriorations in their living conditions in the face of droughts, disease outbreaks, or any other type of unforeseen event, since it is estimated that they require around 3–4 TLU to stay above the poverty line [1]. As a livelihood, the sale of milk is the predominant way of obtaining benefits from cattle farming as it generates income for covering the daily expenses of families (e.g., for food, medicine, clothes, or schooling) [2,4–11]. Culling is secondary, and cattle are used as savings, a store of value that generates income in the short-term and that is saved for difficult periods (e.g., for the purchase of feed) or important expenses such as schooling, converting it into both a means of savings and insurance [4–6,12–17]. Regarding the production system, average farms in the region have less area than necessary to maintain one cow and her calf, in such a way that the predominant practice is cut-and-carry of forages for cattle feeding in stables [18].

In the region, there exists both scarcity and low quality of forage, a situation which is accentuated in dry seasons and influenced by climate change [2,19–21]. This, combined with a lack of quality, efficient, and sustainable production is manifested in poor supply levels of animal sourced foods and has affected food security over time [22]. Between March and July 2022, in Kenya, Somalia, and Ethiopia, the number of children affected by acute hunger, malnutrition, and thirst increased from 7.25 to almost 10 million [22]. Droughts and price hikes over the recent months, related to the COVID-19 pandemic and the war in Ukraine among others, worsen a problem that has historically marked the region [22].

Against this background, a technological change in food systems is needed to overcome the problems of food insecurity and malnutrition. The transition from traditional or low-productive pastures to sustainable forage-based cattle systems with high performance and nutritional quality is one solution that can help the situation [18,21,23–25]. The adoption of improved forage materials by cattle producers allows for obtaining quality animal feed and thus food of animal origin in higher quantities and quality. In an environment where poverty and famines are common, new forage technologies offer the opportunity to provide quality meat and milk to the most vulnerable population. In Kenya, for example, efforts are being made among public, private, and research actors to strengthen both the commercialization and adoption of higher quality forage grass seeds and splits, such as *Urochloa* (syn. *Brachiaria*) and *Megathyrsus maximus* (syn. *Panicum maximum*) hybrids and varieties, among dairy farmers [26].

Before improved forages can be adopted and disseminated; however, they need to be developed and this development needs to be adjusted to the region's needs. Regarding forage technology development, forage breeding is among the most promising alternatives for East Africa [21,25]. Over the last century, plant breeding has contributed significantly to raising crop yields [27]. The improved forages and forage hybrids developed e.g., by the forage breeding programs of the International Center for Tropical Agriculture (CIAT) or the Brazilian Agricultural Research Corporation (EMBRAPA), can increase both the productivity and quality of feed for the dairy sector, and thus contribute to improving food security, incomes, and livelihoods of dairy producer families [19,25]. Likewise, the adoption of improved forage technologies generates positive environmental externalities, for example a reduction of greenhouse gas emissions from cattle systems [21,25,28]. Breeding research for the development of future forage hybrids for the region emphasizes on traits such as higher nutritional quality, nitrogen-use-efficiency (NUE), and the ability to regenerate and avoid soil degradation [29]. Despite both the economic and environmental benefits of forage hybrids, the adoption process of existing commercial hybrids in East Africa is slow and accompanied by numerous challenges, including a lack of awareness and knowledge of the technologies, low state investment, poorly developed input and output markets [28], and, above all, a poorly developed forage seed system and market [30–33].

Under this scenario, the hypothesis of this research article is that an important potential market exists for new forage hybrids in East Africa that can be captured by the private forage seed sector and contribute to increasing livelihoods, food security, and nutrition in the region. This market basically emerges from the huge potential for the adoption of hybrid forages resulting from the superior characteristics the materials offer regarding productivity, adaptability to the environment, and nutritional quality that improve both animal productivity and livelihoods of dairy farmers, while contributing to food security and environmental sustainability in the region. The mentioned hypothesis leads to the following research questions: (i) How big is this potential market for new forage hybrids of *Urochloa* and *Megathyrsus maximus* in East Africa, and (ii) what needs to be done so that the potential can be captured and adoption will happen? The objective of this article is thus to provide an analysis of this potential market for new interspecific *Urochloa* and *Megathyrsus maximus* hybrids for East Africa, and some West African countries. Particularly, this study aims at (i) providing a market segmentation for the two hybrids of interest, (ii) estimating the area that can be covered by the two hybrids in each country of analysis (size of potential market), (iii) estimating the commercial annual and total values the two hybrids could generate in the region (market value), and (iv) describe how this market can be captured to make large-scale adoption reality.

This study is a contribution to the efforts made by the CGIAR Initiative on Market Intelligence, which seeks to expand the social impact of technologies developed by the CGIAR centers in areas such as nutrition, gender equality, and climate change [2,34]. The study thus works towards various of the Sustainable Development Goals, namely no poverty (SDG-1), zero hunger (SDG-2), and climate action (SDG-13), among others. The forage hybrid market segments used in this study were previously identified within the CGIAR EiB (Excellence in Breeding) and BPAT (Breeding Program Assessment Tool) programs between 2017 and 2019. EiB aims at modernizing crop improvement programs for better tackling the needs of farmers from low- and middle-income countries [35]. The BPAT tool is applied for the revision of the different components, capacities, and technical aspects of existing breeding programs, aimed at enhancing the rates of genetic gain [36]. This study is an important contribution to both scientific literature and the development of the forage seed sector in the region since market studies on improved forages are extremely scarce. The results provide relevant information to better understand the possibilities and economic opportunities that a massification of new forage hybrids could have. Similarly, market segmentation allows reducing the levels of uncertainty in terms of where to promote different types of new technologies and thus reduces the risks associated with adoption. This is key since the ultimate objective of plant breeding is to develop new and superior technologies that are adopted by farmers and contribute to changing their livelihoods and the economic development of a country or region.

This study applied quantitative methods for the forage hybrid market segmentation and valuation exercises. First, the forage hybrid market segments were described, based on existing information from the EiB and BPAT exercises and expert consultations. Second, forage requirements for feeding the national cattle herds were determined and the area required to produce the forages were defined based on secondary data from the Food and Agriculture Organization of the United Nations (FAO) and expert consultation. Third, based on existing information from a study that defined potential geographical suitability for the hybrids of interest in the region based on geographic information system (GIS) and multivariate cluster analysis [37], the size of the potential market for the two materials was determined. Fourth, the commercial values of the potential markets were defined using geometric averages for market prices. Lastly, factors that determine the adoption of new forage hybrids were retrieved from literature. The analysis includes several countries in eastern and western Africa, namely Ethiopia, Kenya, South Sudan, Tanzania, Uganda Nigeria, and Mali, which were identified as priority countries in 2020 as part of the EiB and BPAT exercises of CIAT's Tropical Forages Breeding Programs.

This document is composed of this introduction (Section 1), a brief literature review to shed light on both existing scientific evidence and applied methods (Section 2), a description of the forage market segments of interest to provide the required background information for understanding the technologies (Section 3), a section on materials and methods (Section 4), a combined results and discussion section (Section 5), and a section with the major conclusions (Section 6).

2. Brief Literature Review on Similar Studies

This section provides a brief overview on the literature related to market analysis of agricultural technologies and their adoption in agricultural systems with the purpose of providing insights in (i) the current research on the topic, and (ii) the applied methodologies. The methodologies used range from basic survey analysis to discrete choice models impact evaluations, multivariate techniques, and GIS such as the one used in this article.

In Indonesia, in a sample of 182 farmers, the demand for clean potato seeds in formal and informal markets was analyzed, obtaining an estimate of the willingness to pay for a higher quality seed. This study found that potato growers understand the advantages of these seeds and that the main limitation for adoption is the high price of the material. The study estimates that a large number of farmers would obtain benefits from these materials, since yield differences between 30% and 50% were estimated. In some markets, this would increase the willingness to pay by up to 37% [38]. In Kenya, the potential adoption of biotechnologies that protect maize from various types of fungi was analyzed. In a sample of 480 households, a potential adoption of 82% of these technologies was estimated with a logistic discrete choice model, which allowed to infer that both formal education and knowledge of the new technology influence adoption. Likewise, high-income farmers are more willing to make changes to their production systems. The condition of poverty generates significant risk aversion and is a limitation for adoption [39].

Other scholars have used impact evaluation methodologies with the objective of estimating the potential adoption of improved crop technologies, particularly by estimating the average treatment effect (ATE). In this context, the treatment poses scenarios in which the population is exposed to the knowledge of the new technology and can access the product, and thus actual and potential adoption can be obtained. Following this approach, an evaluation in Nigeria estimated the potential adoption of new rice varieties using a probit model. Producers with a higher educational level, age, access to extension services, and knowledge of local varieties were more likely to know and acquire improved seeds. The actual adoption rate was 19%. The results indicate that having the knowledge places the adoption potential at 54% and if producers can obtain the new seed, the value increases to 62% [40]. In Benin, the adoption of improved corn varieties was evaluated in a sample of 490 farmers with a probit model approach. The results revealed that literacy, the relationship with institutions, the area planted with corn, and income from corn production are the main determinants of adoption. A total of 84% of the producers knew the improved seed, with which the adoption was located at 78%. A global knowledge of the technology would imply a potential adoption rate of 93% [41]. A study in Uganda shows the potential adoption of drought-resistant maize in three scenarios, based on three probit models for the evaluation, referring to (a) the producer's knowledge of the new technology, (b) producer knowledge and availability of planting material, and (c) producer knowledge, availability of planting material, and affordable market prices. Based on this, an actual adoption rate of 14% was estimated. The potential adoption rates for the three scenarios were 22%, 30%, and 47%, respectively [42]. In Mali, potential adoption rates for eight climate-smart agriculture technologies were estimated with a logit model. Among these are varieties of crops resistant to droughts, organic fertilizer, and agroforestry. With a sample of 300 families, the observed adoption was between 39% and 77%, depending on the technology. In terms of access to knowledge, potential adoption fluctuated between 55% and 81%. Among the factors that influence adoption, the number of farm workers, access to subsidies, and capacity building/training were identified [43]. The reviewed studies provide consensus that the adoption of new technologies depends on the dissemination of both the technology itself and knowledge about it.

Another method of evaluating the potential market for new improved seed technologies are GIS and multivariate statistical analyses. These techniques use environmental data from official statistics and meteorological sources. For example, using a basin-level hydrological model and simulation techniques, the areas with the best yield of both total aerial biomass and cocoa beans in the humid tropics of southeastern Mexico were identified. The objective was to identify the areas with the greatest potential for productivity and economic benefit. The results show that cocoa is profitable when more than 770 kg of grain/ha is produced and that there are 223,000 ha with potential for this crop. The study uses information on climate, hydrology, soil, plant growth, other environmental variables, and management practices [44]. In Nuevo León, Mexico, the areas with the best productive possibilities for 16 crops were identified using thermal data, soil type data, and thematic maps. Results show that basic grains, vegetables, and fruit trees are suitable in more than 50% of the region's agricultural area. Another relevant result is the more precise identification of regions with frost phenomena. The study highlights the importance of this type of analysis to reduce the risk involved in any business activity in the agricultural sector [45]. Moreover, in Mexico, a potential market index at the state level was developed for corn by building the indicator with variables such as the area planted with traditional and improved varieties. This information was combined with socioeconomic data to obtain the areas with the greatest potential for adoption of improved materials. The regions with the best prospects are the Lower Pacific Tropics with 1,485,272, Valles Altos with 954,197, and the Humid Tropics with 534,279 bags of seed [46].

In the case of forages, market studies are scarce but literature provides insights about a series of difficulties related to technological change. The final adoption decision is in the hands of the producers and this in turn depends on various elements [47]. Institutional, logistical, infrastructural, and information factors are important constraints for adoption. In East Africa, these bottlenecks have been identified through qualitative, quantitative, and mixed methods. In Tanzania, the climate, insufficient availability of seeds, technical deficiencies, low productivity of local livestock, low milk prices, and few incentives for labor in dry seasons are the determinants of low adoption rates of improved forages [48,49]. In Ethiopia, forage adoption is affected by poor transport infrastructure, which increases production costs. Similarly, logistical difficulties affect the distribution of surplus milk. These elements end up offsetting the productivity and profitability gains obtained with the adoption of improved forages [50,51]. Moreover, in Ethiopia, political factors, such as high staff turnover in public institutions, affect the dynamics of the forage sector and create scenarios of uncertainty [51]. In Kenya, households with no land ownership, low educational level of the head of household, large families, and far away from markets are less likely to adopt forage technologies [52]. In Malawi, dairy processing is operating at 20% capacity and consumption is below the African average. Improved forages would significantly contribute to the development of the sector. However, ignorance of forage technologies, market entry barriers, and inadequate approaches in extension programs slow down the adoption of these materials [53]. Several of the studies agree that extension services are one of the main bottlenecks for the adoption and sustainability of new technologies. Technical support does not usually accompany all production stages, which generates significant losses in the early stages of development [48,49,53,54]. As literature shows, to face these limitations and increase adoption rates, it is necessary to consolidate relations between the public and private sectors and research to raise awareness among the rural population about the advantages of new forage technologies regarding productivity, costs, and sustainability. Likewise, it is necessary to strengthen the access to technical and entrepreneurship training, which allows for long-term sustainability of the new technologies.

3. Market Segments for the Forage Hybrids of Interest

This section provides insights into (i) past and current *Urochloa* and *Megathyrsus maximus* breeding efforts and advances at CIAT, (ii) the market segmentation exercise and characteristics for interspecific *Urochloa* hybrids, and (iii) the market segmentation exercise and characteristics for *Megathyrsus maximus* hybrids.

3.1. Urochloa and Megathyrsus maximus Breeding at CIAT

Potential markets for new hybrid materials of *Urochloa* and *Megathyrsus maximus* species are analyzed in this study [2,55,56]. Hybrids are the product of genetic improvements and combine the superior traits of different materials. CIAT began this line of research in 1987 with an interspecific breeding program with *U. brizantha* (CIAT-6294 cv. Marandú), *U. decumbens* (CIAT-0606, cv. Basilisk), and *U. ruziziensis* (BR4X-44-2) [2,47,57]. This research, together with the efforts of the private forage seed sector, allowed the formal release of various forage hybrids, including *U.* hybrids cv. Mulato I and II, Cayman, Camello, and Cobra [58,59]. These *Urochloa* hybrids are interspecific, which means that different species of the same genus were crossed to obtain an improved hybrid [2,60]. Mulato I and II were the first forage hybrids launched in Africa in 2005. Much later, Cayman and Cobra followed in 2019, and Camello in 2020 (Papalotla 2022, personal communication). The market does not yet count with hybrids of *Megathyrsus maximus*, but development has started several years ago, and the release of a first hybrid is only a matter of time. Although CIAT's forage breeding program also focuses on the development of hybrids of

U. humidicola, they are destined for moist soils [61] and thus, not adapted to the conditions of most regions of East Africa [2].

The predominant characteristics a region has regarding its soils, climate, and agricultural practices are key for identifying forage hybrid markets. The technical information on potential new *Urochloa* and *Megathyrsus maximus* hybrids presented in this section is derived from field measurements in pilot experiments. However, the large number of trials required at the early breeding stages made it unfeasible to conduct the pilots in Africa directly [37]; (V. Castiblanco, personal communication, 13 June 2019). Thus, CIAT's breeding programs identified areas with similar geographic and environmental characteristics to those of East Africa and applied the initial hybrid trials in Colombia [2,37].

3.2. Market Segmentation for Urochloa Interspecific Hybrids

Urochloa interspecific hybrids are destined for sub-humid tropical savannahs with low fertility and acid soils in eastern and southern Africa [2]. African soils suffer from desertification, which is negatively affecting yields and undermining the resilience of the agriculture and livestock sector, two detrimental elements of subsistence farming in Africa [62]. *Urochloa* hybrids are used for two purposes, namely (i) free grazing and (ii) cut-and-carry for feeding in stables. Important hybrid traits for the region include performance, response to pests and diseases, targeted production systems, and seed production potential.

The projected performance of new *Urochloa* interspecific hybrids, based on the pilots by CIAT's breeding program, is described below. New hybrid materials are expected to have seed yields equal or superior to the existing commercial offer, even when extreme environmental conditions predominate (e.g., heat, drought, water-logging, acid soils) (Table 1). Seed production potential is important because it means greater productivity and efficiency, which allows new products to be competitively priced in the market. Likewise, materials are expected to be performing equal or superior regarding NUE, as inputs are scarce in the region and the use of existing resources needs to be optimized under the premise of sustainable development [63]. Regarding the forage quality, the new pilot tested *Urochloa* hybrids that have a crude protein (CP) content $\geq$ 10.5% and an in vitro digestibility of dry matter (IVDMD) $\geq$ 62%, both important measures for feed quality [64,65]. Regarding both shade tolerance (important for silvo-pastoral systems) [66] and palatability (important for the selection by the animal) [67], the new hybrids are expected to reach intermediate to high levels (on a scale of 1 to 9). *Rhizoctonia* leaf blight is one of the major diseases for forages in the region, with up to 50% of the planted *Urochloa* affected [68], and new hybrids should rank $\leq$ 2 on a scale of 1 to 5. Regarding the resistance to insects, the analysis is still in the stage of development of a phenotyping methodology. However, the already existing *Urochloa* hybrids have a good response to the spittlebug complex (Hemiptera: Cercopidae), but less to *Tetranychus urticae* (red spider mite), an insect that has affected the Mulato II hybrid and the Basilisk variety in East Africa, for example in Kenya [2,69].

The production system for which interspecific *Urochloa* hybrids are aimed at is dryland cattle production, where rainfed agriculture is predominant and no artificial irrigation techniques are implemented—which comprises large parts of the African soils [70]. The traits considered essential for new interspecific *Urochloa* hybrids are seed yield, forage CP and IVDMD contents, and resistance to pests and diseases. Competitors of new hybrids currently available on the market are (a) Mulato II, (b) Cayman, (c) Camello, and (d) Cobra [2,59]. Table 1 lists the main characteristics of these competitors.

Table 1. Potential competitors for new interspecific hybrids of *Urochloa*.

Characteristics	Mulato II	Cayman	Camello	Cobra
Main features	Good response to drought, acid soils, and high temperatures [2] Combines the best features of other hybrids [2]	Tolerant to humidity and waterlogging [59]	Drought tolerance, quick establishment, good for acid soils [59]	High yield, vertical growth that facilitates cutting [59,71]

Table 1. *Cont.*

Characteristics	Mulato II	Cayman	Camello	Cobra
Resistance to pests and diseases	spittlebug [59]	spittlebug [61]	spittlebug [71]	spittlebug [71]
Required soil fertility level	medium, high [59]	humidity [59]	medium [59]	high (for higher yields) [59]
Palatability	very good [59]	very good [59]	very good [59]	very good [59]
CP (%)	14–22 [59]	10–17 [59]	14–16 [71]	14–16 [71]
IVDMD (%)	55–66 [59]	58–70 [59]	62 [71]	69 [59]
Yield (t/ha/cut)	25 [72]	<24 [73]	27–30 [71]	35–40 [71]
Main use	grazing [59]	grazing [59]	grazing [59]	cut-and-carry [59]

Source: own elaboration based on [2,59,61,71–73].

3.3. Market Segmentation for Megathyrsus maximus Hybrids

Megathyrsus maximus hybrids are destined to cut-and-carry production systems in the sub-humid tropical savannah of eastern and southern Africa, where highly productive and fertile soils predominate. According to the pilot tests carried out in Colombia, *Megathyrsus maximus* hybrids are expected to have seed yields equal or superior to the existing commercial offer, even when extreme environmental conditions predominate (e.g., heat, drought, water-logging, acid soils) and NUE is considered (Table 2). Regarding the forage quality, the hybrids have a crude protein (CP) content $\geq$ 10.5% and an in vitro digestibility of dry matter (IVDMD) $\geq$ 62%. In addition, hybrids have a moderate to high Biological Nitrification Inhibition (BNI) potential, reducing the use of fertilizers in feed production and thus generating savings both in production costs and greenhouse gas emissions [2,74].

Table 2. Potential competitors for new *Megathyrsus maximus* hybrids.

Characteristics	Mombasa	Tanzania	Massai	Mavuno *
Main features	High regrowth rate and good stem-leaf-ratio Medium tolerance to cold and burning Good drought tolerance [72]	Medium drought tolerance [72,75]	Burn and shade tolerance Reduced yield by 50% in dry season [2,72]	Good tolerance to drought, burning, and shade Medium tolerance to humidity [61,76]
Resistance to pests and diseases	spittlebug [72]	spittlebug medium tolerance to coal in the inflorescences [72]	spittlebug sensitive to panicle rot caused by *T. ayresii* [72]	spittlebug [77]
Required soil fertility level	medium to high acid soils [72]	medium to high acid soils [72]	low to medium acid soils [72]	medium acid soils [61]
Palatability	very good [72]	good [75]	good [75]	very good [77]
CP (%)	10–14 [72]	10–12 [72]	7–11 [72]	18–21 [76]
IVDMD (%)	60–65 [72]	62 [72]	55–60 [72]	60 [76]
Yield (t/ha/cut)	25 [72]	18–20 [72]	21 [72]	17–20 [76]
Main use	grazing cut-and-carry [72]	grazing cut-and-carry [72]	grazing cut-and-carry [75]	grazing cut-and-carry [76]

Source: Own elaboration based on [2,61,72,75–77]. * Mavuno was released by Wolf Sementes from Brazil in 2013 [61]. Despite being an *Urochloa* hybrid, due to its high performance, it is considered a potential competitor in the *Megathyrsus maximus* market.

Similar to the case of interspecific *Urochloa* hybrids, the production system for *Megathyrsus maximus* hybrids is rainfed. Potential competitors already available on the market are (a) *Megathyrsus maximus* cv. Mombasa, (b) *Megathyrsus maximus* cv. Tanzania, (c) *Megath-*

yrsus maximus cv. Massai, and (d) *Urochloa* hybrid cv. Mavuno [2,61,72,75–77]. Table 2 summarizes the main characteristics of these materials.

4. Materials and Methods

This section gives an overview on the materials and methods used in this study. First, a brief overview is provided on the information sources consulted for estimating potential forage hybrid markets and market values. Second, the methods for the estimation of both potential markets and market values applied in this study are presented. This includes four main steps, namely (i) estimating the required forage amount for each country, based on the present dairy herd and its needs, (ii) estimating the potential annual hectares for forage cultivation based on this need, (iii) assigning a proportion of the required hectares to the two forage hybrids of interest, based on a Target Population of Environment (TPE) approach, and (iv) estimating the potential market value for each country and forage hybrid of interest. The applied methodological steps are summarized in Figure 1.

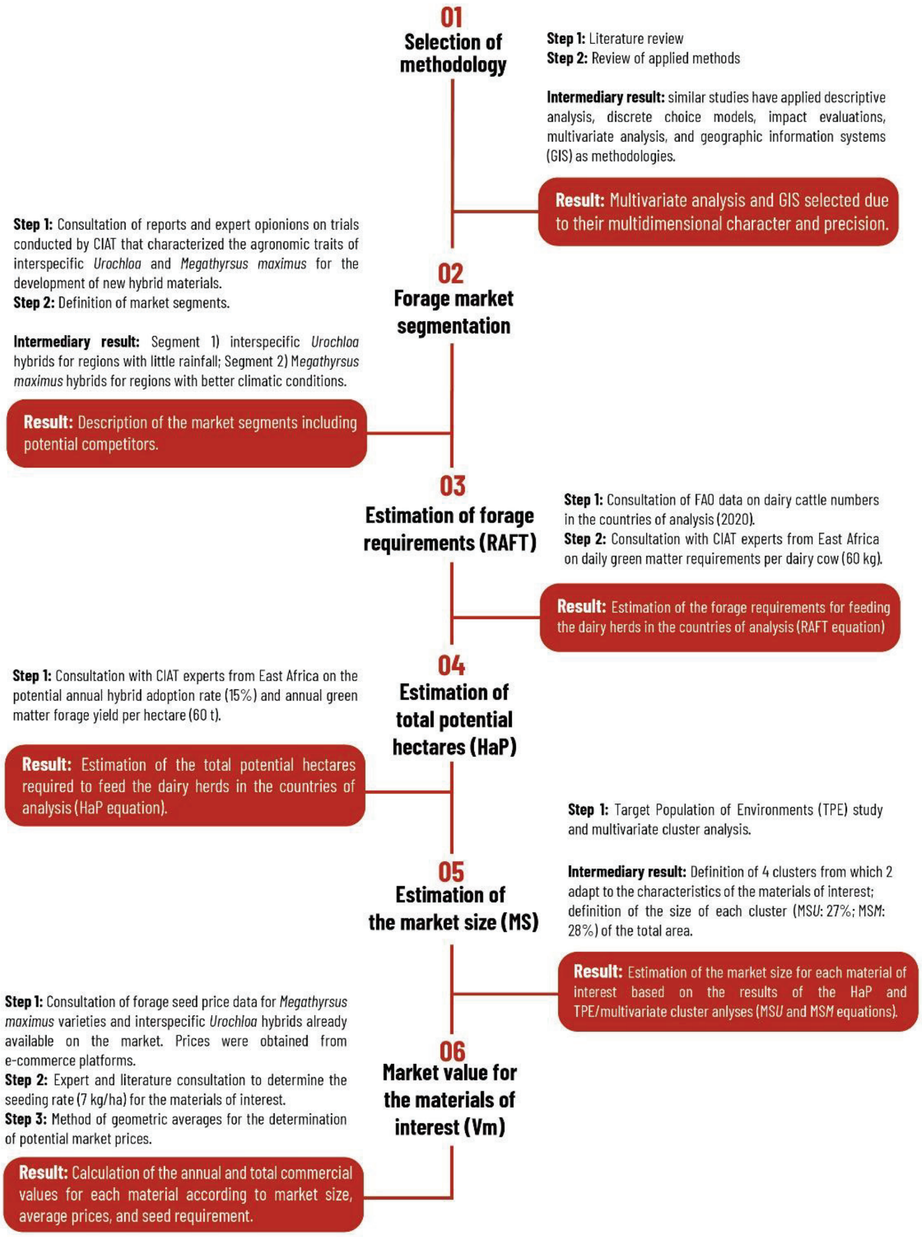

Figure 1. Methodological flowchart for the estimation of potential markets of hybrid forages in Africa.

4.1. Information Sources

Given that dairy production is the most relevant cattle activity in the region, the quantitative approximation of the potential hectares of new hybrid forages is based on the information on cattle heads destined for dairy production. In the FAOSTAT Database (Food and Agriculture Organization Statistics) of the FAO, production, crops, and livestock products were entered, and the information was filtered according to the required criteria [78]. In "element", animals in production were chosen. In "product", primary livestock (list) was displayed by choosing the option "raw milk from bovine cattle". Finally, the year 2020 and the countries of interest were selected. The process produced a data table with the information on the heads of dairy cattle per country. In the calculation, this information will be converted into hectares of forages required to feed these animals.

To define the percentage of adoption of each material, the Target Population of Environments (TPE) study of CIAT's forage breeding programs was consulted, by which the areas that are most suitable for the evaluated forage materials were identified [37]. Information on the market prices of different forage seeds was obtained from the prices published by different seed distributors on electronic commerce platforms for the second half of 2022 [59]. Table 3 summarizes the different variables used in this study and provides information on the sources of information consulted.

Table 3. Variables and information sources.

Variable	Description	Source
Dairy cattle herd (CRL)	Dairy cattle heads per country in 2020	[78]
Daily forage requirement (RDFK)	Daily forage requirement in kg	Expert consultation, [2]
Adoption rate (AR)	Estimated adoption rate of new hybrids in %	Expert consultation, [2]
Average hybrid forage yield (Ytha)	Average hybrid forage yield per hectare in tons	Expert consultation, [2]
Proportion of potential area for new interspecific *Urochloa* hybrids	Proportion of potential area for new interspecific *Urochloa* hybrids in % defined using the TPE study	[37]
Proportion of potential area for *Megathyrsus maximus* hybrids	Proportion of potential area for *Megathyrsus maximus* in % defined using the TPE study	[37]
Sowing rate (S)	Sowing rate of forage hybrids in kg per hectare	Expert consultation, [79]
Seed price forage hybrids (P)	Average market price for a kg of hybrid seed	Expert consultation, [59,79]

4.2. Method for the Estimation of Potential Markets and Market Values

This section describes the methods used to estimate potential markets for new interspecific *Urochloa* and *Megathyrsus maximus* hybrids in East and West Africa, particularly in Ethiopia, Kenya, Tanzania, Uganda, South Sudan, Mali, and Nigeria.

4.2.1. Steps 1 and 2—Estimating Forage Requirements and Potential Hectares for Cultivation

Based on data from the FAO on cattle heads for dairy production for the year 2020, the number of hectares required for forage cultivation were calculated. The estimated area is a conservative assumption since new hybrid forages will have increased performance and require fewer area for the same level of production than the existing commercial offer. The estimation considered the following assumptions based on expert consultation [2]: A daily green matter requirement of 60 kg per animal, a forage adoption rate of 15% per year, and a green matter yield of 60 tons per hectare and year.

By means of Equations (1) and (2), the calculation of the potential hectares was carried out. Equation (1) gives the annual forage requirement in tons. With Equation (2), the hectares of forages required to feed the animals were obtained. The measurement is in green matter. Equations (1)–(4) are based on V. Castiblanco and A. Notenbaert (personal communication, 13 June 2019).

$$\text{RAFT} = \frac{\text{RDFK} \times 365\text{d} \times \text{CRL}}{1.000}, \quad (1)$$

where RAFT is the annual forage requirement in tons, RDFK is the daily forage requirement in kg, and CRL is the number of dairy cattle heads. Substituting this result in Equation (2), the potential hectares are obtained,

$$\text{HaP} = \frac{\text{RAFT} \times \text{AR}}{\text{Ytha}}, \tag{2}$$

HaP is the potential forage hectares required for forage cultivation, AR is the adoption rate, and Ytha is the average hybrid forage yield per hectare in tons. For example, in 2020, Kenya had 5,112,340 dairy cattle. According to this and the established assumptions, this leads to the following estimation for the annual forage requirement:

$$\text{RAFT} = \frac{60\text{kg} \times 365\text{d} \times 5,112,340}{1.000} = 111,960,246 \text{ tons}, \tag{3}$$

and for the potential hectares required for hybrid forage cultivation:

$$\text{HaP} = \frac{111,960,246\text{t} \times 15\%}{60} = 279,901 \text{ ha}, \tag{4}$$

4.2.2. Step 3—Estimating the Market Size: Assigning a Proportion of the Potential Hectares to the Two Forage Hybrids of Interest

The third step was the estimation of the market size through assigning a proportion of the potential area identified in Section 4.2.1 to each of the two hybrids of interest (interspecific *Urochloa* and *Megathyrsus maximus* hybrids). This proportion was obtained from a TPE study conducted by CIAT in 2019 (V. Castiblanco; A. Notenbaert, personal communication, 13 June 2019) [37]. This study applied both GIS and multivariate cluster analysis, and in this way, areas with similar environmental traits in Africa and Colombia could be identified [37] (see Figure 2). This allowed the pilot experiment referenced in Section 3 to be carried out in Colombia. Likewise, four geographic clusters with similar environmental characteristics were identified [37], considering cattle density [80], soil quality data [81], and different precipitation levels [82,83].

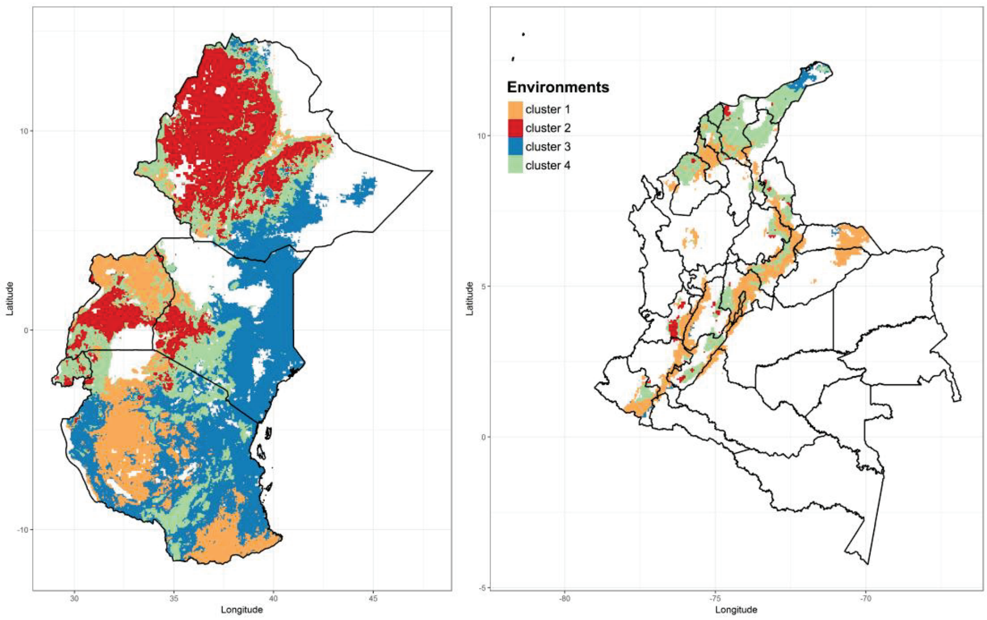

Figure 2. (**left**) Identified geographic clusters for East Africa and (**right**) Colombia [37].

For this analysis, two groups are relevant, namely (a) Cluster 2 (good), colored red on the maps, is characterized by higher precipitation levels and better rainfall distribution throughout the year. It provides the conditions for the adoption of potential *Megathyrsus maximus* hybrids, which have high quality and productivity levels, but require good environmental conditions [2]. Cluster 2 represents 28% of the potential area [37]. Moreover, (b) Cluster 3 (hostile), colored blue on the maps, is characterized by low precipitation levels and poor rainfall distribution throughout the year. It provides the conditions for new interspecific *Urochloa* hybrids, which have a medium to high productivity and are very adaptable to difficult environments [2]. Cluster 3 represents 27% of the potential area [37]. These percentages were applied to the HaP (step 2) to define the size of the potential markets (MS) for both new interspecific *Urochloa* and *Megathyrsus maximus* hybrids. This was done for each of the countries of interest. Equations (5) and (6) allow obtaining the respective values [37]:

$$\mathrm{MS}U = \mathrm{HaP} \times 27\% \tag{5}$$

$$\mathrm{MS}M = \mathrm{HaP} \times 28\% \tag{6}$$

where MS*U* and MS*M* are the market sizes for new interspecific *Urochloa* and *Megathyrsus maximus* hybrids in hectares.

4.2.3. Step 4—Estimating the Potential Market Values

Finally, the commercial value of the identified market segments was estimated, consulting average market prices for the materials considered as competitors for new interspecific *Urochloa* and *Megathyrsus maximus* hybrids (see Tables 1 and 2). Due to the high research and development costs, among others, forage hybrid seeds have a higher market price than other forage varieties. Regarding *Megathyrsus maximus*, there are no hybrid materials available on the market yet; hence, direct price references are missing. To obtain market price estimations for these hybrids, the price difference between interspecific *Urochloa* hybrids and other commercial *Urochloa* varieties was applied to the case of *Megathyrsus maximus*, too. For this, geometric averages were used, as they better capture price dynamics [84]. Equations (7) and (8) allow obtaining the respective values [84]:

$$\mathrm{PMU} = \sqrt[n]{P_1 \times P_2 \times \cdot \times P_n}, \tag{7}$$

$$\mathrm{PMM} = \mathrm{h} \times \sqrt[n]{P_1 \times P_2 \times \cdot \times P_n}, \quad con{\cdot}h > 0 \tag{8}$$

where PMU and PMM are the averages market prices of *Urochloa* and *Megathyrsus maximus*, respectively. The term h represents the margin that increases the price to level it to the hybrids, and n corresponds to the number of data used for the calculation.

Finally, the value of each market was expressed according to Equation (9) [79]:

$$\mathrm{Vm} = \mathrm{MS} \times \mathrm{S} \times \mathrm{P}, \tag{9}$$

The market value (Vm) was calculated for each hybrid, considering the market size in hectares (MS), the sowing rate per ha in kg of hybrid seed (S), and the market price (P) of one kg of seed. Following the literature on the subject, 7 kg of forage hybrid seed is required for each ha [79]. The average market prices for *Urochloa* and *Megathyrsus maximus* varieties were US$ 18.42 and US$ 19.87, per kg of seed, respectively, and for the existing interspecific *Urochloa* hybrids, US$ 25.35. The price premium for *Urochloa* hybrids can thus be estimated to be 37.63%. Applying this price premium to the case of *Megathyrsus maximus* results in a potential market price of US$ 27.34 for a kg of hybrid seed.

5. Results and Discussion

This section provides the results and discussion of this study. In particular, the results obtained from the different estimations are presented and then put into context with current literature on forage hybrid markets and adoption.

5.1. Forage Requirements to Feed the Cattle Herds and Area Required for Forage Cultivation

Dairy production is the most representative cattle activity in the region of analysis. According to the FAO, the dairy cattle herd in Africa for 2020 reached 66,330,001 heads. The largest inventory is concentrated in East Africa, which holds 34,723,481 dairy cattle. Within this region, the largest herds are found in South Sudan (8,432,559 dairy cattle), followed by Ethiopia (7,556,402), Tanzania (7,116,771), Kenya (5,112,340), and Uganda (4,037,038) [78]. To understand the relative importance of the dairy sector, some figures regarding beef cattle are important to consider, since its participation in the region is lower. Africa counts with a total beef cattle herd of 41,720,252 heads, and in East Africa, there are about 14,527,659 beef cattle. The countries with the highest inventory of beef cattle in the region are Ethiopia (4,086,481 beef cattle), Tanzania (3,554,364), Kenya (1,953,734), Uganda (1,217,247), Zambia (1,065,054), and South Sudan (964,884) [78]. Given the importance of the dairy sector in the region, only the information on dairy cattle was considered to estimate potential hectares of improved forages needed to feed the animals according to the methodology exposed in the previous section. A summary of the RAFT and HaP estimates for the analyzed countries can be found in Table 4.

Table 4. Annual forage requirement by the dairy cattle herd and potential annual area for forages.

Country	Dairy Cattle Herd in 2020 (Heads) [78]	RAFT: Forage Requirement (Mt/y)	HaP: Potential Forage Area (ha/y)
Ethiopia	7,556,402	165,485,204	413,713
Tanzania	7,116,771	155,857,285	389,643
Kenya	5,112,340	111,960,246	279,901
Uganda	4,037,038	88,411,132	221,028
South Sudan	8,432,559	184,673,042	461,683
Nigeria	2,213,856	48,483,446	121,209
Mali	1,995,914	43,710,517	109,276

5.2. Size of the Potential Markets

The results of the estimation for the potential market (market size) of new interspecific hybrids of *Urochloa* are provided in Figure 3A. The biggest market can be observed in Ethiopia with a potential of 111,703 ha for interspecific *Urochloa* hybrids, followed by Tanzania and Kenya with 105,204 and 75,573 ha, respectively. Uganda and Nigeria are in the middle range with 59,678 and 32,726 ha, respectively, and Mali, another country from West Africa, holds the smallest market potential (29,505 ha). These figures imply that the mere participation of Ethiopia, Tanzania, and Kenya represents about 70% of the potential area of adoption of new interspecific *Urochloa* hybrids in the analyzed countries, and 83% when only the East African countries are considered.

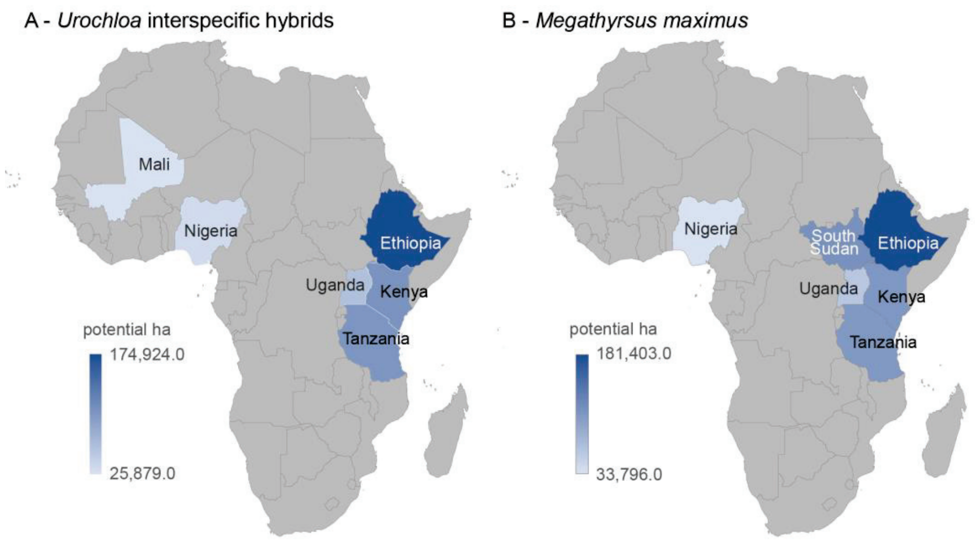

Figure 3. Market size for new interspecific *Urochloa* (**A**) and *Megathyrsus maximus* (**B**) hybrids. Sources: [85] and (V. Castiblanco and A. Notenbaert personal communication, 13 June 2019).

Figure 3B shows the results for the potential market (market size) of *Megathyrsus maximus* hybrids. South Sudan holds the biggest market potential with 129,271 ha, followed by Ethiopia (115,840 ha), Tanzania (109,100 ha), Kenya (78,372 ha), and Uganda (61,888 ha). In West Africa, Nigeria offers a potential market for *Megathyrsus maximus* hybrids of 33,938 ha. These figures imply that the mere participation of South Sudan, Ethiopia, and Tanzania represents about 67% of the potential area of adoption of *Megathyrsus maximus* hybrids in the analyzed countries, and 72% when only the East African countries are considered. These results show the most representative markets in the analyzed countries, according to areas best suited to adopt one of the two technologies of analysis.

Although no previous studies have delved into this type of analysis for tropical forages, geographic profiling techniques through environmental, climatic, and edaphic conditions have been implemented to evaluate other crops (see Section 2) [44–46]. The methodological approach used in this article is thus in line with these studies regarding two aspects, namely (i) the identification of potential areas to successfully implement a specific crop, and (ii) the identification of the production potential to be significantly higher than the current one, given the expected yields of the new technologies with superior characteristics.

5.3. Market Values

The estimation of the commercial value complements this analysis and is an essential element for decision-making by dairy producers, the private forage seed sector, and the public sector. The consultation of current market prices for both commercialized *Urochloa* cultivars and interspecific *Urochloa* hybrids resulted in a price premium of 37% for the hybrids. For *Megathyrsus maximus*, no hybrids are on the market yet that would serve for price comparison and guidance. To get an idea of the price of a higher quality material of *Megathyrsus maximus*, the *Urochloa* market was used as a reference and based on the differential found there, the potential price premium for hybrid seeds of *Megathyrsus maximus* was estimated at 37%. In a context where buyers are aware of the improved characteristics of new materials, willingness to pay is expected to be higher, since a greater investment will be compensated by efficiency gains, as well as higher productivity and income, as shown in a study on potato seed from Indonesia, where price increases in private sector markets of between 6% and 37% could be absorbed by the additional yields [38]. The estimated annual market values in millions of US$ are presented in Figure 4.

Figure 4. Estimated annual market values in millions of dollars for new interspecific *Urochloa* (**a**) and *Megathyrsus maximus* (**b**) hybrids.

The total annual market value for both technologies is estimated at US$ 174,665,945, out of which *Megathrysus maximus* hybrids make up 58% and new interspecific *Urochloa* hybrids 42%. Regarding new interspecific *Urochloa* hybrids, the annual market value is US$ 73,521,066, and the largest market shares are held by Ethiopia, Tanzania, and Kenya with values close to US$ 19.8, 18.6, and 13.4 million, respectively. Regarding *Megathyrsus maximus* hybrids, the annual market value is US$ 101,144,879, and the largest market shares are held by South Sudan, Ethiopia, and Tanzania with values close to US$ 24.7, 22.1 and 20.8 million, respectively. Table 5 provides a summary on the potential market and annual market values for the analyzed countries.

Table 5. Summary of potential market sizes and values for new forage hybrids in Africa.

Country	New Interspecific *Urochloa* Hybrids		*Megathyrsus maximus* Hybrids		Vm: Total Annual Market Value (US$/Country)
	MS: Potential Market Size (ha)	Vm: Annual Market Value (US$)	MS: Potential Market Size (ha)	Vm: Annual Market Value (US$)	
Ethiopia	111,703	19,818,364	115,840	22,173,319	41,991,682
Tanzania	105,204	18,665,332	109,100	20,883,276	39,548,609
Kenya	75,573	13,408,261	78,372	15,001,524	28,409,785
Uganda	59,678	10,588,040	61,888	11,846,184	22,434,224
South Sudan	n/a	n/a	129,271	24,744,292	24,744,292
Nigeria	32,726	5,806,335	33,938	6,496,284	12,302,619
Mali	29,505	5,234,733	n/a	n/a	5,234,733
Total	414,388	73,521,066	528,409	101,144,879	174,665,945

On the other hand, it should be noted that the assumption of an adoption rate of 15% implies, at least theoretically, that the adoption of the new materials can occur in less than seven years, which means that the total market values for new interspecific *Urochloa* and *Megathyrsus maximus* hybrids would be US$ 490,140,439 and US$ 674,299,195, respectively. The obtained estimates for both the annual and total market values for the two hybrid forage materials are in line with the scarce literature and estimations on commercial values and growth potential of tropical forages in the global South. Private research companies such as Morder Intelligence valued the global forage market for 2020 at approximately US$ 20.33 billion and project that by 2026, it will reach about US$ 30.91 billion [86]. Calculations for Brazil indicate that, in 2019, the seed trade for tropical grasses exceeded 1.4 billion Reais, which was equivalent to almost US$ 269 million, noting that low-quality seeds participate with 30% of the total market [87]. A study on the extent and economic significance of cultivated forages in developing countries estimated the current total value of planted forages in developing countries at US$ 63 billion, corresponding to a coverage of 159 million hectares [23].

5.4. Requirements for a Development of This Market and Widespread Adoption of New Forage Hybrids

The results presented in this article suggest significant possibilities for both the commercialization of the new forage hybrid seeds and their adoption by dairy farmers. Growing improved forages as feed for dairy cattle is a valuable alternative to address the problems of food security and malnutrition in the region, since they increase both animal productivity and meat and milk quality. In this way, the change from production systems based on traditional pastures to systems that involve highly productive and more sustainable technologies would have positive effects on the poorest and most vulnerable population.

Another set of studies aims at estimating actual and potential adoption rates through impact evaluation techniques [40–43]. Although they are not focused on market segmentation by product, as is the objective of this research, they do contribute to the discussion by providing empirical evidence on the importance of adoption factors, such as the dissemination of knowledge and provision technical assistance to the potential users of the new technologies. The present study did not focus on the analysis of adoption factors but instead on providing decision-making support for the forages seed sector on potential opportunities for investment. However, investments in forage hybrid seed production and dissemination alone will not suffice to increase adoption rates of new technologies among dairy producers in East Africa despite tackling the lack of basic seed [30]. Literature, mostly for Latin American where the adoption of cultivated forages is more advanced compared to East Africa, shows that it depends on numerous additional factors. These include risk factors (risk aversion, perception of risks regarding future returns) [88–90], knowledge and information about the technology itself (establishment and management processes and costs, benefits and risks associated with the technology) [91–93], labor requirements [94], access to productive inputs and capital (credit) [95–97], product differentiation strategies [98], extension and technical assistance [47,92,99–102], the knowledge and innovation system [47,103,104], social capital and social networks (e.g., through farmer groups) [85,105–109], land prices, land tenure, land speculation [71,110,111], existing and evolving regulatory frameworks and political/institutional factors [112–114], and conflict [115].

Regarding regulatory frameworks and political and institutional factors, several studies, such as those by Enciso et al. [47], Orr [116], or Karandikar et al. [117], have shown that the institutional sector is important for facilitating or undermining the dissemination and adoption of improved agricultural technologies such as forage hybrids. Public policies without a clear focus can create distortions in the process. Technological developments and the marketing of new hybrid forages need to integrate the private sector with public extension, research, and distribution systems [47,117]. The confluence and cooperation of actors allow structuring policies according to the local realities and needs of the targeted producers. In short, the sustainability of these systems depends on the collaboration of different actors, which is not guaranteed in East Africa as studies from Kenya, Tanzania, and Ethiopia show [31–33]. Likewise, the regulatory frameworks for forage seed production and certification in East Africa are complex and in cases too demanding for seed companies to comply with, leading to withdrawals from both seed bulking and production, for example in Kenya [31] and Tanzania [32], and to weak formal seed systems. Informal seed systems, for example the exchange of seeds or vegetative material among smallholder farmers, on the other hand, are often marginalized, incriminated, and not considered in the legal frameworks in the region [118,119].

Under the umbrella of the so-called Industrial Revolution 4.0 (IR4.0), digital technologies such as the Internet of Things, Big Data, and Artificial Intelligence have been increasingly incorporated in food systems [120]. Regarding the topic of the present study, the IR4.0 offers numerous opportunities for both the development of a hybrid forage seed sector in East Africa and the adoption of the hybrids by dairy farmers. Big data, for example, are already being used to support the selection of tropical forages based on specific agro-ecological conditions with clear indications on how to grow the materials, and thus reduce the risk of failure in forage adoption [121]. Likewise, mobile applications are being developed that include Artificial Intelligence to support dairy farmers with decision-making, such as the DigiCow and Digital Dairy apps in Kenya [122,123].

In summary, both the results of the present study as well as the above-described evidence on the possibilities and limitations for the adoption and dissemination of new forage hybrids in East Africa can be related to the Quintuple Helix innovation model [124]. According to the model, socio-ecological transition can only happen if collaboration among a broad set of actors happens, i.e., among the higher education, economic, and political systems, and if this is put into the context of both a media- and culture-based public and the natural environment of society. For the case of forage hybrid adoption for increasing food security and environmental sustainability in East African dairy systems, collaboration among the different actors is thus essential. This includes national and international research and education institutions, forage seed producers and distributors, forage and dairy value chain actors, public sector actors for seed regulation and extension, and financing institutions. It also includes the consideration of social capital (e.g., traditions and values) and capital of information (e.g., communication, social networks), as well as natural capital (e.g., resources, environmental conditions) in both the development and scaling of new forage technologies.

Finally, it is worth mentioning that most market research on improved crops focuses on identifying and delimiting the geographical areas with the greatest possibilities for adoption. Likewise, market studies on improved forages are scarce. The present article combined two methodological approaches, namely (i) the estimation of potential areas where two hybrid forages can be planted and the amount that is needed by the dairy cattle herd present in the countries of analysis, considering specific environmental and productive conditions present in the region of analysis, and (ii) the estimation of the commercial value for each of the two technologies in each of the analyzed countries. Both the methodological approach and obtained results presented above thus add significant value to the scientific readings on the subject.

6. Conclusions

The estimations of potential markets (market sizes and values) for new interspecific *Urochloa* and *Megathyrsus maximus* hybrid forages for the dairy sector in East Africa provided in this article indicate an important opportunity for making changes in the local food systems. Moving from dairy systems based on traditional or low-quality pastures towards systems that integrate improved forage materials, i.e., hybrids, provides opportunities for improving both the availability and nutritional quality of animal source food, i.e., milk, and thus contributes to achieving food security and combating hunger in the region. Likewise, taking advantage of and developing these markets implies an opportunity to promote a sector that has the capacity to generate income and livelihoods for the most vulnerable part of the population. From a point of view of economic development, the promotion and consolidation of these markets can be an effective economic policy to improve indicators of poverty, unemployment, growth, and price stability, since dairy is a fundamental activity for the economic structure in the region and its development has a positive impact on the entire macroeconomic environment. The development of potential forage hybrid markets, however, requires that adequate market conditions exist. In this sense, a favorable commercial and institutional environment needs to emerge that supports the production, distribution, and adoption of forage hybrids. This is a determining element since it will provide a regulatory environment that attracts investments in seed production and distribution as well as the necessary incentives for dairy producers (e.g., access to knowledge, seeds and other inputs, or credit) to make informed adoption decisions. Alongside, communication and collaboration between the various actors must be enhanced to jointly work on the difficulties that arise with the adoption of forage hybrids. An adequate information system is essential for decision makers to establish policies and implement timely actions according to the local contexts. Considering these aspects is thus essential for the development of a competitive forage hybrid seed market so that promising materials can be properly registered and made available to farmers.

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

Abbreviations

TLU: Tropical Livestock Units; syn.: synonym; CIAT: International Center for Tropical Agriculture; EMBRAPA: Brazilian Agricultural Research Corporation; CGIAR: Consultative Group on International Agricultural Research; SDG: Sustainable Development Goals; EiB: Excellence in Breeding; BPAT: Breeding Program Assessment Tool; GIS: Geographic Information System; ATE: Average treatment effect; NUE: Nitrogen Use Efficiency; CP: Crude Protein; IVDMD: In Vitro Dry Matter Digestibility; BNI: Biological Nitrification Inhibition; TPE: Target Population of Environment; FAO: Food and Agriculture Organization of the United Nations; RDFK: daily forage requirement in kg; CRL: number of dairy cattle heads; RAFT: annual forage requirement in tons; HaP: potential forage hectares; PMU: average market price *Urochloa* hybrids; PMM: average market price *Megathyrsus maximus* hybrids; MSM: market size for *Megathyrsus maximus* hybrids; MSU: market size for interspecific *Urochloa* hybrids; Vm: market value; IR4.0: Industrial Revolution 4.0.

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