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New Insights in Agriculture

Sustainability, Digitalization and Food Safety

Edited by
Kristina Kljak, Klaudija Carović-Stanko, Darija Lemić, Jernej Jakše,
Kurt A. Rosentrater, Arup Kumar Goswami and Craig Sturrock

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Review

Earth Observation-Based Rice Mapping Studies in Vietnamese Mekong Delta Compared to Global Context: A Bibliometric Analysis

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Abstract: A bibliometric study on mapping the rice cropping systems in VMD is crucial for understanding the trend of EO-based rice mapping and how remote sensing technologies are essential to address the food security issue in the region. This article presents an overview of Earth observation (EO)-based rice mapping strategies since 1979, prioritizing the scope of data, approaches, and techniques derived from 3700 research articles worldwide and contrasting them with the Vietnamese Mekong Delta (VMD). Various quantitative analyses were conducted through bibliometric analysis using the VOS viewer and Scopus database. Optical images, particularly the Landsat (~16%) and MODIS (~12%) time series datasets, were the most commonly utilized globally. MODIS data (~31%) had the highest share in the VMD context, followed by Landsat data (~19%), while Sentinel series (~13% for global and ~16% for VMD) data became more popular in recent years. Research on rice mapping using UAVs has been gradually creeping into rice mapping research globally, but a gap is yet to be filled in the VMD. The most widely used approaches for rice mapping globally were Random Forest, Support Vector Machine, and Principal Component Analysis. Spectral indices like EVI, NDVI, and RVI were commonly used for rice mapping and monitoring. The findings underscore the critical role of EO-based rice mapping studies in the VMD in addressing sustainability and food security challenges.

Keywords: Earth observation; rice mapping; Scopus; Vietnamese Mekong Delta; bibliometric analysis

1. Introduction

The global population is anticipated to surge to nearly 9.8 billion by 2050 (UN-DESA 2017), with Asia contributing 54.34% to the world's population (UN World Population Prospects 2019), demanding additional food production. Rice, a staple crop for more than half the world's population [1], is cultivated in over 100 countries. Countries that produce and consume rice testify to the fact that rice is grown in a range of habitats, from tropical to temperate, with varying water regimes and topographic circumstances. From the driest deserts to the world's most humid locations, rice is produced everywhere. It is grown at Al Hasa Oasis, Saudi Arabia, where annual rainfall is less than 100 mm, and along the Arakan coast in Myanmar, where the growing season has an average of more than 5100 mm of rainfall. The areas are considerably different in temperature, such as in Otaru, Japan, which averages 17 °C, whereas the Upper Sind region of Pakistan experiences 33 °C [2]. Furthermore, more than 110,000 kinds of rice are cultivated, each with a unique quality and nutritional makeup [3]. Rice provides 80% of the energy needs of almost 2 billion people in Asia alone. It mainly comprises 80% carbohydrates, 7–8% protein, 3% fat, and 3% fibre [4]. In 2012, 11.5% of the world's cultivable land was covered by paddy fields. About 19% of the world's daily calories come from rice, which was consumed annually at an average of 65 kg per person between 2010 and 2011 [5] (IRRI, AfricaRice and CIAT 2010). Despite a sizable worldwide rice cultivation area and rising rice production in many nations, the

overall demand frequently exceeds the supply [1]. Additionally, it is anticipated that the world will consume 873 million tonnes of rice in 2030 [6]. In the global context, rice must be given the utmost consideration due to its significance as a staple food for more than 90% of the population in underprivileged and developing nations; its contribution to Sustainable Goal target 2—Zero Hunger; and its significance in international trade [3].

Mapping rice cropping systems is crucial and has been increasingly explored using Earth observation (EO) data to estimate the area under cultivation, yield, seasonality, and many more [7–10]. The widespread geographical coverage and freely available EO data with increased spatial and temporal resolution are a boon for studying the different perspectives of rice cultivation, from phenology to yield assessment. Depending upon the availability of the data sources, paddy mapping strategies are classified into three parts. Using optical satellite-based methods based on local to global scales, rice cultivating areas can be mapped using the Finer Resolution Observation and Monitoring of Global Land Cover (FROM-GLC); Medium-Resolution Imaging Spectrometer (MERIS); Moderate-Resolution Imaging Spectroradiometer (MODIS); Landsat series comprising TM, ETM, and OLI; hyperspectral datasets; AHVRR; and Sentinel-2 dataset time series. Secondly, microwave- or radar-based satellite data using Sentinel-1, RADARSAT, Envisat, etc., can be used. Thirdly, a fusion or combination of both optical and microwave datasets can be used for rice mapping [11]. A number of published studies have had difficulties identifying and classifying paddy rice pixels in varied environments due to commonly employed coarse spatial (MODIS, 500 m) and low-temporal-resolution (Landsat, 16 days) data [12–14]. Since paddy rice fields in South and Southeast Asia are small due to land fragmentation, applying MODIS leads to low classification accuracy attributed to mixed pixels incorporating several crops [15]. However, employing Sentinel-2 data, which have higher revisit frequency and greater spectral and radiometric resolution, could increase the precision of classification by capturing spatial variety in agricultural management practices [16]. The ability to estimate phenological events is further enhanced by data derived from time series analysis of EO data [17,18], such as the Normalized Difference Vegetation Index (NDVI) [19], the Enhanced Vegetation Index (EVI) [20], the Normalized Difference Land Surface Water Index (LSWI) [21], the Normalized Difference Water Index (NDWI) [22], the Normalized Difference Flood Index [23], and other indices. Recently, machine learning and deep learning techniques in EO-based rice mapping have significantly increased [18,24,25]. Google Earth Engine (GEE), a cloud-based repository for satellite imagery and processing tools, has grown due to its potential for handling sizable-volume datasets and its capability to visualize, process, and analyse big data. Recently, these index-based studies have been approached using the GEE platform for mapping and monitoring rice using time series and phenology-based algorithms of vegetation indices [26], and due to their advantages of cloud computing and rapid monitoring they are being widely explored [27,28]. An effective literature analysis technique would be beneficial to support upcoming studies, summarize historical evolution, and uncover hotspots. Bibliometric analysis incorporates an interdisciplinary combination of computing, facts, and data; has robust quantitative functions; offers a thorough and systematic statistical appraisal of the literature from many domains; and effectively describes the general trajectory of a subject's or field's development [29]. The bibliometric analysis tool has been used in studies related to the physiology and management of rice [30–32] and perennial staple crops [33]; studies on the application of fertilizers in rice farming [34]; rice cultivation and irrigation exposure [35]; the review on top-cited papers in global rice research [36] (rice cultivation and the impacts of climate change [37]; trends and research features on greenhouse gas emissions from rice production [38]; research trends in rice remote sensing [39]; and research on rice cultivation and its interconnection with greenhouse gases [40]. The application of bibliometric analysis on EO-based rice mapping focusing on the Vietnamese Mekong Delta (VMD) has not been attempted. The Mekong Delta is Vietnam's most significant agricultural and aquaculture production zone, producing 50% of the nation's rice, 80% of the nation's fruit, and 60% of the country's fish (International Centre for Environmental Management 2012). In 2019,

the VMD represented 54.46% of the country's rice cultivation area, making it the primary rice-producing region (General Statistics Office—GSO 2018). Thus, this investigation tried to dig deep into rice mapping and excavate the annual trend in the literature of applying EO data in rice research through a Scopus-listed keyword co-occurrence analysis using the bibliometric method. The VMD stands out as a critical area in regions where rice is vital to the economy and food security. This article presents a comprehensive bibliometric analysis that aims to unravel the role of EO-based rice mapping studies in the VMD compared to global studies. The analysis seeks to shed light on the contributions of these studies to sustainability and food security in the region.

2. Materials and Methods

2.1. Study Area

Vietnam heavily relies on rice production in the Mekong River Delta for its food supply and national economy. Considered one of the most fertile agricultural regions globally, Vietnam is the world's second-largest rice exporter and the seventh-largest rice consumer. Rice cultivation in Vietnam follows three distinct cropping seasons: winter–spring (December to March), summer–autumn (April to August), and autumn–winter (September to November). Farmers typically sow on either irrigated or non-irrigated fields in the autumn–winter season, from mid-July to the end of August [41]. These different seasons allow for continuous rice production throughout the year. Three ecosystems within the country's geographic regions influence Vietnam's rice-growing culture. The northern delta, characterized by a tropical monsoon climate, experiences cold winters and relies on rainfed and flood-tolerant rice varieties. On the other hand, the highlands of the north cultivate upland rice varieties due to their specific conditions. Finally, the southern delta, i.e., the VMD, dominates rice cultivation in Vietnam and benefits from a warm and humid climate year-round, accompanied by abundant sunshine (Figure 1).

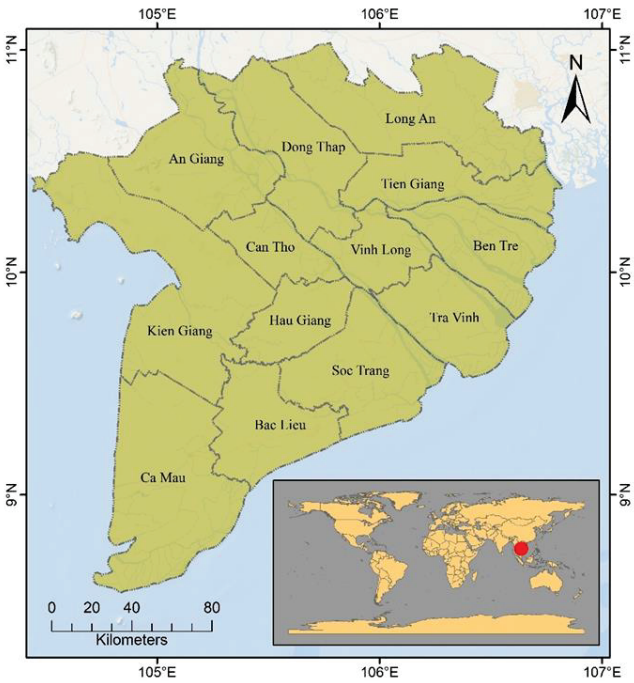

Figure 1. Study area.

2.2. Data

Scopus (https://www.scopus.com, accessed on 1 October 2023), a repository for scientific publications, is one of the most extensive global collections of abstracts and citations from the peer-reviewed literature from Elsevier Group. Scopus' preview database was exclusively selected primarily for two reasons, i.e., it has a sizable collection of top-

notch-quality scientific research publications and a widespread reputation in academia for conserving high-quality, peer-reviewed investigations and articles, and the catalogue of bibliometric output produced by the directory makes text mining and bibliometric analyses convenient [42]. The information search was carried out considering a few criteria set by the author based on the perception and the requirement of the analysis. The filtered data could then be exported from the web repository of Scopus (1979 to 2022) in CSV format for analysis.

2.3. Method

A keyword plays a vital role in capturing the core idea of a study, and a cluster of keywords together conveys the essence and outline of the study [43]. Thus, keywords are used to depict research boundaries and forecast upcoming trends, since keywords are a viable way to describe research hotspots. The domain or subject matter that is most intimately correlated to the issue covered in the author's study is typically listed along with several keywords. It is also typical for reviewers, and editors in particular, to augment such material with additional keywords gleaned from databases in accordance with the publication's topic content. In this vein, the unified keywords (Table S1) used for text mining were Rice, Paddy, Remote Sensing, Geospatial, Mapping, Earth observation, and GEE to study the various remote sensing applications using the preview of rice mapping and monitoring studies. These particular keywords were used in the search engine so that the body of literature in the form of articles, reviews, conference papers, letters, conference reviews, book chapters, editorials, data papers, errata, notes, short surveys, books, and reports, with the specific words or various combinations within the title, abstracts, and keywords, could be extracted for use in the study. Using these keywords mentioned above in the search tab of the Scopus database, 3700 papers on the themes were considered initially. By specifying the export type "complete records and cited references", the data were downloaded and saved in CSV format. They were then imported into the VOS viewer for citation analysis. Utilizing the Scopus database (bibliometric data), network and overlay visualizations were made using the VOS viewer to spot co-occurrences and concentrations of articles. The VOS viewer (version 1.6.18, 2022, Leiden University, Leiden, The Netherlands) is used to build and display bibliometric networks. These networks can be created using citations, co-authorship, or bibliographic coupling (Figure 2).

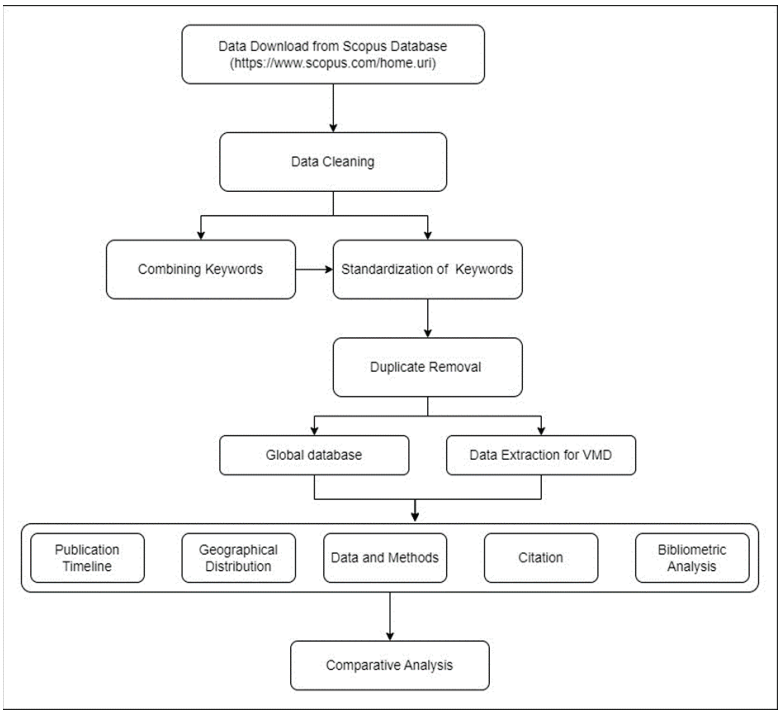

Figure 2. Methodology flowchart.

3. Results and Discussion

3.1. Publication History

Rice cultivation is extensively practiced in Southeast Asia, with India, China, Bangladesh, Thailand, Indonesia, and Vietnam being the top producers. These countries are also the major contributors to scientific research on rice mapping using remote sensing techniques. The Vietnamese Mekong Delta has shown a significant increase in research on rice mapping using EO data in recent years. The application of EO data for rice mapping gained momentum in the 1980s and has since seen substantial growth.

The scientific and academic research on rice mapping across the globe started in 1974 (4) and gradually showed an increasing trend. The breakthrough in the number of publications occurred in 2005 (77), with the highest number of articles published in 2020 (350) (Figure 3).

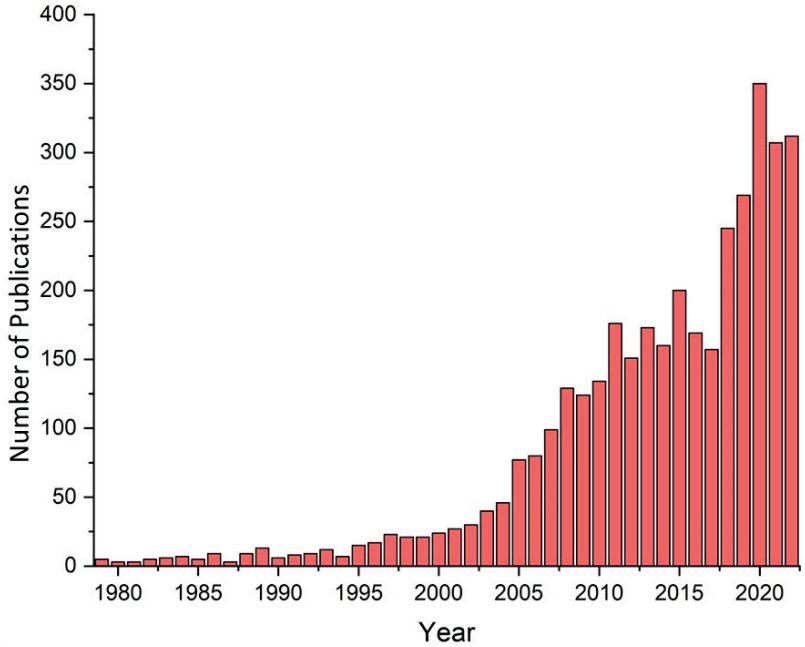

Figure 3. Year-wise publication globally.

The scientific investigation of rice mapping in the VMD started in 1997 and gradually showed an increasing trend. The peak number of publications per year was in 2018 and 2021 (10), followed by 2020 (8), 2012, 2013, and 2022 (7) (Figure 4). Japan was the first country to carry out rice research, in "On the seasonal winds in autumn over Kawagishi village, the valley of tenryū", in the *Journal of Agricultural Meteorology* in 1953. The first paper based on the direct implication of rice mapping using EO data was "Temporal Study on Paddy (Rice) Using X-Band Scatterometer" in a conference proceeding in the *Proceedings of the International Symposium on Remote Sensing of Environment* published in 1979 in India. The first few papers on rice cultivation in the VMD, "Landcover classification over the Mekong River Delta using ERS and RADARSAT SAR images" and "Application of multitemporal ERS SAR in delineating rice cropping systems in the Mekong River Delta" were published in the conference proceeding of the International Geoscience and Remote Sensing Symposium (IGARSS). The first paper to be published in China based on rice monitoring using EO data, named "Regional paddy monitoring system using NOAA HRPT data", was published in 1989 in *Digest—International Geoscience and Remote Sensing Symposium (IGARSS)*. The first publication in Bangladesh was published in 1990 in the conference proceeding Proceedings of the International Symposium on Remote Sensing of Environment. The dominant leap in the research of rice mapping using remote sensing techniques started in 1980, and this has substantially increased in the last decade. Before

these years, the number of publications was limited to one per year, with most of the years without any and lacking direct implications of EO data analysis.

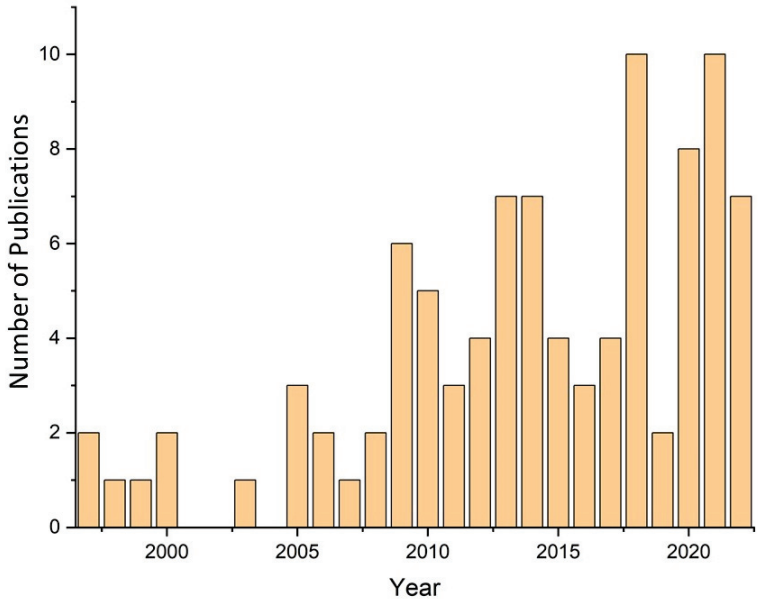

Figure 4. Year-wise publication in the Vietnamese Mekong Delta.

3.2. Country-Wise Publication

Rice cultivation is extensively practiced in Southeast Asia due to its favourable climate. Bangladesh, Cambodia, China, India, Indonesia, Iran, Japan, Laos, Malaysia, Myanmar, Nepal, North Korea, Pakistan, Philippines, South Korea, Sri Lanka, Taiwan, Thailand, and Vietnam are the leading rice farming areas. India, China, Bangladesh, Thailand, Indonesia, and Vietnam fall under the top six rice-producing countries (FAO 2023, https://www.fao.org/faostat/en/#home, accessed on 1 October 2023). Global rice mapping research using EO data is spread over the southeastern and eastern zones, where the areas under cultivation and harvesting are high. Consequently, China, India, Japan, Indonesia, Vietnam (Mekong Delta Region), and Bangladesh are the major countries using remote sensing techniques for rice research (Figure 5). It is clear from the Scopus database that the chief rice-producing nations are the major contributors to the scientific investigation of rice mapping using remote sensing techniques. There are several exceptions, such as Japan, which ranks twelfth in rice production yet third in the amount of scientific research. However, Bangladesh, the third-largest rice producer, only provides 4% of the EO-based rice mapping repository. These areas are predominated by two or three cropping seasons. Vietnam, being an exception, has five cropping seasons for rice cultivation. China, Bangladesh, and Indonesia have three rice cropping seasons, whereas India, Thailand, Philippines, Myanmar (Burma), and others have only two dominant rice cropping seasons. (Source: https://ipad.fas.usda.gov/cropexplorer/cropview/commodityView.aspx?cropid=0422110, accessed on 1 October 2023). India is one of the largest producers of rice, followed by China and Bangladesh. The leading exporters are Japan, China, Myanmar, and Vietnam. China, the second producer and exporter of rice, ranks first in scientific investigations of rice mapping through remote sensing techniques. India, the largest producer and the ninth-largest exporter, does not lag in research and development as it has the second-highest number of scientific publications in this domain. Vietnam holds the sixth position in scientific research for rice mapping using remote sensing techniques and is the fifth-largest producer globally. Consequently, Bangladesh, the third-largest producer and fifth-largest exporter has around 1.8% of research articles on rice mapping using EO data.

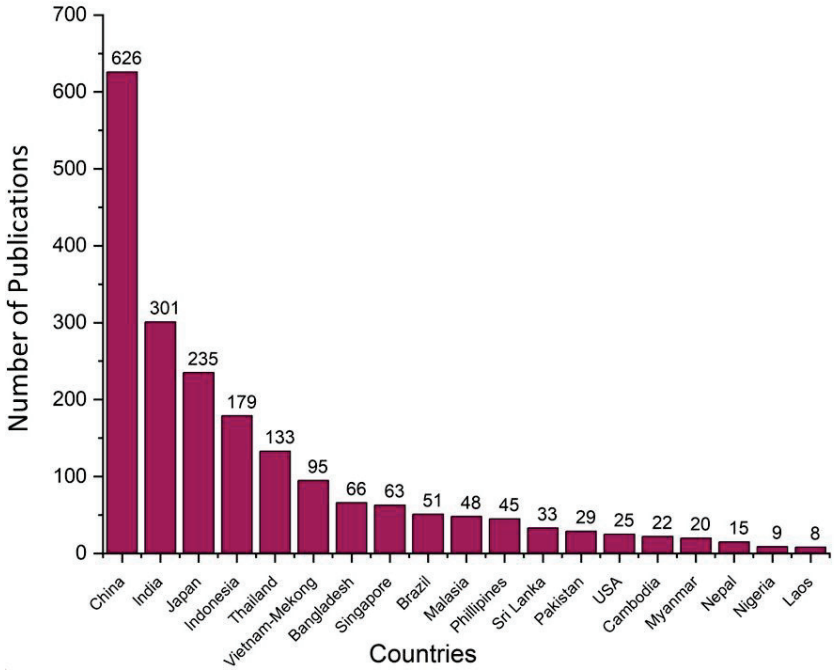

Figure 5. Country-wise publication.

Thus, research on rice mapping using EO data is prominent in major rice-producing countries like China, India, and Vietnam. These countries also have multiple cropping seasons for rice cultivation. Other significant rice producers like Bangladesh also contribute to research but to a lesser extent. Remote sensing techniques are vital in monitoring and managing rice cultivation, supporting sustainable agriculture in these regions.

3.3. EO Data and Methods Used in the Publications

Different sensors and satellites mounted on airborne and spaceborne platforms can constantly capture and monitor the Earth's surface to gather a wide range of data. These images are used in agricultural studies to monitor the transplanting, growth, and harvesting phases; detect anomalies; estimate yield; and map the extent of cultivation. Several approaches, such as Support Vector Machine (SVM) [44], Random Forest (RF) [45,46], time series analysis [47,48], and phenological indices [49], have been developed to map rice-producing regions worldwide (Table 1).

Table 1. Approach/method used in the publications.

Approaches/Platform	Number of Publications	
	Global	**Mekong**
Random Forest	168	24
Linear Mixture Model	7	2
Empirical Mode Decomposition	13	6
Semiautomatic Hierarchical Clustering Algorithm	17	1
Isodata	18	2
Time series analysis	33	22
Principal Component Analysis	50	3
Support Vector Machine	165	4
GEE	89	3

The highest application of MODIS satellite data is seen in the VMD region, followed by the Landsat time series satellite data (Table 2). Contrarily, from a global perspective, Landsat time series data represent a larger share than MODIS data. Thus, it is understood that the optical datasets predominate in rice mapping using EO datasets. The advancement in

geospatial domains, with liberated and open data policies from the United States Geological Survey (USGS) providing Sentinel 2 MSI datasets and Copernicus Open Access Hub of the European Union providing Sentinel-1 datasets, radar images hold a significant position in the study of rice mapping using EO data. The Sentinel-1 sensor, with its cloud-penetrating property, is more famous for mapping and monitoring rice cultivation. The application of HJ-1A/B (CCD1/2) is limited globally, but no application is found in the VMD. AVHRR hyperspectral images are used in only two publications that focused on the study of VMD, whereas there is no application in the global domain. Commercial satellite data such as SPOT, Terrasar-X, and Radarsat have also occupied a place in studying rice mapping using remote sensing techniques.

Table 2. Earth observation (EO) satellite sensors' characteristics and related publications.

Satellite/Sensor	Spatial Resolution (m)	Temporal Resolution (Days)	Number of Publications		Accessibility
			Global	Mekong	
Landsat (OLI/ETM/TM)	30 m	16	578	18	Open Access
Sentinel-1	5–40	12	323	12	Open Access
Sentinel-2 (MSI)	10–20	5	164	3	Open Access
Modis (Terra/Aqua)	250–1000	1–2	448	29	Open Access
UAV			191	0	Commercial
HJ-1A/B (CCD1/2)	30	2–4	10	0	Open Access
SPOT (HRV (SPOT1-3) VGT (SPOT-4) HRG/HRS/VGT(SPOT-5))	1000	1	181	7	Commercial
COSMO-SkyMed (SAR)	3–15 m	16	12	1	Commercial
TerraSAR-X (SAR)	3–10 m	11	31	5	Commercial
ENVISAT (ASAR)			53	6	Open Access
RADARSAT-1 (SAR)	10–100 m	24	18	1	Commercial
RADARSAT-2 (SAR)	3–100 m	24	62	2	Commercial
ALOS-2 (PALSAR-2)	25 m	14	12	2	Commercial
AVHRR			0	2	Open Access
Total			3700	94	

Note: ASAR—Advanced Synthetic Aperture Radar; CCD—Charge-Coupled Device; ETM+—Enhanced Thematic Mapper Plus; HRG—High-Resolution Geometric Imaging Instrument; HRS—High-Resolution Stereoscopic Imaging Instrument; HRV—High-Resolution Visible; MODIS—Moderate Resolution Imaging Spectroradiometer; MSI—Multispectral Instrument; OLI—Operational Land Imager; SAR—Synthetic Aperture Radar; SPOT—Satellite pour l'Observation de la Terre; TM—Thematic Mapper; UAV—Unmanned Aerial Vehicle; VGT—VEGETATION.

Landsat and MODIS are the most frequently used optical remote sensing satellites for rice mapping. Radar data, namely Sentinel-1 and TerrasAR-X, have often been employed in recent studies [50,51]. Some of the literature using satellite-based remote sensing techniques in rice mapping, such as Liew (1998) [52], used Synthetic Aperture Radar (SAR) imagery from the multitemporal ERS-2 satellite to map and delineate regions in the VMD that were cultivated with various types of rice crops. Sakamoto et al. (2009) [53] provide a strategy for assessing spatiotemporal changes in the farming systems of the VMD based on MODIS time series imagery. In the context of the VMD, rice mapping using Landsat data contributes to approximately 19%, whereas MODIS data contribute 31%, giving MODIS the lion's share of the available research in this area. A total of 89 scientific publications have used GEE for rice mapping across the globe, whereas a mere share of only three publications using GEE have focused on the VMD. The top three approaches or methods for global rice mapping are RF, SVM, and time series analysis. In the VMD region, Random Forest is also the top-applied approach, followed by time series analysis and Empirical Mode Decomposition. In recent years, Unmanned Aerial Vehicles (UAVs) [54] have emerged as a low-cost alternative in sensing technology mapping and monitoring natural resources. The first application of UAVs in vigour mapping based on the Normalized Differentiated Vegetation Index (NDVI), studied in Italy, proved highly appropriate for precision agriculture in medium-

sized farms [55]. Using UAVs in rice is critical for classification, assessing phenological behaviour, yield estimation, and activating many researchers to create a global, national, and regional rice database [56].

Traditional machine learning techniques such as RF, SVM, and time series analysis have been widely used. Newer approaches with these methods and the GEE platform have given a new dimension to studying EO-based rice mapping. The application of UAVs in rice mapping, used for crop health detection, yield estimation, and vegetation vigour mapping, is gradually gaining global relevance. However, UAV research in rice mapping in the VMD has yet to be started, providing further avenues for research exploration.

The phenological indices-based assessment of rice mapping using time series EO data is widely practiced worldwide for scientific investigations. Among the various vegetation indices, EVI holds the lion's share in studying rice mapping using EO data globally and in the VMD. NDVI is the second-highest method applied as a phenological index for global rice mapping, but contrarily, it is the third-highest method for VMD after the RVI. NSWI and LSWI are two indices that are used comparatively more for rice mapping in the VMD than in the global perspective (Figure 6). Thus, EVI, NDVI, and RVI are the top three applied indices for monitoring and mapping rice cultivation.

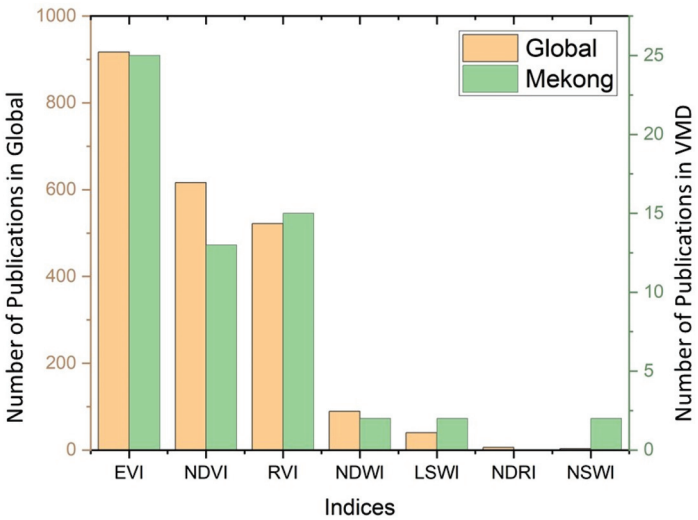

Figure 6. Comparison of phenological indices.

Therefore, remote sensing plays a crucial role in rice mapping globally, with prominent use in major rice-producing countries like China, India, and Vietnam. Different sensors and satellites, including MODIS, Landsat, and Sentinel-1, are widely employed for capturing Earth surface data. Optical datasets are predominant in rice mapping using EO data, but radar data from sensors like Sentinel-1 and TerraSAR-X are gaining relevance. Traditional machine learning techniques like Random Forest and Support Vector Machine are commonly used, while newer approaches with the application of these methods on the GEE platform are opening new possibilities. UAVs are also emerging as a low-cost alternative for monitoring rice crops. Phenological index-based assessment, particularly with EVI, NDVI, and RVI, is extensively used for rice mapping globally. The VMD region has shown significant research interest in this field, and there is further potential for exploration, especially in UAV research.

3.4. Publication Outlets and Citations

The top four highest cited papers in the study of rice mapping over the VMD are "Remote sensing of rice crop areas" [57], "Mapping rice paddy extent and intensification in the Vetnamese Mekong River Delta with dense time stacks of Landsat data" [58], "Mapping the irrigated rice cropping patterns of the Mekong Delta, Vietnam, through hyper-temporal spot NDVI image analysis" [59], and "Mapping rice cropping systems in Vietnam using

an NDVI-based time-series similarity measurement based on DTW distance" [19]. The highest citations, above 100, are in the journals *Proceedings of the National Academy of Sciences of the United States of America*, *International Journal of Remote Sensing*, and *Remote Sensing of Environment*. Five articles have between 80 and 100 citations in the journals of *Remote Sensing*, *Science of the Total Environment*, *Environment*, *Development and Sustainability*, *Landscape* and *Urban Planning*, and *IEEE Transactions on Geoscience and Remote Sensing*. On the other hand, 34 articles pertinent to rice mapping using EO data were found without any citations. Those papers mainly belong to conference proceeding articles. The top five highest articles globally are "Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s" [60], with a cite score of over 1000; "Spatial and temporal patterns of China's cropland during 1990–2000: An analysis based on Landsat TM data" [61]; "A crop phenology detection method using time-series MODIS data" [62]; "Mapping paddy rice agriculture in southern China using multi-temporal MODIS images" [63]; and "Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images" [64], which has a citation score of above 600. The highest cited paper was published in the *Journal of Geographical Sciences* and *Remote Sensing of Environment*. Out of the total list of publications globally, only 83 articles show a cite score above 100, followed by 46 between 80 and 100 citations. There are around 600 articles with a cite score ranging between 10 and 30. More than 1100 articles without citations were related to symposiums, conference proceedings, and journal articles (Figure 7).

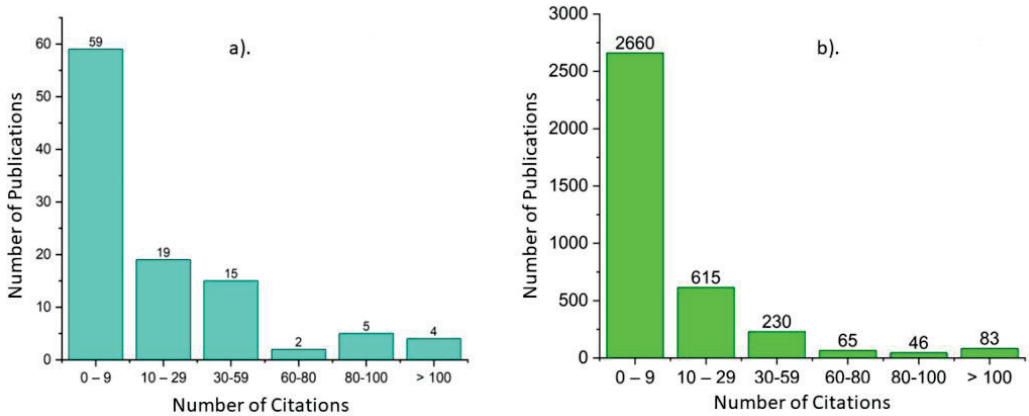

Figure 7. Citation comparison: (**a**) VMD publications, (**b**) global publications.

Rice mapping research in the Vietnamese Mekong Delta (VMD) has resulted in highly cited papers, with four prominent ones garnering over 100 citations. However, there are also 34 articles without any citations, mostly from conference proceedings. Globally, rice mapping research has produced top-cited papers from various research areas, with "Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s" being the highest cited paper. Several highly cited articles have been identified, such as "Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s" [60] and "Mapping paddy rice agriculture in southern China using multi-temporal MODIS images" [63]. The top-cited articles specific to the VMD area include works by Sakamoto et al. (2006) [65], Kuenzer and Knauer (2013) [57], Kontgis et al. (2015) [58], and Nguyen et al. (2012) [59]. The journals "Remote Sensing of Environment" and the "International Journal of Remote Sensing" have the highest citations in this research field. The co-occurrence analysis of keywords revealed eight, four, and two clusters for the top three, five, and ten co-occurrences, respectively, indicating the critical research fronts in rice mapping using EO data. Over time, the number of publications on the VMD has increased, with the highest number observed in 2020 and 2021. Similarly, the uppermost number of journal publications specific to the VMD was recorded in 2018 and 2020, spanning from 1997 to 2022.

While some articles have received high citation scores, a significant number have not received any citations, showcasing the diverse nature of research in this field.

3.5. Co-Occurrence and Connectivity Analysis

Using the full counting approach, 837 unique keywords were used for the co-occurrence analysis. The keywords were divided into clusters based on the colour scheme, ranging from dark blue to yellow.

A bibliometric network was constructed by adopting the full counting technique, where each link that results from an interaction has a total weight of 1, suggesting that the total weight of a choice is equivalent to the number of linkages emanating from it [66]. In cases where full counting is used, the occurrences variable reflects the aggregate number of times an expression appears across all the research articles. The interconnected web and the circles describe the periodic arrangements of research publications. The dark blue colour symbolizes papers before 2010, and the yellow colour variation represents the publications of recent years. The clusters were formed based on the co-occurrence of keywords for the year-wise publication on rice mapping using EO data. The connectivity network of all keywords examined using the VOSviewer (version 1.6.19) is displayed in the figure (Figure 8). The analysis and connectivity diagrams were made using default parameters. A co-occurrence of only 18, 53, and 117 of the comprehensive 837 keywords was found at least ten, five, and three times, respectively.

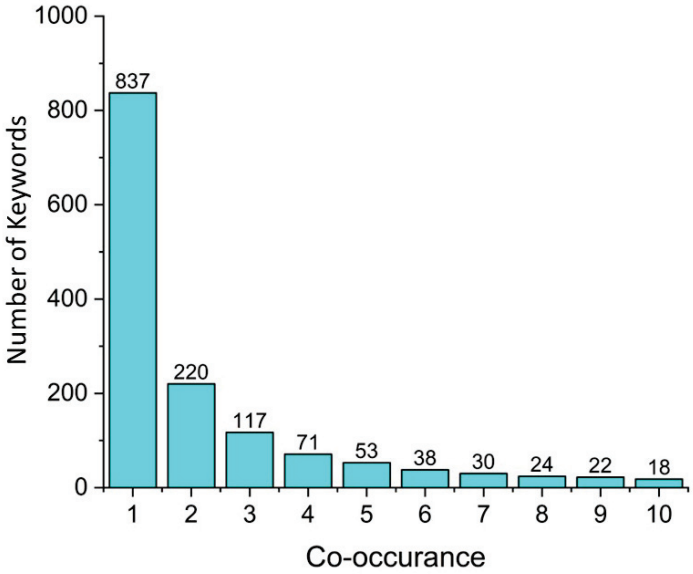

Figure 8. Number of co-occurring keywords.

The interconnections between the clusters include the keywords based on the number of co-occurrences, and the radius of the circles symbolizes the number of publications in which each term appears. In general, a keyword repeats relatively frequently in circles of larger sizes. Consequently, if two words co-occurred more commonly in the analysed list of publications, they appeared closer to one another. The word "remote sensing", located in the focal point of the image in a large font, is related to several other items, suggesting that it is a significant subject or area of research in the dataset under analysis. Several colour-coded term clusters surround it, indicating that the terms are interconnected with other terms within the framework of the literature or data under analysis. With each colour denoting a thematic group, the clusters appear to be arranged around remote sensing-related subjects. Terms such as "paddy field", "agriculture", and "food supply", for instance, may be included in a cluster pertaining to the use of remote sensing in agricultural settings. The lines indicate the correlations or co-occurrences between the terms. With the aid of this visualization, authors can rapidly comprehend the main areas of study within

a field, their connections, and potentially even the topics' historical development. The thickness of the connecting lines indicates the degree of link between phrases; larger lines denote stronger connections. These visual clusters make understanding the conceptual relationships between concepts and the degree of their interdependence easier. A timeline with a gradient from 2010 to 2022 is also included at the bottom of the image. This timeline is used to illustrate how the words or focal areas in remote sensing have changed over time. This temporal feature enables viewers to follow the evolution of the field's focus over time. Similarly, the citation clusters help the reader quickly comprehend the citation and how it relates to the literature's keywords. The visualizations show that links turn from blue to yellow in hue as the number of citations grows.

There are seven significant clusters, which stand for seven different subfields of rice study. Other colours are associated with various groups of keywords, indicating the yearly significance of keywords, such as the gradient from blue to yellow, which denotes the associated publication year. The yellow colour suggests connectivity of significant keywords in recent years; the dark blue link indicates keywords used in the older literature. The network visualization shown in the figure below has four clusters, which are colour-coded using red, blue, green, and yellow. The red network denotes cluster 1 comprising 18 keywords like aquaculture, Asia, drought, Eurasia, farming system, flood, GIS, irrigation, Landsat, Lulc, MODIS, paddy field, rivers, satellite data, Southeast Asia, Thailand, time series, and Vietnam. The second cluster is coded in green with 16 keywords, which are backscattering, biology, classification, Decision Tree, forestry, image classification, mapping, NDVI, polarization, radar remote sensing, SAR, Sentinel-1, space optics, space-based radar, vegetation, and vegetation index. Climate change, crops, Enhanced Vegetation Index, food supply, mean square error, Mekong Delta, Mekong River, remote sensing, rice, rice monitoring, rice production, rice systems, and rice yield are the 14 keywords that come under the third cluster that is coded using blue. Lastly, agricultural production, agricultural robots, agriculture, cultivation, and image processing are categorized in cluster 4, demarcated using yellow (Figures 9–11).

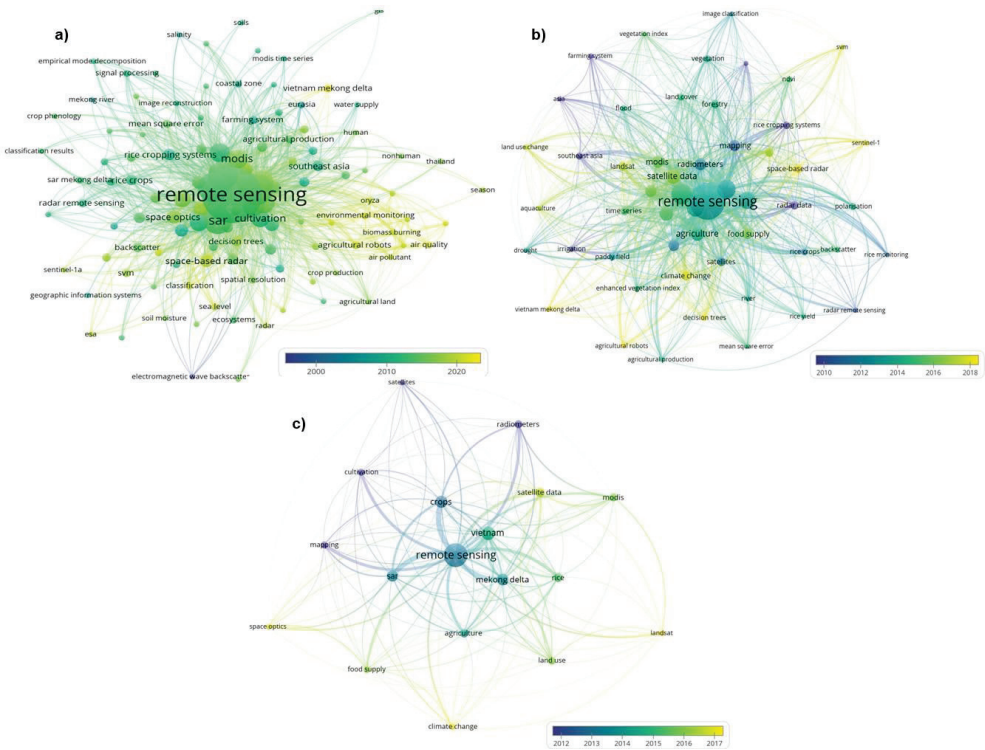

Figure 9. Publication year: (**a**) 3 co-occurrences, (**b**) 5 co-occurrences, and (**c**) 10 co-occurrences.

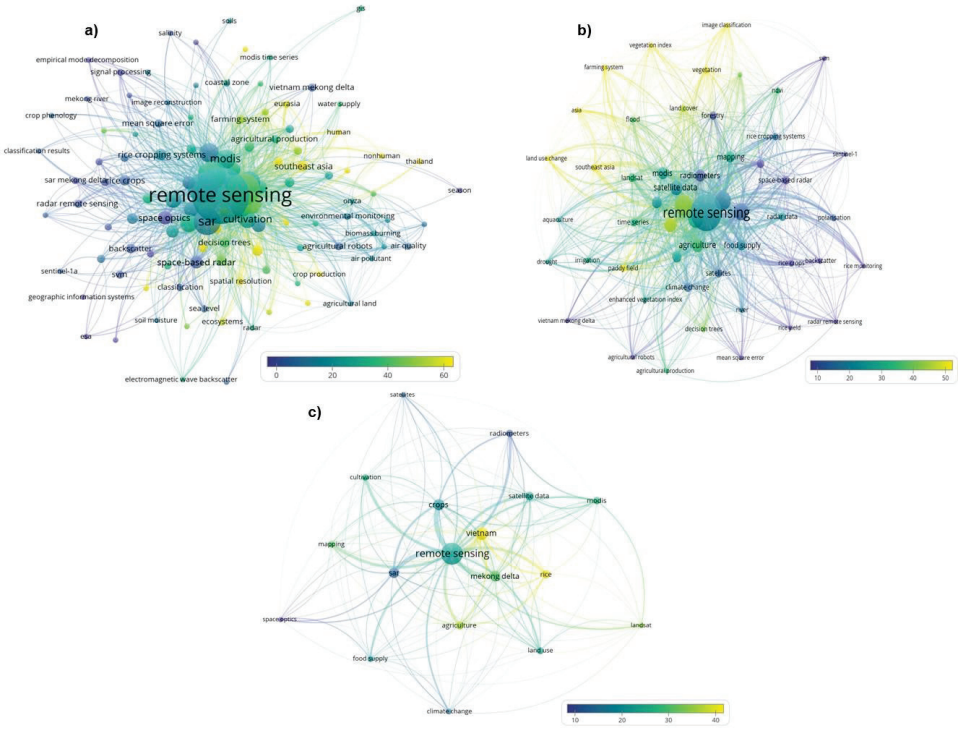

Figure 10. Citations: (**a**) 3 co-occurrences, (**b**) 5 co-occurrences, and (**c**) 10 co-occurrences.

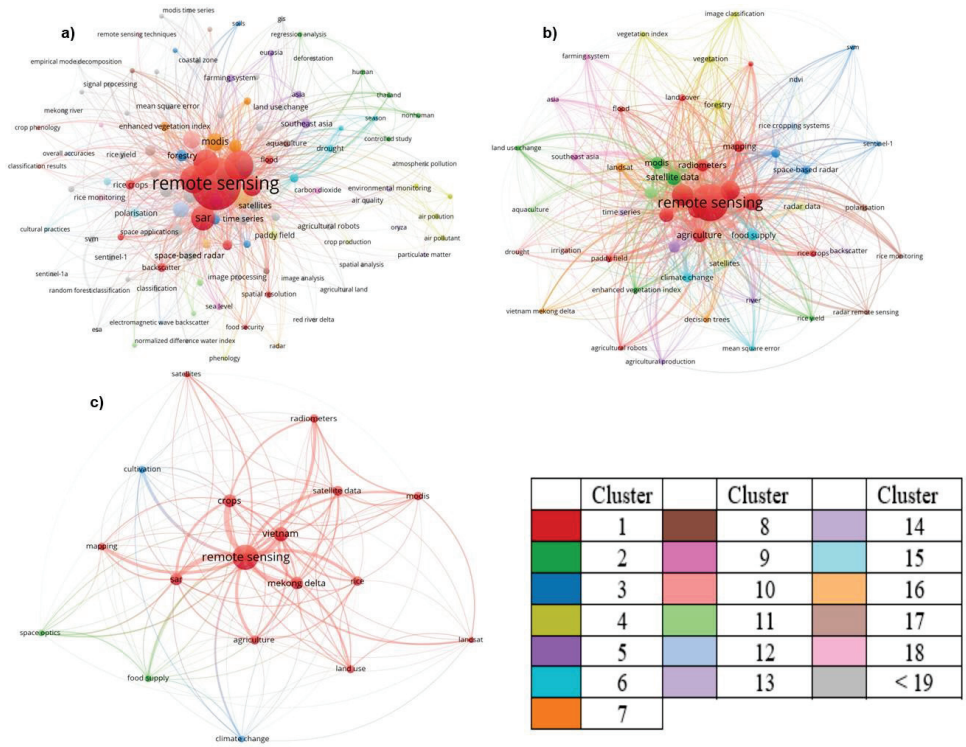

Figure 11. Clustering: (**a**) 3 co-occurrences, (**b**) 5 co-occurrences, and (**c**) 10 co-occurrences.

The analysis revealed a notable increase in publications on EO-based rice mapping in the VMD and the global context over recent decades. However, it became evident that the VMD is an area of particular interest, accounting for a significant portion of the research output. This emphasis can be attributed to the region's importance in rice production and the increasing demand for sustainable agricultural practices. The citation analysis highlighted seminal studies that have significantly influenced the field and served as a

foundation for subsequent research. Thematic analysis of the selected publications revealed common research themes, including mapping rice cropping patterns, monitoring yield variability, assessing water management practices, and studying the impacts of climate change on rice production. These studies have contributed to a better understanding of the dynamics of rice cultivation in the VMD and provided valuable insights into improving sustainability and food security. The research output in this region reflects the pressing need for accurate and up-to-date information to support effective land management decisions, water resource allocation, and climate change adaptation strategies [67] (Figure 11).

4. EO-Based Rice Mapping and Its Linkages with SDGs and Food Security

EO-based rice mapping studies directly align with SDG 2 (Zero Hunger) by providing accurate information on rice cropping patterns, yield variability, and water management practices. These studies support efforts to enhance food security and promote sustainable agricultural practices in the VMD. The insights gained from such studies can inform decision-making processes related to crop management, resource allocation, and adaptation strategies, ultimately contributing to the goal of ending hunger and achieving food security. Secondly, EO-based rice mapping studies contribute to SDG 15 (Life on Land) by monitoring and assessing the impacts of climate change on rice production. These studies provide valuable information for land management and conservation efforts. Understanding the dynamics of rice cultivation and its relationship with land use can support sustainable land management practices and help protect ecosystems in the VMD, contributing to preserving biodiversity and promoting sustainable land use.

Furthermore, EO-based rice mapping studies indirectly contribute to other SDGs, such as SDG 13 (Climate Action), by providing insights into the vulnerability of rice production to climate change and facilitating the development of climate-resilient agricultural practices. Additionally, these studies can contribute to SDG 6 (Clean Water and Sanitation) by assessing water management practices in the context of rice cultivation and supporting the sustainable use of water resources in the region. Thus, EO-based rice mapping studies provide valuable insights and information that can support sustainable agricultural practices, enhance food security [68], promote climate resilience, and contribute to conserving ecosystems in the VMD. By addressing these sustainability challenges, EO-based rice mapping studies play a crucial role in advancing progress towards the broader agenda of the UN SDGs.

5. Conclusions

The bibliometric analysis carried out in the present study provides a quantitative and comprehensive overview of rice mapping using EO data. Compared to global studies, the bibliometric analysis presented here provides valuable insights into the role of EO-based rice mapping studies in the VMD. These studies have significantly contributed to understanding rice cultivation dynamics, monitoring agricultural practices, and improving sustainability and food security in the region. The findings highlight the importance of continued research efforts and collaboration to address the evolving challenges faced by the VMD and similar agricultural regions worldwide.

Evidence of AI/ML techniques integrated with EO data for rice mapping in the VMD is limited. It is expected that these kinds of studies may gain momentum in the near future. However, using bibliometric analysis may also give further scope for studies on the application of rice mapping using EO datasets, such as the amount of methane emission and its impact on climate change. EO-based rice mapping has scope for aiding in coping with natural calamities like floods and drought, where rice mapping can provide information on crop growth/yield estimation and thus provide a rapid assessment for estimating food production, a path towards food security and crop insurance.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su16010189/s1.

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Critical Limit of Manganese for Soybean in Soils of Three Agro-Ecological Zones of Bangladesh

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Abstract: Manganese (Mn) is an essential micronutrient for plants, which influences multiple physiological systems. Determination of the critical limit (CL) of Mn in the soil is necessary for Mn fertilizer application as this limit delineates the deficiency, optimum, and toxicity ranges of Mn. A pot experiment was performed in the winter season with 20 soils collected from three Agro-Ecological Zones (AEZs) of Bangladesh to determine the CL of Mn for soybean (*Glycine max* L.). Manganese was applied in soil @ 0, 1, 2, and 4 ppm, and the experiment was laid out in a factorial and completely randomized design with three replications. The CL of Mn was determined by the Cate-Nelson graphical and statistical approach and was found 3.60 and 3.55 μg g^{-1}, respectively. Applying 1 μg g^{-1} Mn in soil significantly enhanced root and shoot weight, as well as seed yield of soybean compared to no Mn application. In field conditions, a significant positive response of soybean yield was found up to the CL of Mn. The findings of the study could help predict possible Mn deficiency in soil and soybean response to Mn fertilizer, which is important in decision-making for efficient fertilizer management practices to ensure the yield potential of soybeans.

Keywords: manganese; critical limit; soybean; agro-ecological zones; soil

1. Introduction

Soybean (*Glycine max* L. Merrill) is a popular oil seed crop with high food value. It is an excellent source of easily digestible protein, which complements the stable, rich diet in humans [1]. Mature raw soybean seed contains 36.5% protein, 20% lipids, 30% carbohydrates, and 9% dietary fiber [2]. Soybean was grown in 57,646 ha of land in Bangladesh with a production of 91,177 million tons having a yield of 258 kg/ha in the year 2020–2021 [3]. Soybean is a drought [4] and salinity-tolerant crop, thus suitable to cultivate in coastal areas in the Noakhali, Lakshmipur, and Bhola districts of Bangladesh, where cultivation of other crops during the dry winter season is not suitable. New methods and protocols should be described in detail, while well-established methods can be briefly described and appropriately cited. The nodule bacteria (*Bradyrhizobium japonicum*) in the roots of soybean plants can fix atmospheric nitrogen (N), which plays an important role in soil fertility enrichment [5]. An estimated 2.5 to 2.6 million tons of soybean meal are consumed in Bangladesh each year [6]. The country imports an estimated 0.35–0.04 million tons of soybean meal per annum [7]. By increasing soybean production, we can meet the demand

for soybean edible oil and poultry feed. Soybean yields in Bangladesh are significantly lower than anticipated levels. Balanced fertilization can help boost current yield and production levels significantly. Soybean yield can be improved by applying a trace amount of Manganese (Mn), as reported by some researchers [8–10].

In plants, Mn is involved in multiple physiological systems such as photosynthesis, respiration, nitrogen assimilation, nitrogen transformation, etc. [11]. Manganese plays a pivotal role in pollen germination, development and elongation of pollen tube and root cell and in resistance against pathogens [12]. Manganese deficit causes interveinal chlorosis in younger leaves [13] but Mn toxicity shows chlorotic and necrotic spots on older leaves [14] affecting metabolic processes like enzyme activities leading to sterility. Some factors including soil reaction, organic matter content, aeration and moisture status influence Mn availability in soil [15,16]. Manganese availability rises with the fall of soil pH. Manganese deficiency is frequently observed in soils with high pH such as alkaline and calcareous soils and also in poorly aerated soils [17].

For balanced fertilizer application, it is necessary to determine the critical concentration of an essential nutrient element, as this concentration distinguishes deficiency from sufficiency. The critical limit of nutrients is not constant for all the soils and crops and is affected by soil texture, crop cultivar, occasional variation, and soil testing approaches. Therefore, it is necessary to determine the location or crop-specific critical limit for individual nutrients for an area, region, or country. To identify soils of particular areas as deficient and non-deficient of Mn, the determination of the critical limit of Mn in the soil is necessary. This will also help formulate Mn fertilizer recommendations for better crop performance.

Soybean is particularly a Mn-loving crop [18]. In Bangladesh, there is no information concerning Mn fertilizer used on crops. Manganese is used as a fertilizer for soybeans in the Indian subcontinent. Different critical values of available Mn in a particular soil for soybeans are reported for different extractants. Moreover, these limits varied with the soil as well as the extractants used within the same soil [19]. Soil conditions differ from region to region and can vary considerably even within a small field. Therefore, critical deficiency levels determined for one soil may differ from another soil, especially when large geographical areas are considered. In 1997, the critical limit of Mn in Bangladesh soils (Eastern Gangetic Plain) was established at 1.0 ppm by the diethylene triamine-penta acetic acid (DTPA) extraction process, which is still in use irrespective of soil type and crops [20]. The critical Mn level of 3.3 $\mu g\ g^{-1}$ was found for soybeans in neighboring India for similar soils (East Gangetic Plain) [21].

Micronutrient deficiency is considered one of the emerging challenges to food and nutrition security in many countries of the world, including Bangladesh. In recent years, there has been a huge pressure on our soil to produce more food, and therefore, micronutrient deficiencies arise as a consequence of soil fertility depletion, causing a hidden hunger. Accordingly, micronutrient fertilizer application has been increased for fulfilling the micronutrient requirement of crops as well as for maintaining sustainable crop productivity [20]. To ensure global food security, a multifaceted and sustainable approach is needed that will increase crop production as well as promote the resource use efficiency of crops. The effective management of micronutrients in the soil-crop system by soil or foliar application may help mitigate micronutrient deficiency in soils and crops, reduce micronutrient malnutrition in humans and animals, and enhance sustainable crop production and crop quality. As Mn is biochemically involved in plant production, maintaining its availability up to an adequate level is imperative for sustainable food security. Therefore, it is crucial to identify the CL of Mn for specific soils and crops to enable the farmers to increase soybean production and to reduce Mn depletion by application of Mn fertilizers when the Mn content in soils goes below the CL. The critical limit of extractable Mn in the soil can be used to predict the crop yield response to the application of Mn using fertilizer. This also aids in determining the amount of Mn fertilizer required for crop growth as it distinguishes deficiency from sufficiency. For better prediction of Mn deficiency, the CL must be refined or revalidated with reference to the present environment, soil characteristics,

and crop species, which will play a major role in decision-making for balanced fertilization and ensuring better crop yield performance. Considering the above facts, an effort was taken to evaluate the critical limit of Mn for soybeans in soils of different Agro-Ecological Zones (AEZs) for balanced fertilization.

2. Materials and Methods

2.1. Soil Sampling, Preparation and Analysis

Agroecology incorporates ecological principles and ecosystems with the aim of conserving, protecting, and reinforcing natural ecosystems, as well as sustaining and diversifying the countryside [22]. Based on different landforms, soils, hydrology, and agro-climatic conditions, there are 30 agro-ecological zones in Bangladesh [23]. Among them, Old Himalayan Piedmont Plain (AEZ 1), High Ganges River Floodplain (AEZ 11), and Young Meghna Estuarine Floodplain (AEZ 18) are some important agro-ecological zones where contrasting soils are found with diverse physicochemical characteristics. The evaluation of Mn status, its effect on crop growth, and the critical limit of Mn has not yet been explored recently for soybean cultivation in these regions. Soil sample collection was performed at a depth of 0–15 cm from these three AEZs. The represented areas were Ramgoti, Kamalnagar and Subornochar (AEZ 18), Kustia Sadar (AEZ 11), and Dinajpur Sadar (AEZ 1). The sampling locations are depicted in Figure 1. The general features of the studied soils are listed in Table 1.

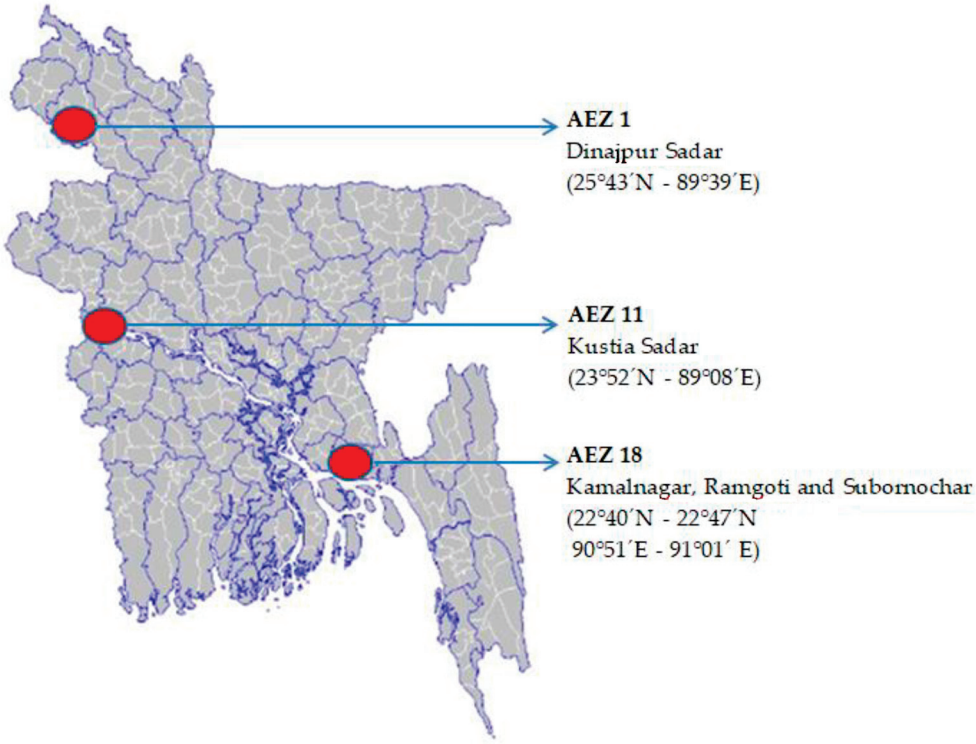

Figure 1. Selected areas from three AEZs of Bangladesh with geographical locations.

There were twenty bulk soil samples chosen from a broad range of variables and organized as low to high with respect to the available Mn status based on previous CL [20]. After drying in the shade, the samples were ground by a mortar and pestle, followed by sieving through a 2 mm sieve for analysis. Analyses of the processed soil samples were performed to determine important physicochemical properties such as texture, pH, electrical conductivity (EC) and organic matter (OM) (Table 2). The mechanical analysis of soils was performed using the hydrometer method [24] and the textural classes were identified from Marshall's triangular co-ordinate using USDA system. Glass-electrode pH meter and an electrical conductivity meter were used to measure soil pH and EC,

respectively in 1:2.5 and 1:5 soil-water ratios, respectively [25,26]. Organic matter status of the soil samples was determined using the wet oxidation method [27].

Table 1. General information on the sampled soils.

Soil Samples	Location	Series	AEZ	USDA Soil Taxonomy
S_1	Subornochar (22°42′ N 91°01′ E)	Ramgoti	18	Typic Haplaquepts
S_2	Ramgoti (22°41′ N 90°54′ E)	Nilkamal	18	Typic Haplaquepts
S_3	Kamalnagar (22°44′ N 90°51′ E)	Ramgoti	18	Typic Haplaquepts
S_4	Ramgoti (22°43′ N 90°57′ E)	Ramgoti	18	Typic Haplaquepts
S_5	Kustia Sadar (23°52′ N 89°08′ E)	Ishwardi	11	Aeric Haplaquepts
S_6	Kamalnagar (22°47′ N 90°52′ E)	Ramgoti	18	Typic Haplaquepts
S_7	Kustia Sadar (23°52′ N 89°08′ E)	Ishwardi	11	Aeric Haplaquepts
S_8	Ramgoti (22°43′ N 91°01′ E)	Ramgoti	18	Typic Haplaquepts
S_9	Kamalnagar (22°44′ N 90°51′ E)	Ramgoti	18	Typic Haplaquepts
S_{10}	Dinajpur Sadar (25°43′ N 89°39′ E)	Gongachara	1	Typic Haplaquepts
S_{11}	Dinajpur Sadar (25°43′ N 89°39′ E)	Gongachara	1	Typic Haplaquepts
S_{12}	Kamalnagar (22°43′ N 90°54′ E)	Ramgoti	18	Typic Haplaquepts
S_{13}	Kamalnagar (22°43′ N 90°51′ E)	Ramgoti	18	Typic Haplaquepts
S_{14}	Ramgoti (22°43′ N 90°57′ E)	Ramgoti	18	Typic Haplaquepts
S_{15}	Kamalnagar (22°45′ N 90°52′ E)	Ramgoti	18	Typic Haplaquepts
S_{16}	Ramgoti (22°41′ N 90°54′ E)	Nilkamal	18	Typic Haplaquepts
S_{17}	Ramgoti (22°41′ N 90°54′ E)	Nilkamal	18	Typic Haplaquepts
S_{18}	Kamalnagar (22°43′ N 90°51′ E)	Ramgoti	18	Typic Haplaquepts
S_{19}	Dinajpur Sadar (25°43′ N 89°39′ E)	Gongachara	1	Typic Haplaquepts
S_{20}	Ramgoti (22°40′ N 90°54′ E)	Nilkamal	18	Typic Haplaquepts

Table 2. Physical and chemical properties of the experimental soils.

Soil Samples	pH	EC (dS m^{-1})	OM (%)	Textural Class
S_1	5.37	1.01	1.72	Silt loam
S_2	6.56	1.06	2.02	Silt loam
S_3	5.76	4.01	1.97	Silt loam
S_4	6.53	3.50	1.72	Silt loam
S_5	7.79	0.27	2.32	Clay loam
S_6	6.68	4.15	2.24	Silt loam
S_7	7.85	0.23	2.81	Clay loam
S_8	6.52	0.93	2.24	Silt loam
S_9	5.89	3.86	2.45	Silt loam
S_{10}	5.30	0.15	1.16	Loam
S_{11}	5.20	0.11	0.86	Sandy loam
S_{12}	6.59	1.20	2.42	Silt loam
S_{13}	5.46	1.07	2.16	Silt loam
S_{14}	6.61	4.08	2.24	Silt loam
S_{15}	6.44	3.86	2.38	Silt loam
S_{16}	6.60	1.00	2.19	Silt loam
S_{17}	6.77	1.32	2.53	Silt loam
S_{18}	5.31	1.34	2.16	Silt loam
S_{19}	5.50	0.26	0.79	Sandy loam
S_{20}	6.41	1.22	2.39	Silt loam
Mean	6.26	2.04	1.73	

The status of both macro and micronutrients in soils is shown in Table 3. Among the macronutrients, total N was measured using micro-Kjeldahl technique [28], available phosphorus (P) using Olsen method (for neutral and alkaline soil) [29] and Bray and Kurtz method (for acid soil) [30], whereas available Sulphur (S) was estimated by extraction with $CaCl_2$ solution (15%) followed by turbidimetric determination using a spectrophotometer [31]. For measurement of the exchangeable bases viz. Potassium (K), Calcium (Ca), and Magnesium (Mg), 1 M NH_4OAc solution having pH 7 was used [32]. On the other hand, available soil micronutrients, namely Copper (Cu), Iron (Fe), Mn, and Zinc

(Zn), were assessed by 0.005 M DTPA extraction technique using an atomic absorption spectrophotometer [33]. Available Boron (B) was measured using a hot water 0.02 M $CaCl_2$ solution (1:2) extraction followed by determination using azomethine-H [34].

Table 3. Nutrient status of soils collected from different AEZs.

Soil Samples	N	K	Ca	Mg	P	B	S	Cu	Fe	Mn	Zn
	%		cmol (+) Kg^{-1}					$\mu g\ g^{-1}$			
S_1	0.09	0.12	4.11	1.97	7.40	0.12	55.7	1.34	55.6	1.78	0.88
S_2	0.10	0.16	4.03	2.29	11.0	0.10	31.8	1.84	59.9	2.61	0.59
S_3	0.10	0.24	4.62	2.57	6.90	0.11	35.9	2.06	87.1	2.72	0.37
S_4	0.09	0.12	4.11	2.03	1.20	0.18	76.1	0.91	32.6	2.74	0.32
S_5	0.12	0.52	16.0	3.53	6.02	0.65	23.1	5.29	71.1	2.81	1.05
S_6	0.11	0.23	4.02	3.36	1.80	0.15	74.5	1.95	33.0	2.88	0.42
S_7	0.14	0.57	15.3	3.28	5.53	0.60	28.1	5.56	76.5	3.07	1.39
S_8	0.11	0.16	4.76	2.74	7.50	0.14	29.9	1.58	57.2	3.14	0.66
S_9	0.12	0.22	4.37	2.61	8.20	0.09	27.8	2.55	135	3.19	0.63
S_{10}	0.06	0.14	1.94	0.56	5.50	0.20	10.0	1.53	101	3.23	1.40
S_{11}	0.04	0.11	1.15	0.36	7.60	0.24	12.1	0.78	57.6	3.86	0.60
S_{12}	0.12	0.20	2.15	1.17	1.80	0.18	51.1	2.16	120	4.08	0.68
S_{13}	0.11	0.21	2.51	1.24	2.00	0.15	49.0	2.34	118	4.11	0.70
S_{14}	0.11	0.13	4.30	2.30	2.00	0.21	84.5	1.19	30.6	4.12	0.33
S_{15}	0.12	0.20	4.01	3.23	2.20	0.16	55.3	2.65	35.7	4.13	0.62
S_{16}	0.11	0.12	4.56	2.57	5.80	0.09	51.9	1.51	47.0	4.46	0.98
S_{17}	0.13	0.12	5.95	2.52	3.20	0.16	74.6	1.43	32.2	5.33	1.22
S_{18}	0.11	0.23	2.83	1.45	3.70	0.17	38.0	2.63	129	5.36	0.77
S_{19}	0.04	0.27	2.48	1.16	3.50	0.15	17.9	1.28	53.2	5.99	1.70
S_{20}	0.12	0.12	6.66	2.78	3.20	0.18	66.5	1.75	35.0	6.76	1.48
Mean	0.10	0.21	4.99	2.12	4.80	0.20	44.7	2.12	68.3	3.82	0.84

2.2. Pot Trial

In Rabi season of 2019–2020, a pot trial was conducted at the Soil Science Field Laboratory of Bangladesh Agricultural University, Mymensingh. The experiment was conducted with 20 soils and four levels of Mn (Mn_0, Mn_1, Mn_2, and Mn_4) viz. 0, 1, 2, and 4 $\mu g\ g^{-1}$ in a factorial completely randomized design (CRD) with three replications. A number of 240 plastic pots with an eight-kilogram capacity (24 cm in diameter) were filled with 20 soils collected from different locations (mentioned in Table 1) of AEZ 1, 11 and 18, where soil moisture content was maintained at field capacity (@ 25% moisture v/v). According to FRG [20], N, P, K, S, Zn and B were applied from urea, triple super phosphate, muriate of potash, gypsum, zinc sulphate and boric acid, respectively at the dose of 27, 30, 40, 14, 1 and 0.5 kg ha^{-1}, respectively. All these chemical fertilizers were applied at full doses to all the soils. Manganese was applied in soils from analytical grade Mn sulphate ($MnSO_4.H_2O$). To add 0, 1, 2 and 4 μg Mn g^{-1} soil, the required amount of $MnSO_4.H_2O$ was 0 $\mu g\ g^{-1}$ soil (i.e., 0 kg ha^{-1}), 3.07 $\mu g\ g^{-1}$ soil (i.e., 6.14 kg ha^{-1}), 6.14 $\mu g\ g^{-1}$ soil (i.e., 12.28 kg ha^{-1}), and 12.28 $\mu g\ g^{-1}$ soil (i.e., 24.56 kg ha^{-1}). BARI Soybean-6 was used as a test crop. Six seeds were sown in each pot and after emergence three seedlings were allowed to grow. Intercultural operations such as weeding, irrigation and pest control were performed as per requirement of the crop. The soybean plants were harvested after 116 days of sowing. The harvested root, shoot and seed samples were prepared and dried at 65 °C in an oven till constant weight was obtained. The dry weight of root, shoot and seed of soybean for each pot was recorded. The seed yield was calculated at 14% moisture basis.

2.3. Determination of Critical Limit of Mn Using the Graphical Method

The CL of Mn in the studied soils was determined by the graphical method, as suggested by Cate and Nelson [35]. The yield of soybean was obtained at the 100%

flowering stage of the crop and was converted into Bray's percent yield by using the following equation.

$$\text{Bray's \%yield} = \frac{\text{Yield without Mn}}{\text{Yield at optimum Mn treatment}} \times 100$$

The critical level of nutrients in soil was derived by plotting the nutrient on 'X' axis and Bray's percent yield on 'Y' axis as described by Prasad et al. [36]. A cross is placed over the data and moved to the upper left and lower right to have a minimum number of points, as suggested by Cate and Nelson [35]. In this method, the dividing line between two groups was drawn roughly, and the lines for vertical and horizontal directions on a scatter diagram were superimposed subjectively. In order to solve it, a statistical model was followed, which was developed by Cate and Nelson [37] in accordance with Waugh's recommendations [38].

2.4. Determination of Critical Limit of Mn Using the Statistical Method

The CL of Mn in the soils under study was also calculated using a statistical approach as developed by Cate and Nelson [37], where the initial soil test values of Mn were in ascending order, and Bray's percent yield was placed against each soil test Mn value. The pairs of soil test values and relative yield were kept in order throughout the analyses [39,40]. According to Siva Prasad et al. [36], the correction factor (C.F.) and a total corrected sum of squares (T.C.S.S.) were calculated from Bray's percent yield by using the following formula

$$\text{C.F.} = \frac{\{\sum Y\}^2}{\text{n}} = \frac{\sum\{Y_1+Y_2+Y_3.....+Y_n\}}{n} \text{ and}$$
$$\text{T.C.S.S.} = \sum_{i=1}^{n} Y^2 - \text{C.F.} = \sum\left(Y_1{}^2 + Y_2{}^2 + Y_3{}^2 \ldots\ldots\ldots + Y_n{}^2\right) - \text{C.F.}$$

The data were grouped into two classes, i.e., the samples S1 to S10 were considered population 1 and S11 to S20 were considered population 2. Plant available Mn was included in population 1 = $\frac{P_1+p_2+.....P_n}{P}$.

The corrected sum of squares of derivation from the mean of population 1 (CSSI) = $\sum P_1{}^2 + P_2{}^2 + ...P_n{}^2 - \frac{\sum(P_1+.....P_n)}{n}$.

If Kn is the number of observations in population 2, then the mean relative yield in population 2 = $\frac{K_1+k_2.....+K_n}{n}$.

The PCL, i.e., postulated critical limit (split between two populations) was calculated as follows

$$\text{PCL} = \frac{\text{Least value in population 1} - \text{1st value in population 2}}{2}$$

As a consequence, the predictability value R^2 was computed from the following equation.

R^2 = {TCSS − (CSS1 + CSS2)}/TCSS where
TCSS = Total Corrected Sum of Squares
CSS1 = Corrected Sum of Squares of Population 1
CSS2 = Corrected Sum of Squares of Population 2

From the highest R^2, the postulated critical limit was found.

2.5. Validation Study at Field Condition

A field trial was conducted to assess soybean (BARI Soybean-6) response to Mn fertilization at AEZ 18 in Subornochar upazila (22°42′ N, 91°01′ E) during the Rabi season of 2020–2021 where available soil Mn was 1.78 mg kg^{-1} (S_1). For the field study, the same fertilizers were used, as mentioned in Section 2.2. Manganese was applied from $MnSO_4$ on the basis of soil test values considering CL. The treatments were 50% CL (1.8 μg Mn g^{-1}

soil, i.e., 3.6 kg Mn ha^{-1}), 75% CL (2.7 μg Mn g^{-1} soil, i.e., 5.4 kg Mn ha^{-1}), 100% CL (3.6 μg Mn g^{-1} soil, i.e., 7.2 kg Mn ha^{-1}) and 125% CL (4.5 μg Mn g^{-1} soil, i.e., 8.9 kg Mn ha^{-1}). Each treatment was replicated four times in a randomized complete block design (RCBD). During final land preparation, a basal dose of 27 kg ha^{-1} of N, 30 kg ha^{-1} of P, 40 kg ha^{-1} of K, 14 kg ha^{-1} S, 1 kg ha^{-1} of Zn and 0.5 kg ha^{-1} of B were applied according to the soil test basis from urea, TSP, MoP, gypsum, zinc sulphate and boric acid, respectively. The unit plot size was 4 m × 3 m and the total number of the unit plots was 16 (4 × 4). Manganese was applied as $MnSO_4.H_2O$ by mixing with seeds at sowing. The required amount of $MnSO_4.H_2O$ was 5.53 μg g^{-1} soil (i.e., 11.06 kg ha^{-1}) for 50% CL, 8.29 μg g^{-1} soil (i.e., 16.58 kg ha^{-1}) for 75% CL, 11.05 μg g^{-1} soil (i.e., 22.10 kg ha^{-1}) for 100% CL, and 13.8 μg soil (i.e., 27.60 kg ha^{-1}) for 125% CL. Maintaining a distance of 4 cm, the seed sowing was performed @ 55 kg ha^{-1}. For proper development of the crop, suitable intercultural and management operations were conducted. At the full matured stage, harvesting was performed after 116 DAS. The seed yield was calculated considering 14% moisture level and the yield data were analyzed in the same manner as the pot experiment.

2.6. Analysis of Data

Statistical analysis of the data was carried out by F-test to evaluate the significance of the treatment effects [41]. Using DMRT (Duncan's Multiple Range Test), the comparison of the treatment means was performed. With the help of a computer package program, "MSTAT-C", the analysis of variance (ANOVA) for different parameters was performed.

3. Results

3.1. General Characteristics of Soils Used in the Study

Four major characteristics of soil, viz. pH, EC, organic matter content, and textural classes, are mentioned in Table 2. Soil pH differed from 5.20 to 7.85 (mean value 6.26), EC varied from 0.11–4.15 dS m^{-1} (mean value 1.73 dS m^{-1}), and organic matter status ranged from 0.79 to 2.81% (mean value 2.04%). Based on pH, the soils of the studied locations were strongly acidic to slightly alkaline in reaction. Dinajpur Sadar (AEZ 1) recorded the lowest pH of 5.20, whereas the highest pH (7.85) was observed in Kustia Sadar (AEZ 11). The EC classes were non-saline to slightly saline. The maximum EC value (4.15 dS m^{-1}) was found in Kamalnagar upazila under AEZ 18, whereas the minimum EC (0.11 dS m^{-1}) was recorded in Dinajpur Sadar of AEZ 1. About 85% of the soils were medium, 5% of soils were low, and the rest 10% soils were very low in organic matter status. Again, the organic matter content in soil was minimum (0.79%) in Dinajpur Sadar, whereas the maximum content (2.81%) was observed in Kustia Sadar. Most of the soils were silt loam in texture, although sandy loam and loam soils were found in Dinajpur Sadar and clay loam soils were recorded in Kustia Sadar.

The status of both macro and micronutrients in the selected soils is shown in Table 3. In the soil set, total N content varied from 0.04 to 0.14%, whereas exchangeable K, Ca, and Mg status ranged from 0.11 to 0.57, 1.15 to 16.0, and 0.36 to 0.53 cmol (+) kg^{-1}, respectively. Available P, B, and S amounts differed from 1.20 to 11.0, 0.09 to 0.65, and 10.0 to 84.5 μg g^{-1}, respectively. The status of available Zn, Cu, Fe, and Mn of the soils fluctuated from 0.32 to 1.70, 0.78 to 5.56, 30.6 to 135, and 1.78 to 6.76 μg g^{-1}, respectively, in the studied soil sets having mean values of 0.84, 2.12, 68.4 and 3.82 μg g^{-1}, respectively. The Zn level was very low to optimum. Considering the critical value of Mn in soils (1.0 μg g^{-1}), 5% of soils (S_1) was grouped into medium (1.51–2.25 μg g^{-1} Mn), 25% (S_2–S_6) optimum (2.26–3.0 μg g^{-1} Mn), 20% (S_7–S_{10}) high (3.10–3.75 μg g^{-1} Mn) and 50% (S_{11}–S_{20}) very high classes (>3.75 μg g^{-1} Mn) according to FRG [20]. On the other hand, the status of both Cu and Fe was very high in soils of the selected AEZs.

3.2. Effect of Mn on Root, Shoot, and Seed Weight of Soybean

The data mentioned in Table 4 suggest that various levels of Mn applied to different soils had a significant impact on soybean root, shoot, and seed weight. Manganese influenced the root weight of soybeans. The highest root weight of 2.21 g pot^{-1} and the lowest root weight of 1.89 g pot^{-1} were achieved from Mn_1 and Mn_0 treatments, respectively. The difference between these treatments was significant. The present study revealed that Mn possesses a considerable effect on the shoot weight of soybeans grown in the soils of selected AEZs. The significantly highest shoot weight (16.6 g pot^{-1}) was obtained in Mn_1-treated soils over control, which was followed by Mn_2 and Mn_4. As the dose of Mn increased, the shoot weight gradually decreased. The effect of Mn was considerable in increasing the seed weight of soybeans. The Mn_1 treatment produced the highest seed weight of 11.8 g pot^{-1} followed by Mn_2 and Mn_4 over control.

Table 4. Root, shoot, and seed weight of soybeans are affected by different levels of Mn in different AEZs.

Treatments	Root	Shoot	Seed
	Dry Weight (g pot^{-1})		
	AEZs		
AEZ 18	2.03	15.9	11.3
AEZ 11	2.08	15.9	11.3
AEZ 1	2.05	15.7	11.0
LSD	0.17	0.49	0.66
SE (±)	0.09	0.96	0.34
	Mn level		
Mn_0	1.89b	14.2b	10.0b
Mn_1	2.21a	16.6a	11.8a
Mn_2	2.08ab	16.5a	11.6a
Mn_4	2.02ab	15.9a	11.5a
LSD	0.20	1.11	0.76
SE (±)	0.10	0.56	0.39
	Level of significance		
AEZ	ns	ns	ns
Mn level	**	***	***
AEZ × Mn level	ns	ns	ns

ns = Not-significant; ** = Significant at 1% level of probability; *** = Significant at 0.1% level of probability. Figures in a column having common letter(s) do not differ significantly according to DMRT.

3.3. Critical Limit of Soil Mn for Soybean

Figure 2 shows the graphical representation of relative yield and soil test available Mn in the form of XY scattered graph points. A horizontal line was drawn at that point by averaging Bray's percentage yield. A perpendicular line was also drawn, and the point where the perpendicular line crosses the X axis is the soil critical level. Thus, according to the graphical method, the scatter diagram indicated the critical limit as 3.60 μg g^{-1}, below which the response of Mn application to soil may be expected in the case of soybean. The Bray's yield corresponded well with the Mn content of the soil, and it varied from 65.2 to 95.6% (Table 5).

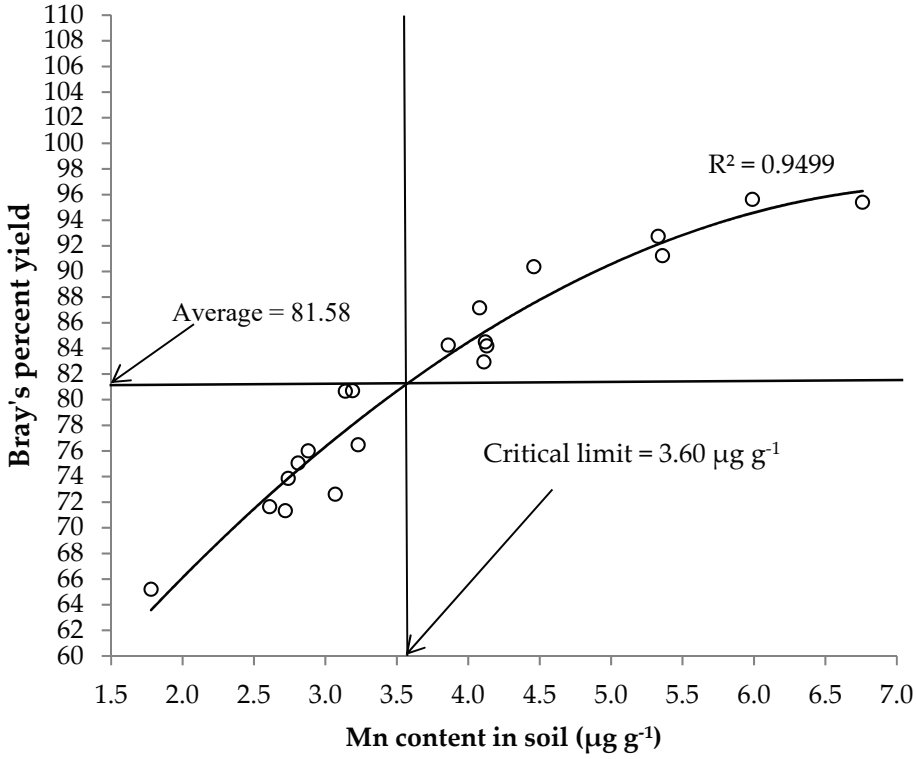

Figure 2. Critical limit of Mn for soybean production in soils of different AEZs.

Table 5. Initial soil Mn, Seed yield (g pot^{-1}) with and without Mn, and Bray's %yield.

Initial Soil Mn (μg g^{-1} soil)	Mn Levels (μg g^{-1} Soil)				Bray's %Yield
	Mn_0	Mn_1	Mn_2	Mn_4	
1.78	9.14	14.0	13.3	11.1	65.2
2.61	9.71	11.7	12.9	13.6	71.6
2.72	9.11	12.8	9.62	10.6	71.3
2.74	9.02	12.2	10.6	9.06	73.8
2.81	9.29	11.7	11.9	12.4	75.0
2.88	9.04	10.2	11.9	9.60	76.0
3.07	9.29	11.6	11.6	12.8	72.6
3.14	10.6	12.8	13.2	13.1	80.6
3.19	9.02	10.4	11.2	9.33	80.7
3.23	9.75	12.8	11.2	11.7	76.5
3.86	9.16	9.74	10.9	9.45	84.2
4.08	9.65	9.71	10.6	11.1	87.2
4.11	9.20	10.1	11.1	9.80	82.9
4.12	9.35	10.1	11.1	9.39	84.5
4.13	11.3	12.0	13.5	10.4	84.2
4.46	12.0	13.2	12.1	13.3	90.4
5.33	11.9	12.8	12.2	12.5	92.7
5.36	12.4	13.6	12.9	13.3	91.2
5.99	12.4	13.0	11.4	10.9	95.6
6.76	11.8	12.2	12.4	12.1	95.4

By statistical method, the critical limit of available Mn in soil for soybean was found to be 3.55 μg g^{-1} (Table 6). The soil available Mn content varied from 1.78 to 6.76 μg g^{-1}, and Bray's percent yield varied from 65.19 to 95.61, and these were used to fix the critical limit of Mn in soil. The R^2 values ranged from 0.23 to 0.73. The highest R^2 (0.73) showed the postulated critical limit of Mn for soybean, and it was 3.55 μg g^{-1} soil.

Table 6. Statistical method showing the critical limit of Mn in soil for soybean.

Soil Samples	Soil Available Mn	Bray's %Yield	Last Value of Soil Mn in P1	Mean Bray's %Yield in P1	CSS1	Mean Bray's %Yield in P2	CSS2	PCL	R^2
S_1	1.78	65.19							
S_2	2.61	71.61	2.61	68.40	20.61	2437.55	1209.86	2.67	0.23
S_3	2.72	71.34	2.72	71.48	26.37	2572.78	1075.05	2.73	0.31
S_4	2.74	73.81	2.74	72.58	41.09	2724.16	979.61	2.78	0.36
S_5	2.81	75.04	2.81	74.43	57.67	2894.81	896.25	2.85	0.40
S_6	2.88	68.33	2.88	71.69	65.51	3088.93	617.17	2.98	0.57
S_7	3.07	72.58	3.07	70.46	67.97	3311.39	433.99	3.11	0.69
S_8	3.14	80.66	3.14	76.62	147.46	3568.59	395.43	3.17	0.66
S_9	3.19	80.68	3.19	80.67	209.59	3869.77	350.16	3.21	0.65
S_{10}	3.23	76.47	3.23	78.58	218.93	4227.62	211.23	**3.55**	0.73
S_{11}	3.86	84.27	3.86	80.37	322.99	4659.14	188.10	3.97	0.68
S_{12}	4.08	87.12	4.08	85.70	467.97	5189.93	182.57	4.10	0.59
S_{13}	4.11	82.96	4.11	85.04	518.09	5859.40	131.93	4.12	0.59
S_{14}	4.12	84.46	4.12	83.71	582.08	6729.70	88.42	4.13	0.58
S_{15}	4.13	84.18	4.13	84.32	633.59	7907.13	22.62	4.30	0.59
S_{16}	4.46	90.38	4.46	87.28	795.29	9588.51	13.60	4.90	0.49
S_{17}	5.33	92.76	5.33	91.57	998.46	12,186.3	12.32	5.35	0.37
S_{18}	5.36	91.2	5.36	91.98	1140.61	16,732.6	0.03	5.68	0.28
S_{19}	5.99	95.61	5.99	93.41	1383.03	26,733.1		6.38	
S_{20}	6.76	95.38	6.76	95.50	1594.65	66,734.1			

PCL = Postulated critical limit; CSS1 = Corrected sum of squares of derivation from population 1; CSS2 = Corrected sum of squares of derivation from population 2; P1 = Population 1; P2 = Population 2.

3.4. Yield of Soybean in Case of Field Trial

Manganese application significantly influenced soybean seed yield, as shown in Figure 3. The maximum yield was 1.96 t ha^{-1} obtained from 100% CL, whereas the minimum yield was 1.65 t ha^{-1} recorded in 50% CL.

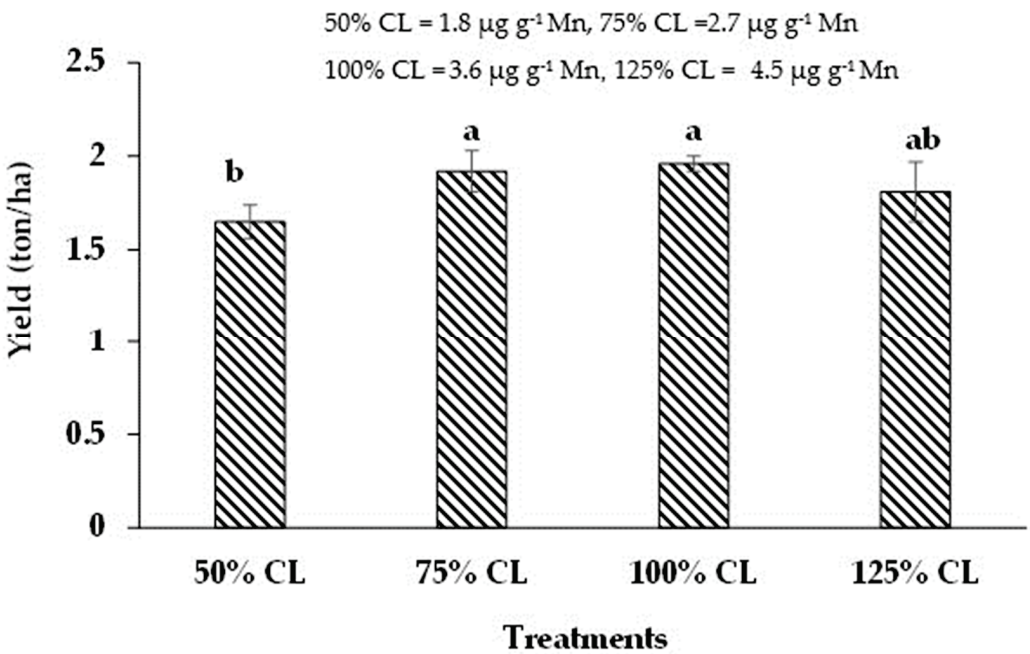

Figure 3. Effect of Mn application on soybean seed yield in AEZ 18. Different lowercase letter(s) represent significant difference among treatments according to DMRT.

4. Discussion

Twenty typical soils were chosen from 240 soils in different locations, covering three AEZs (AEZ 18, AEZ 11, and AEZ 1) with varying physicochemical properties. The critical limit of soil Mn for soybeans in three selected AEZs was detected in this study. The critical Mn level is a soil test level that indicates the division between responsive and non-responsive conditions to Mn application. According to Siva Prasad [36], this level produces the best separation between soils that give a yield response for crops from those that do not. The critical level is successful in identifying the deficient and sufficient nutrient concentrations for a variety of plant and tree species [42]. Determination of the critical limits of nutrients helps in the validation and interpretation of soil test results and in making precise fertilizer recommendations by soil categorization [43]. The critical levels can be used to estimate the probability of fertilization responses [44]. The different critical values of Mn for soybeans could be attributed to the diversified properties of soils. A variation in sample sites can cause a significant change in nutrient-critical levels, as suggested by Rahman et al. [45]. In the graphical technique, the plotting of calibration data is done as Bray's %yield versus soil test value. In Figure 2, depicting the critical limit of Mn in soil using the graphical method, the points in the upper left quadrangle reflect soil test values that are below the critical limit, indicating that plant response is likely when Mn is added. The points in the lower right quadrant indicate a situation when Mn content exceeds the CL. The horizontal and perpendicular lines were drawn while all points were distributed in the lower left and upper right quadrangle in Figure 2. The perpendicular line crosses the *X*-axis at a value of 3.60, which is considered the CL for available Mn in soils of the three AEZs. Thus, soils having <3.60 μg Mn g^{-1} soil (i.e., 7.2 kg Mn ha^{-1}) will respond to Mn fertilizer application at the flowering stage to achieve yield in the case of soybean.

According to FRG [20], the CL for Mn in soils of different AEZs of Bangladesh was 1 μg g^{-1}, although no record was found for soybean crops. This increase in CL for Mn may be due to adequate Mn status in soil and the interaction of other elements, especially Fe. The critical Mn level for soils used for soybean production in India was reported as 3.3 μg g^{-1} [21]. The statistical method for determining critical levels of Mn in soil was used to obtain the soil test value received from the soybean crop experiment (Table 6). Isolation of the threshold value of available Mn in the soil can be performed by taking into account the maximum R^2 value with the corresponding presumed CL for soybean, which can be pointed out at 3.55 μg g^{-1}. According to some previous reports, the graphical method for estimating CL gives a higher value compared to the statistical method [46]. Either of the methods (graphical or statistical) can be utilized to ascertain the CL of nutrients in the soil, as the values of CL determined using two different methods are very close. To ensure higher crop output, the authors suggest using the maximum critical value calculated from both the graphical and statistical methods, as a significant percentage of soils will not be able to comply with the CL. As reported by Rahman et al. [45], a compatible approach can predict the amount of plant-available nutrients and crops' response to fertilizer application in various types of soils. Therefore, in order to find out the optimum fertilizer demand for a crop, it is crucial to determine CL using two different methodologies.

Manganese is associated with numerous metabolic functions in plant cellular compartments and is of paramount importance as a micronutrient for plant growth. Soybean is a high Mn-responsive crop [47]. In many regions of the world, soybeans are more often deficient in Mn than in other micronutrients and respond well to Mn fertilizers when deficient. Diagnosis and prevention of any nutrient deficiency and toxicity require knowledge of the critical value of that particular element in soil and plant, as suggested by Reddy et al. [42]. The critical limit can be used to find Mn-deficient soils from non-deficient and can provide information on the Mn status of soils. Elucidation of a critical level of Mn delineates the deficiency, optimum, and toxic range of Mn, which is very important with respect to fertilizer application at peak demand and improves the yield of soybeans in Mn-deficient soils. According to Randall et al. [48], soil or foliar application of Mn is most

effective in soybeans when applied at the early blossom or early pod set stage or in multiple applications at these stages.

In this study, soybean root, shoot, and seed weight increased markedly and significantly over control due to Mn addition in soil. Application of Mn at 1 μg g^{-1} rate gave the highest seed yield and showed the maximum increases in dry weight of different organs of soybean. Further, the Mn application improved the number of pods and seeds in soybeans). The improvement in soybean yield might be due to the role of Mn in enhancing photosynthesis efficiency and carbohydrate (starch) synthesis, as suggested by Mousavi et al. [49]. Ghasemian et al. [8] showed that Mn addition gave the highest seed number and seed weight per plant, pod number, and seed yield, as well as producing the highest biological yield of soybean. A similar effect was found by Kwano et al. [50]. Several workers reported that Mn increased the root, shoot, and yield of different crops. A 25% reduction in photosynthesis and a 20% decrease in dry matter yield in Mn-deficient spinach plants were demonstrated by Bottrill et al. [51]. Arya and Roy [52] found similar results in broad beans. Akay and Uzun [53] reported that fresh yield of broccoli responded positively to Mn addition. In our field study, Mn fertilization significantly increased soybean yields at AEZ 18, although maximum yields were achieved with the margin of critical limit (100% CL) of Mn. The field validation showed that the estimated CL of Mn (3.60 μg g^{-1}) represents the better response of soybean yield.

There is an optimum concentration level at which each nutrient is neither deficient, wasteful, nor toxic. A very low concentration of a micronutrient like Mn can sometimes cause deficiency, and on the contrary, a higher concentration can block the uptake and utilization of other nutrients and can lead to toxicity in the soil and plant. The best strategy to overcome nutrient deficiencies and avoid toxicities is to adopt balanced fertigation and apply fertilizers on the basis of soil tests.

5. Conclusions

The critical limit of a nutrient element plays an important role in farm-level decision-making making, especially for balanced fertilization to increase the yield and quality of crops. The present study showed that soil Mn content and Mn application rate had a significant impact on the root, shoot, and seed weight of soybeans. According to the findings, approximately 50% of the soybean-grown soils in three AEZs showed a significant response to added Mn, where Mn deficiency was nil. We conclude that the additional Mn supply would increase soybean yield in soils with an Mn content of less than 3.60 μg g^{-1}. The critical limit for soil available Mn was 3.60 μg $g^{-1,}$ as noted by the graphical method, and 3.55 μg g^{-1} by statistical method for the selected AEZs. The CL of Mn for soybean showed in the present study was higher in both methods than the previous CL, i.e., 1.0 μg g^{-1} soil as suggested by the Fertilizer Recommendation Guide. The developed CL from the present study may be used for prediction of Mn deficiency in soils and yield response of soybean to Mn addition which is necessary at farm level planning particularly for the application of balanced nutrient to ensure better soybean production. Nevertheless, it is tough to fix a constant value of critical limit of soil available Mn in various types of soils owing to soil heterogeneity, crop species and different varieties of a given species.

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Effect of Maize Hybrid in Complete Feed on the Production Performance and Economic Considerations in Laying Hens

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Abstract: The nutritional value of maize grain can be influenced by its genetic background, which can lead to differences that could affect laying hens due to the high proportion of maize hybrids in the complete feed. This study aimed to investigate the effects of modern maize hybrids on hen production and egg quality. Dietary treatments differed only in a grain of 15 high-yielding maize hybrids, added at a fixed proportion of 600 g kg^{-1} and without additional pigments. By 3 in each cage, 225 Lohmann Brown hens were allocated to 15 dietary treatments in a completely randomized block design (15 treatments × 5 cages). The experiment lasted 10 weeks, during which the number and weight of eggs were recorded daily, and diet intake was recorded weekly. Eggs for quality analysis were collected once per week during the last five weeks of the experiment. Dietary treatments differed ($p < 0.05$) in complete feed intake (119.7–123.1 g), egg weight (58.02–61.51 g), daily egg mass (56.17–60.16 g), and feed conversion ratio (2.01–2.19). As expected, dietary treatments did not affect egg traits such as shape index, albumen height, Haugh units, shell strength, thickness, and weight, but differed ($p < 0.05$) in yolk color (6.28–8.76) and yolk (14.74–16.03 g) and albumen (34.39–39.29 g) weights. The findings suggest that using different maize hybrids in complete feeds used in egg production systems may lead to small but significant differences in some hen production and egg quality traits, which in turn affect farmers' income.

Keywords: laying hen; maize hybrid; production performance; feed conversion ratio; economic calculations

1. Introduction

Animal nutrition affects the health, welfare, and production of animals, as well as the quality and safety of the product, but also the sustainability of the animal production system [1]. Numerous factors affect the total cost of animal production, but feed costs are the most important component, accounting for up to 70% of total production [2]. Any increase in feed costs leads to a decrease in farmers' income and forces them to optimize feed use in order to maintain the profitability of the production system. The changes in feed prices over the last decade, and especially the increase in recent years due to adverse weather conditions and political situations in some regions, have led farmers to reevaluate their feed use and look for solutions to improve their overall income. These solutions consist of techniques like modifying feed specifications for optimal net gain, feeding as closely as feasible to set standards or requirements, incorporating alternative (or even multifunctional) ingredients, or increasing the diet's digestibility [3]. Regardless of the solution adopted, the feeding strategy today must aim to balance animal performance with environmental protection, animal welfare, and economic profit.

Climate change and the growing human population pose a challenge to any animal production system, and it is in this context that the concept of a sustainable animal diet is

defined. According to Makkar [4], in addition to the currently accepted nutritional criteria for providing economically viable and safe animal products through the production of safe feeds, the concept also includes the importance of efficient use of natural resources, environmental protection, sociocultural benefits, and ethical integrity and sensitivity. In addition, he stated that the efficient use of feed resources and the application of appropriate feeding strategies are crucial to meeting the requirements of all four dimensions of the concept of sustainable animal diets.

The profitability of an animal production system depends on the performance of the animals in relation to the feed input. In this context, feed efficiency is one of the most important factors, as its increase helps to balance animal performance with environmental protection, animal welfare, and economic profit [2]. Even small changes in feed efficiency can have a significant impact on the economic benefits of the animal production system. Different processing technologies for feeds and complete feeds as well as supplementation with different additives could be applied to achieve higher digestibility and therefore higher feed efficiency [5–7]. However, even small changes in complete feed ingredients, such as the feed genotype, could also be a potential factor in improving feed efficiency [8].

Egg production is an important animal production system because eggs are an important food worldwide [9]. Modern laying hen hybrids used on farms nowadays have high egg production, and complete feeds must provide the required nutrients for optimal egg production, health, and welfare. Laying hens have a preference for certain nutrients in the diet, such as protein, fiber, and calcium, and they are able to balance their diet by selecting nutrients and increasing consumption of feed particles rich in the deficient nutrient [10]. Furthermore, laying hens prefer coarser particle sizes in complete feeds and cereals are the main energy feed in their diet [11]. In addition, laying hens have the ability to deposit nutrients in the yolk, and supplementing their diet with nutrients has a positive effect on the nutritional value of eggs [12–15].

Maize grain is a multifunctional feed that provides energy, slowly digestible and resistant starch, and carotenoids that act as provitamin A vitamins, antioxidants, and pigments [16–18]. However, differences between maize genotypes may result in variable chemical composition [19]. Commercially available hybrids differ in their chemical and physical properties. According to the feed tables of Sauvant et al. [20], the crude protein of 2634 maize samples varied between 74 and 88 g kg^{-1}, while starch content varied between 622 and 660 g kg^{-1}. Moreover, grain hardness, expressed as a flotation test value, ranged from 1391 to 3505 in 36 commercial hybrids tested by Kljak et al. [21], while test weight varied from 74.1 to 82.3 kg hL^{-1}. These differences could affect properties directly related to nutrient utilization, such as starch digestibility kinetics [22], and consequently affect animal production performance. Although Moore et al. [23,24] concluded that the differences between six maize hybrids used in complete feed preparation were not large enough to affect the production performance of broilers, layers, and pigs, a recent study by Melo-Durán et al. [8] showed that maize genotype affects nutrient digestibility and growth performance of broilers and that this effect was related to the content and the nature of non-starch polysaccharides. In all these studies, the proportion of grain in the complete feeds was the same and they differed only in the maize hybrid. It should be noted, however, that studies evaluating the effects of maize hybrids on hen production performance are lacking because differences among commercial maize hybrids were not thought large enough to result in significant differences in hen production performance. Recent studies have focused on quality protein maize and transgenic maize, but the production performance of laying hens was mostly similar to the control with commercial maize hybrids [25–27].

Although further studies should be conducted to investigate the reasons why maize hybrids might affect animal production performance, the possibility that only a change in hybrids used in the preparation of complete feeds could positively affect feed utilization and animal performance could increase the profitability of the animal production system. Therefore, the aim of the present study was to investigate the effects of modern

commercially available maize hybrids on the production performance of laying hens and to determine what economic impact they could have on the egg production system.

2. Materials and Methods

The animal experiment was conducted in accordance with the Croatian directives (Animal Protection Act, OG 102/17 and 32/19, and Regulation on the Protection of Animals Used for Scientific Purposes, OG 55/13, 39/17 and 116/19), which correspond to the European guidelines for the care and use of animals used for scientific purposes. The animal procedures used in this study were approved by the Ethics Committee for the protection of animals used in scientific research within the Ministry of Agriculture of the Republic of Croatia (EP 349/2022).

2.1. Maize Hybrids and Treatment Diets

Fifteen high-yielding yellow maize hybrids (*Zea mays* L.) belonging to various maturity groups (Table 1) were selected for this study based on grain physical and chemical properties. In the preliminary study, 103 commercial maize hybrids were screened for numerous properties and selected for this study to ensure variability in endosperm microstructure and thus nutrient utilization [22,28].

Table 1. Tested modern maize hybrids belonging to various maturity groups.

Hybrid	Abbreviation	Type	FAO Maturity Group
Hybrid 1	H1	Semi-flint	330
Hybrid 2	H2	Dent	350
Hybrid 3	H3	Dent	350
Hybrid 4	H4	Dent	390
Hybrid 5	H5	Hard dent	380
Hybrid 6	H6	Dent	400
Hybrid 7	H7	Dent	410
Hybrid 8	H8	Dent	450
Hybrid 9	H9	Dent	450
Hybrid 10	H10	Quality dent	460
Hybrid 11	H11	Quality dent	500
Hybrid 12	H12	Quality dent	510
Hybrid 13	H13	Quality dent	510
Hybrid 14	H14	Dent	570
Hybrid 15	H15	Dent	580

Maize hybrids were produced in the growing season of 2021 on the experimental field in central Croatia near Zagreb (45°51′00″ N, 16°10′01″ E). The soil texture was silty clay with 59.6% silt, 39.3% clay, and 1.1% sand, 4.2% organic matter with pH of 7.7. Each hybrid was planted in a 6 m wide (8 rows) and 50 m long plot, following the recommendations of their seed companies for optimum planting density. All hybrids were grown under the same environmental conditions using an intensive production system [29]. The daily average minimum and maximum temperatures (°C) and precipitation (mm/day) for the vegetation season were the following: 2.66, 13.87, and 1.2 for April; 8.20, 20.15, and 2.70 for May; 13.25, 28.25, and 3.55 for June; 15.73, 29.51, and 0.85 for July; 13.49, 27.72, and 2.95 for August; 9.40, 23.94, and 2.20 for September; and 4.71, 14.15, and 2.35 for October, respectively [30]. After physiological maturity, ears were hand-harvested from five places of the central six rows representing five replicates. The remaining six inner rows were combine-harvested for the production of complete feeds. The harvested ears and grains were dried at 40 °C to approximately 120 g kg^{-1} moisture and stored in bags until preparation of the experimental complete feeds.

The complete feeds were formulated to contain the same ingredients and differed only in the maize hybrid. All complete feeds were formulated according to recommendations of the National Research Council [31] and adapted to Lohmann Brown laying hens according

to the management guide [32] for nutrient supply to laying hens in the initial phase of egg production (19 to approximately 50 weeks of age; Table 2) with table values for the chemical composition of maize grain and soybean meal containing 45% of crude protein. To reduce compositional differences, the basal mixture contained all the ingredients for laying hen complete feeds from the same batch, except for the maize grains. Immediately prior to the preparation of the complete feeds, the maize grain was ground through a 6 mm sieve and mixed with the basal mixture to the same percentage (60%). No additional pigment was added. All diets were mixed immediately before the start of the dietary experiment and packed in feed bags with a capacity of 10 kg. A total of 200 kg of each complete feed was prepared. A composite sample of each complete feed was prepared and the chemical composition determined using standardized methods (Table 3).

Table 2. Composition of complete feeds.

Ingredient	Content (g kg^{-1})
Maize	600
Soybean meal	262
Sunflower oil	30
Calcium carbonate	88
Monocalcium phosphate	12
Sodium chloride	4
DL methionine	1.5
Vitamin premix [1]	1.2
TRT Poultry Pack [2]	1.3
Calculated composition	
Apparent metabolic energy/MJ kg^{-1}	11.51
Crude protein/%	16.91
Crude fat/%	5.55
Crude fiber/%	2.81
Starch/%	40.65
Lysine/%	0.88
Methionine/%	0.42
Ca/%	3.8
p total/%	0.6
p available/%	0.43
Linolenic acid/%	3.16

[1] The vitamin premix provided per kg of diet: vitamin A 10,000 IU, vitamin D3 2500 IU, vitamin E 200 mg, vitamin K3 3 mg, vitamin B1 1 mg, vitamin B2 45 mg, vitamin B3 30 mg, vitamin B5 10 mg, vitamin B6 3 mg, vitamin B7 50 mg, vitamin B9 0.5 mg, vitamin B12 25 mg, choline 400 mg, antioxidant (BHA, EQ) 50 mg. [2] TRT Poultry Pack (Alltech Ireland Ltd., Dunboyne, Ireland) provided per kg of diet: I 1 mg, Fe 5 mg, Cu 5 mg, Mn 30 mg, Zn 30 mg, Se 0.2 mg.

Table 3. Chemical composition of experimental complete differing in maize hybrid.

Hybrid	Moisture	Ash	Ca	Crude Protein	Crude Fat	Starch	NDF [1]
				g kg^{-1}			
H1	87	129	155.8	39.6	58	403	87.4
H2	88	119	161.1	37.6	54	411	92.2
H3	84	127	161.3	40.0	51	417	82.2
H4	85	126	159.8	39.3	57	421	78.3
H5	83	117	156.1	35.7	53	425	79.6
H6	79	127	158.3	40.3	54	436	74.6
H7	86	122	158.0	38.3	57	439	84.3
H8	89	120	163.2	38.5	57	405	76.9
H9	92	123	152.8	38.7	56	411	75.5
H10	93	121	156.3	39.0	51	429	90.3

Table 3. *Cont.*

Hybrid	Moisture	Ash	Ca	Crude Protein	Crude Fat	Starch	NDF [1]
				g kg^{-1}			
H11	94	122	159.0	37.5	57	407	75.2
H12	92	118	165.0	37.0	53	430	88.1
H13	87	119	163.0	37.3	59	431	78.5
H14	88	116	164.5	39.1	57	439	87.1
H15	86	118	166.4	38.5	57	431	88.3

[1] NDF—neutral detergent fiber.

2.2. Hens, Housing, and Experimental Design

A total of 225 Lohmann Brown laying hens (18 weeks old) were randomly assigned in groups of 3 to 1 of 75 metal battery cages designed for the experiments (1269 cm^2 for each hen in each cage). Diets and water were provided ad libitum to the hens. The room temperature was 20 ± 3 °C and the light period consisted of 16 h of light per day throughout the experimental period.

After allocating hens to the cages, a 4-week period for adaptation to experimental conditions and the beginning of egg production peak began. All hens were fed a diet based on barley instead of maize grain and with the same calculated nutrient composition as the experimental diets (Table 2). After adaptation, cages were randomly assigned to 1 of 15 dietary treatments (15 diets differing in maize hybrid; 5 replicates per dietary treatment). The experimental period lasted ten weeks. Hens were weighed at the beginning and at the end of the experimental period. Throughout the experimental period, the number of eggs laid was recorded daily, while complete feed intake was recorded weekly [33]. Egg production was calculated as the total number of eggs per cage divided by the number of hens per cage. Daily egg mass was calculated by multiplying egg weight and egg production [15]. Feed conversion ratio (FCR) was calculated by dividing the amount of complete feed consumed per day by the egg mass produced daily [7]. Assuming that the first three weeks were used for adaptation to the diet, the fourth week of the experimental period was considered as the sampling period and the values recorded during this period were used for statistical analysis. In addition, during the last five weeks of the experimental period, all eggs were collected once a week for analysis.

2.3. Analyses of Maize Grain

Grain samples were ground in a laboratory mill (Cyclotec 1093, Foss Tocator, Hoganas, Sweden) with a 1 mm sieve immediately before analysis. All samples were analyzed for crude chemical composition using standard methods. Dry matter (DM) was determined according to the ISO 6496:1999 method [34]. Briefly, 3 g of the sample was dried at 103 °C for 4 h. Ash was determined according to the ISO 5984:2002 method [35]. Briefly, 1 g of the sample was ashed at 550 °C for 4 h. Crude protein was determined according to the ISO 5983-2:2009 method [36]. The sample (1 g) was digested at 420 °C with the addition of concentrated sulfuric acid and a mixture of potassium sulfate and copper sulfate pentahydrate. The digested sample was distilled in an automatic Kjeltec 8200 system (Foss, Hilleroed, Denmark) with the addition of a 35% sodium hydroxide solution. The released ammonia was collected in a 4% boric acid solution and titrated with a 0.1 mol L^{-1} hydrochloric acid. The nitrogen content in the sample was calculated from the acid consumption. Crude protein content was calculated by multiplying the nitrogen content by a factor of 6.25. Crude fat was determined according to the ISO 6492:1999 method [37]. Briefly, 1 g of the sample was extracted with diethyl ether using the Soxtec 1040 automated system (Foss Tecator, Höganäs, Sweden). Starch was determined using a commercial test kit, Total Starch Assay (K-TSTA; Megazyme International, Wicklow, Ireland), according to the AOAC 996.11 method [38]. The sample (0.1 g) was incubated with 3 mL of thermostable α-amylase in acetate buffer (100 mM, pH 5.0) in a boiling water bath for 6 min. Then, 0.1 mL of amyl-glucosidase was added and the mixture was vortexed and incubated in the bath at 50 °C

for 30 min. The entire contents were then quantitatively transferred to 100 mL volumetric flasks. An aliquot of the solution was centrifuged at 3000 rpm for 10 min (Centric 322 A, Tehtnica, Železniki, Slovenia) and an aliquot of 0.1 mL of the solution was incubated with 3 mL of GOPOD at 50 °C for 20 min. The absorbance of the solution was measured at 510 nm on a UV/vis spectrophotometer (Heliosγ, Thermo Electron Corporation, London, UK), and the amount of starch in the sample was calculated using the obtained absorbance values of the samples and the glucose standard included in the test kit.

2.4. Egg Quality Analysis

All collected eggs were analyzed for quality traits immediately after collection. Firstly, the weight and length of the eggs were determined with a caliper and used to calculate the shape index. Then, whole eggs were placed in the Digital Egg Tester (DET 6000, Nabel, Kyoto, Japan), and the strength of the shell was determined. After the eggshell was broken, the albumen and egg yolk were placed on the plate of the instrument, and the height of the albumen, the Haugh units and the color of the yolk were measured. After measurement, the yolk was separated from the albumen and the weight of each was recorded. Finally, the eggshell was rinsed and dried at room temperature for 24 h, weighed, and the thickness of the shell was determined using the same Digital Egg Tester.

2.5. Economic Calculations

Calculations of complete feed costs were based on costs identified in the present study. Additional costs that were not made (pigments) were calculated based on the costs provided by the Croatian feed mills. The purchase value of eggs used was the value provided by the Croatian farmers. All calculations were based on a farm with 5000 laying hens, as farms with more than 5000 hens account for more than 70% of farms in the European Union [39]. In addition, the dietary costs of egg production were calculated based on egg production, daily intake, and the cost of complete feed identified in the present study. This cost was considered 70% of the total cost of egg production and was used to calculate the total cost of egg production.

2.6. Statistical Analysis

The obtained results were analyzed using SAS statistical software (version 9.4; SAS Institute Inc., Cary, NC, USA). The dietary experiment was conducted in a randomized complete block design with 15 dietary treatments with 5 replicates, defining a cage with three hens (replicate) as the experimental unit. Differences between the treatment diets were subjected to repeated measurement analysis using the MIXED procedure, with maize hybrid as fixed effects. Differences between hybrids in chemical composition were determined using analysis of variance with hybrid as a fixed effect using the MIXED procedure. Mean values were defined using the least squares means statement and compared using the PDIFF option; letter groups were determined using the PDMIX macro procedure. The threshold for statistical significance was defined as $p < 0.05$.

3. Results and Discussion

3.1. Maize Hybrids

In the present study, complete diets of the experimental treatments were formulated according to the values in the standard feeding tables, so that each diet contained 600 g kg^{-1} of maize grains. Possible differences in the chemical composition of the tested hybrids were not taken into account before the preparation of the complete feeds, as the intention of this study was to follow standard practices on farms. In addition, the tested maize hybrids were grown on the same test field to minimize the effects of agroclimatic conditions on their chemical composition, i.e., that the differences between the tested hybrids could be attributed to genotype. Genotype is the most important factor determining the chemical and physical properties of maize grain [19], but management and environmental conditions during the growing season can also influence these properties [40,41]. The maize hybrids

were analyzed for moisture, ash, crude fat, and starch content (Table 4) and differed in the contents of all these nutrients. The greatest difference among the hybrids tested was in the crude fat content; the hybrid with the highest content (H7) had a content approximately 40% higher than the hybrid with the lowest content (H3). Crude protein content ranged from 81.26 to 86.69 g kg^{-1} DM, while most hybrids had starch content below 700 g kg^{-1} DM (651.1–694.7). Six hybrids had starch content above this value, ranging from 712.6 to 749.0 g kg^{-1}. Tested hybrids had contents of all these nutrients that were within the range reported by Zurak et al. [28] for 103 commercial maize hybrids (ash from 9.62 to 16.43 g kg^{-1}, crude protein from 71.43 to 110.00 g kg^{-1}, crude fat from 22.76 to 51.83 g kg^{-1}, and starch from 612.23 to 793.93 g kg^{-1}). The content of these nutrients affects the nutritional value of maize since they represent potential nutrients that laying hens can utilize. Although maize has low protein content, it provides about 20% of the protein in poultry diets due to its high proportion in the diet [41].

Table 4. Chemical composition of grains from commercial maze hybrids used in this study [1].

Hybrid	Moisture	Ash	Crude Protein	Crude Fat	Starch
	g kg^{-1}	g kg^{-1} DM [2]			
H1	112.0 c	15.77 a	81.26 d	42.34 ab	667.4 cd
H2	110.2 cd	13.94 cdef	83.45 bcd	37.09 efg	678.3 cd
H3	105.2 ef	13.63 cdefg	81.85 cd	31.29 j	675.9 cd
H4	97.0 g	14.40 bc	81.77 cd	35.21 gh	671.4 cd
H5	100.6 fg	13.12 fg	81.41 d	32.46 ij	694.7 bc
H6	87.6 h	13.81 cdefg	81.80 cd	37.92 def	712.6 b
H7	101.0 fg	13.57 cdefg	85.21 ab	44.05 a	746.4 a
H8	110.0 cd	13.50 defg	82.42 cd	34.42 hi	654.1 d
H9	110.6 cd	13.04 g	82.15 cd	40.02 cd	665.8 cd
H10	130.0 a	14.94 ab	86.69 a	38.16 cdef	694.4 bc
H11	113.4 c	13.98 cde	86.68 a	40.37 bc	673.7 cd
H12	119.6 b	14.31 bcd	83.25 bcd	38.84 cde	723.1 ab
H13	120.6 b	14.10 cd	84.11 bc	37.76 def	749.0 a
H14	107.0 de	13.22 efg	81.38 d	37.18 efg	746.8 a
H15	103.6 ef	14.06 cd	82.62 cd	36.15 fgh	721.8 ab
p	<0.001	<0.001	<0.001	<0.001	<0.001
SE	1.65	0.30	0.91	0.82	10.33

a–j: Different letters indicate a statistically significant difference in the content of nutrients between maize hybrids at $p < 0.05$. [1] Each hybrid had five repetitions. [2] DM—dry matter.

When comparing the chemical composition of the tested hybrids with the values in the standard feed tables reported by Sauvant et al. [20], the values of the tested hybrids in the upper range of the contents of crude fat and starch were comparable to the values in the feed tables (37 and 641 g kg^{-1}, i.e., 42.8 and 741.9 g kg^{-1} DM, respectively). Crude protein content was lower than the average value in the feed tables (81 g kg^{-1}, i.e., 93.4 g kg^{-1} DM) for all hybrids tested. These differences were most likely the result of high yields and genotype variations since the hybrids in the present study were grown according to the manufacturer's recommendations for cultivation and agrotechnical measures. On the other hand, the values in the standard feed tables of the National Academies of Sciences, Engineering, and Medicine [42] are closer to the values of the hybrids used in the present study. More than 11,000 maize samples contained an average of 8.5, 3.84, and 70.4 g kg^{-1} DM of crude protein, crude fat, and starch, respectively.

3.2. Production Performance of Laying Hens

The laying hens used in the present study were at peak egg production during the sampling period, so no differences between dietary treatments in this performance trait were expected (Table 5). Hens fed all treatment diets had egg production greater than 94%. In addition, hen weights were similar for all treatments at both the beginning and end of the experimental period. At the beginning of the experimental period (at 22 weeks of age),

the average weight of the hens was 1786 g, which corresponds to the performance target weight according to the management guide for Lohmann Brown hens (1760 g) [32]. At the end of the experimental period (32 weeks old), the average weight of the hens was 1824 g, which was 100 g below the performance target weight. Despite the lower body weight than expected, the similarity of the treatments suggests that the hens used the nutrients for egg production rather than weight gain.

Table 5. Production performance of laying hens fed dietary treatments differing in maize hybrid [1].

Hybrid	Daily Intake	Egg Production	Egg Weight	Egg Mass	FCR [2]	Hen Weight	
						At the Beginning	At the End
	g	%	g	g		g	g
H1	122.02 ab	94.11	59.87 abc	57.01 de	2.156 ab	1808	1785
H2	121.67 b	94.94	61.51 a	59.41 ab	2.069 abc	1802	1825
H3	123.15 a	95.30	59.40 bc	58.57 abcd	2.112 abc	1805	1804
H4	121.77 ab	95.99	60.52 ab	58.81 abcd	2.079 abc	1754	1782
H5	121.53 b	96.10	60.66 ab	58.74 abcd	2.098 abc	1823	1873
H6	121.74 ab	97.65	59.15 bc	58.07 bcde	2.119 abc	1748	1780
H7	121.62 b	96.97	60.25 ab	59.21 abc	2.059 bc	1807	1904
H8	119.72 c	96.09	60.00 ab	58.34 abcd	2.009 c	1735	1836
H9	121.96 ab	95.85	59.75 abc	57.90 bcde	2.105 abc	1766	1838
H10	121.55 b	94.30	59.38 bc	57.06 de	2.161 ab	1737	1770
H11	121.81 ab	97.23	61.44 a	60.16 a	2.056 bc	1801	1837
H12	121.09 bc	95.89	60.99 ab	59.56 ab	2.018 c	1792	1813
H13	122.42 ab	96.92	60.16 ab	57.31 cde	2.186 a	1818	1851
H14	121.69 ab	96.09	58.02 c	56.17 e	2.164 ab	1808	1836
H15	122.18 ab	95.88	61.25 a	59.43 ab	2.095 abc	1759	1768
p	0.035	0.408	0.024	0.014	0.045	0.230	0.389
SE	0.644	1.83	0.661	0.745	0.033	26.4	37.4

a–e: Different letters indicate a statistically significant difference in the content of nutrients between maize hybrids at $p < 0.05$. [1] Each dietary treatment was allocated to six cages (repetitions) and observations per cage were recorded weekly from the fourth week to the end of the experiment. [2] FCR—feed conversion ratio.

Dietary treatments differed in daily intake of complete feed, egg weight, egg mass, and FCR (Table 5), and since the complete feeds of dietary treatments differed in the maize hybrid, these differences can be attributed to the maize hybrid used in the complete feeds. However, it should be noted that most hybrids were similar in these production traits and significant differences were observed between dietary treatments resulting in the highest and lowest values. For example, the lowest daily intake was 119.72 g (H8), and hens fed this complete feed consumed 3.43 g less than hens fed dietary treatment H3. In addition, the lowest egg weight and egg mass were found in hens fed dietary treatment H14 (58.02 and 56.17 g), which were 3.49 g lower than the egg weight of dietary treatment H2 and 3.99 g lower than the egg mass of dietary treatment H11. The lower FCR implies a better utilization of the complete feed and, accordingly, dietary treatments H8 and H12 were the most efficient, although significant differences between these treatments were observed only for H1, H10, H13, and H14.

According to the performance goals [32], the daily complete feed intake in peak production of Lohmann Brown hens is 110–120 g per day. The values determined in the present study were only up to 3 g above this range. A possible reason for this discrepancy could be the slightly lower crude protein content of the complete feeds than calculated using the standard values of the feed table (Table 3). The hens are able to regulate protein intake depending on the crude protein content offered [43], so they compensated for the lower crude protein content by consuming more complete feed. However, the values for complete feed intake in the present study are similar to those reported by Pérez-Bonilla et al. [44] for Lohmann Brown hens with a body weight of 1860 g fed complete feeds based

on a combination of maize, wheat, and barley with 185 g kg^{-1} of crude protein and added oil (36 or 18 g kg^{-1}) from 22 to 55 weeks of age. The authors compared different levels of crude protein in complete feeds (185, 175, and 165 g kg^{-1}) and found no effects on the hen production performance. In addition, Moore et al. [23] showed that change in maize hybrids in Hy-Line W-36 laying hens at 53 to 67 weeks of age can lead to differences in intake of complete feed, although the levels were lower, which is consistent with the results of the present study. The average egg weight for the sampling period was 60.08 g, which was within the range of egg weight targeted as a performance goal (from 58.59 at 26 to 62.0 g at 32 weeks of age) [32]. In contrast to the egg weight, the average egg mass during the sampling period for all dietary treatments (58.09 g) was closer to the value corresponding to the performance goal for 32-week-old hens (59.1 g). This observation was expected, as almost all hens were at peak production at the beginning of the experimental period. Compared to previous studies, the hens in the present study laid eggs up to 5 g lighter than those fed complete feeds based on cereals [11,44,45]. However, egg production was lower in the abovementioned studies, resulting in FCR values that were slightly lower or similar to the present study (1.98 to 2.09). Furthermore, the tested hybrids resulted in higher egg weight and egg mass compared to hens fed diets containing 472 g kg^{-1} of maize grain in a study by Lázaro et al. [6] (57.4 and 54.3 g) but resulted in higher FCR than hens fed diets containing 466.9 g kg^{-1} of maize grain and 88.5 g kg^{-1} of wheat, in mesh or crumble form, (1.82–1.96) in a study by Ege et al. [5].

3.3. Egg Quality

The tested dietary treatments affected some egg quality traits, namely yolk color and the weight of yolk and albumen (Table 6). The eggs were analyzed immediately after egg collection, and no effect on albumen height or Haugh units was expected. The values obtained in the present study were comparable to those obtained in previous studies: 7.7 mm for albumen weight and 85.65 for Haugh units in a study by Ege et al. [5], 80.8 for Haugh units in a study by Safaa et al. [11], and 70.07–74.96 for Haugh units in a study by Wu et al. [46]. Since the shell strength could be influenced by the calcium source and its content in the complete feed [47] and all dietary treatments contained the same calcium source in the same proportion, no effect of the dietary treatments was expected either. The range of values obtained in the present study is in the higher range of values reported in previous studies (3.83–5.31) [48,49]. Although previous studies have shown that changing the grain or its processing in the complete feed had no effect on egg quality traits [11,45], the differences between the maize hybrids in the present study appear to be large enough to affect some egg properties. The most prominent effect was on the yolk color.

Maize grains are the only cereal with a high content of carotenoids [50], and since no additional pigments were added to the complete feeds, the yolk color in the present study is the result of maize carotenoids. Maize hybrids differ significantly in carotenoid profile [51], resulting in a different carotenoid profile and color of yolk [52], which is consistent with the results of the present study. Although the maize hybrids in the present study did not achieve as high yolk color values as supplementation with synthetic pigment containing canthaxanthin in the study by Kljak et al. [14], the contribution of maize carotenoids to yolk color is not negligible. In the case of dietary treatments used in the present study, this could be used to reduce the amount of supplemental pigments and thus the cost of complete feeds. In addition, it is possible that the selection of maize hybrids for sustainable egg production also takes into account carotenoid content and profile, suggesting that maize hybrids could be the only source of carotenoids for desirable yolk color [52].

Weights of yolk and albumen are also influenced by nutrition [53–56], so differences among maize hybrids in chemical traits led to differences among dietary treatments in these egg traits. Differences in the contents of crude protein and crude fat, as shown in Table 4, and most likely in the content of linoleic acid [57], of the maize hybrids contributed to the variations in the weights of yolk and albumen. The effect of maize hybrids on these two egg traits is consistent with the effect found for egg weight (Table 5).

Table 6. Quality traits of eggs from laying hens fed dietary treatments differing in maize hybrid [1].

Hybrid	Shape Index	Albumen Height	Yolk Color	Haugh Units	Shell Strength	Shell Thickness	Shell Weight	Yolk Weight	Albumen Weight
	%	mm			kg cm^{-2}	mm	g	g	g
H1	79.55	7.81	7.36 cdef	87.75	5.05	0.401	7.69	14.74 c	38.87 ab
H2	78.14	7.72	7.84 bc	86.50	5.12	0.405	7.85	15.30 abc	39.29 a
H3	79.16	7.38	6.28 g	85.41	5.02	0.387	7.42	15.17 abc	36.79 abcd
H4	79.11	7.29	6.64 efg	84.73	5.03	0.381	7.54	15.22 abc	38.12 abc
H5	80.06	7.24	7.10 cdefg	82.80	5.36	0.392	7.57	16.03 a	37.75 abc
H6	78.89	7.78	6.69 efg	88.03	4.85	0.386	7.74	15.55 abc	35.95 cd
H7	81.40	7.11	7.51 cde	83.56	5.16	0.392	7.49	14.96 bc	37.12 abcd
H8	79.03	7.37	7.35 cdef	85.50	5.04	0.387	7.64	15.44 abc	36.53 abcd
H9	80.70	6.80	6.80 defg	80.07	5.41	0.391	7.44	15.62 abc	37.91 abc
H10	79.74	7.44	7.82 bc	85.49	4.94	0.378	7.47	15.36 abc	37.19 abcd
H11	80.15	7.18	8.48 ab	83.76	4.60	0.388	7.62	15.85 ab	37.29 abc
H12	79.34	7.15	8.76 a	82.86	5.38	0.396	7.73	15.30 abc	38.72 abc
H13	80.73	7.27	7.60 cd	84.67	5.30	0.403	7.67	15.66 abc	36.26 bcd
H14	80.30	6.93	6.59 fg	82.66	4.86	0.391	7.58	14.96 bc	34.39 d
H15	81.14	7.24	7.64 bcd	82.66	4.66	0.382	7.68	15.66 abc	38.12 abc
p	0.203	0.708	<0.001	0.691	0.11	0.334	0.978	0.038	0.036
SE	0.768	0.33	0.31	2.42	0.21	0.007	0.20	0.339	1.00

a–g: Different letters indicate a statistically significant difference in content of nutrients between maize hybrids at $p < 0.05$. [1] Each dietary treatment was allocated to six cages (repetitions) and samples were collected and analyzed weekly during the last five weeks of the experimental period.

3.4. Economic Considerations

As mentioned above, the observed differences in production performance between the different dietary treatments are a result of maize hybrids. It appears that a high proportion of maize grains in the complete feeds could lead to the effects of maize genotype on the production performance of laying hens. However, these differences appear to be small when evaluated on a small scale. On a large scale, i.e., on farms with more than 5000 hens, these differences could help to reduce the egg production costs without significantly changing the current production and by simply selecting the maize hybrid to produce the complete feed. Based on the results of this study, 5000 hens consume between 218.5 and 224.7 tons of complete feed over a year. Based on the costs used to produce complete feed in the present study, this difference in consumption results in a cost reduction of EUR 4300 if the hybrid with the lowest complete feed intake from the present study is to be used. This cost reduction is even higher when egg costs are considered. When considering the production cost of one egg, the difference is EUR 0.005 between the hybrid with the highest (EUR 0.128) and the one with the lowest (EUR 0.123) egg production cost (Figure 1). However, on a large scale, this difference could be EUR 6378 if only the cost of complete feed is considered.

On the other hand, the eggs of all tested dietary treatments were classified as M grade eggs (53 to 63 g), which means that the differences between treatments in egg weight do not necessarily contribute to overall income. However, in terms of total egg production, dietary treatments with the highest daily egg mass could result in 7.3 tons higher annual egg mass production on a farm with 5000 hens compared to the dietary treatment with the lowest daily egg mass. With further adjustments to the composition of the complete feed based on the chemical analysis of the main feeds, the weight of the eggs could be higher and classified as L eggs, which could contribute to the overall revenue of the egg production system due to the higher purchase price of L eggs compared to M eggs. If the energy intake in the complete feed is constant, higher egg weight could be achieved with higher protein content [58].

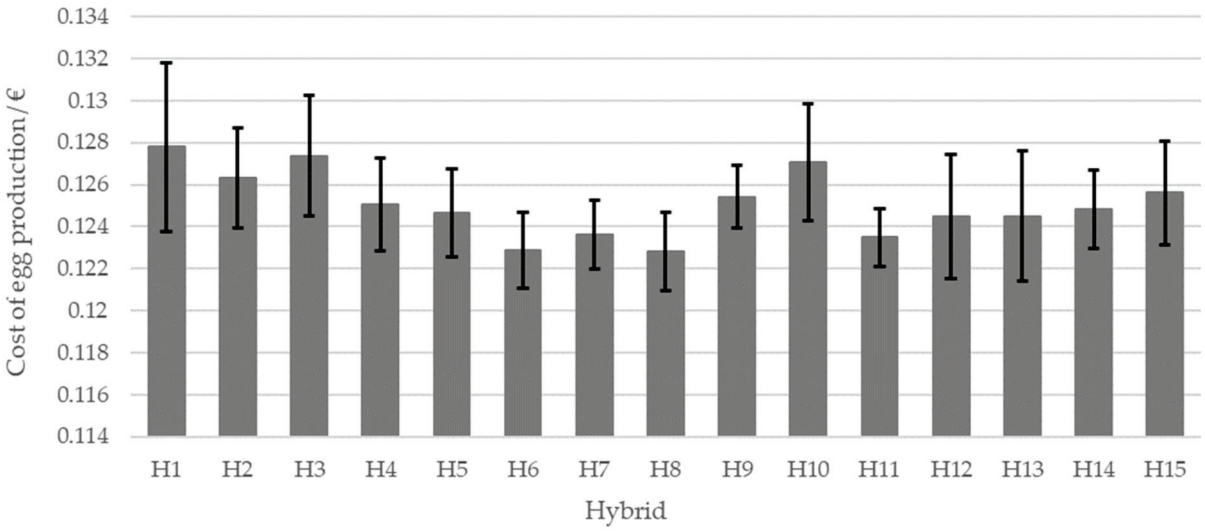

Figure 1. Calculated cost of egg production for eggs laid by laying hens fed dietary treatments differing in maize hybrid. Calculations are based on the complete feed costs identified in the present study and the assumption that feed costs represent 70% of the total cost of egg production.

Although the egg production system depends on numerous factors that could affect hen performance and the nutritional value of the complete feed, the present study was conducted to evaluate whether only a difference in maize hybrid in the complete feed would have an effect on the egg production system. Based on differences in hen performance and economic benefits, some of the hybrids used in this study were identified as more suitable for a more efficient egg production system. Based on complete feed consumption, H8 resulted in the lowest FCR and egg cost, indicating that this hybrid was most suitable for cost-effective egg production among the tested hybrids. Hybrids H6 and H7 achieved similar egg costs, regardless of the higher FCR. On the other hand, H11 had the highest egg weight and egg mass, and the resulting egg cost was similar to the three previously mentioned hybrids.

From the standpoint of yolk color and costs to achieve desirable yolk color value, the cost reduction could not be achieved when considering synthetic pigments due to their low price. Still, it could be achieved when considering natural sources, of which only the extract of marigold (*Tagetes erecta*) is commercially available [59]. Consumers today are concerned about the use of synthetic additives, and achieving egg yolk color with natural sources could be used to market eggs from a particular egg production system. The price of marigold extract depends on the content of the extract and can be up to EUR 300. Then, the proportion of the added extract depends on the carotenoid content. Assuming that up to 1 g of this extract was added per kg of complete feed, up to 6.3 kg less of this pigment source could be used in dietary treatments with the lowest complete feed intake compared to the highest intake. Skřivan et al. [60] achieved a yolk color of 10.55 with supplementation of 950 mg kg^{-1} commercial marigold extract containing 21.26 g lutein and 9.65 g zeaxanthin per kg of extract. If the desired value for yolk color is higher, even higher supplementation should be applied, which further increases the amount of pigment necessary for the production of complete feeds.

4. Conclusions

Differences among modern commercial maize hybrids used to produce complete feeds for laying hens resulted in differences in the production performance of the hens. The traits that differed in the experiment conducted were complete feed intake, egg weight and mass, and FCR. Compared to the hybrid with the highest result, the hybrid with the lowest result had 3.43 g higher complete feed intake, 3.49 g higher egg weight, and 3.99 g higher daily

egg mass. Overall, the hybrid with the best feed consumption ratio required 177 g less complete feed to produce 1 kg of eggs compared to the hybrid with the highest ratio.

Since the eggs of all dietary treatments were of the same grade, the increase in egg weight found in the present study most likely would not contribute to the profit from egg sales. On the other hand, the selection of maize hybrids could contribute to a reduction in feed costs due to the potentially lower total complete feed intake and contribute to the profitability of the egg production system. These annual cost reductions on a large scale (i.e., on a farm with 5000 hens) could be as high as EUR 4300 when considering complete feed intake or up to EUR 6378 if egg cost is considered. The second contribution of the maize hybrid selection for egg production could be in yolk color that is produced by natural pigments, which could be used for marketing products containing natural ingredients.

Although the egg production system depends on numerous factors, the results of the present study have shown that only one modification of the maize hybrid used for the complete feeds for laying hens should be considered in the economic calculations of the animal production system. Egg farms could identify the most suitable maize hybrids for the specific needs of their production system and use them in the preparation of complete feeds.

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Institutional Review Board Statement: This study was conducted according to the European guidelines for the care and use of animals used for scientific purposes and approved by the Ethics Committee for the protection of animals used in scientific research within the Ministry of Agriculture of Republic of Croatia (EP 349/2022; date of approval 31 January 2022).

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to the use of commercial maize hybrids in this study and intellectual property rights of the hybrid producers.

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

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Sensory Profile of Semi-Hard Goat Cheese Preserved in Oil for Different Lengths of Time

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Abstract: The aim of this study was to investigate the sensory profile of semi-hard goat cheese preserved in an oil mixture (extra virgin olive oil from Mljet and refined sunflower oil; 50:50). Five batches of cheese were made, and each batch was divided into three groups: (i) ripening in air (group 1—control group), (ii) ripening in oil after 10 days of ripening in air (group 2), (iii) ripening in oil after 20 days of ripening in air (group 3). After 60 days of ripening, quantitative descriptive analysis (QDA) was performed by six trained experts and texture was analyzed with a texture analyzer. The correlations between the descriptive sensory scores of texture and the texture analyzer results were significantly related. Compared to the control group, the oil-ripened cheeses had significantly ($p < 0.05$) higher oily odor and taste intensity and greater elasticity and stickiness determined by fingers, but thinner rind, lower cross-sectional color intensity, and lower crumbliness in the mouth. Ripening in oil improved rind thickness, taste, texture, and cross-sectional properties. Group 3 cheeses were preferred in terms of appearance, cross-section, odor, and taste, suggesting that prolonged ripening in air before immersion in oil positively affected the sensory characteristics of the cheese.

Keywords: semi-hard goat cheese; ripening in oil; sensory profile; quantitative descriptive analysis; texture

1. Introduction

About a quarter of the world's supply of edible food is wasted. The causes of food waste can be at any level between production, harvest, distribution, processing, and the consumer behavior [1]. The valorization of food losses has gained much importance in the last decade due to the amount of waste generated daily and the burden these losses place on industry and the environment [2,3]. How long food remains edible and nutritious depends on numerous factors that affect the growth rate of spoilage microorganisms. Some storage methods, especially traditional ones (e.g., drying, salting, smoking, etc.), require relatively little energy, while newer, industrial methods require much greater energy input [4].

The Mediterranean diet is a model for a healthy diet [5], which is mainly attributed to the consumption of extra virgin olive oil (EVOO) [6]. Although EVOO is mostly used fresh, it is not uncommon to use it to preserve various food groups e.g., vegetables, fish as well as dairy products [7]. Dairy products represent a significant part of the modern diet, and by choosing traditional cheeses, consumers not only show their concern for nature, the origin of raw materials and products, but also contribute to the preservation of traditions and support economic development [8,9], especially in areas with limited resources [10] such as islands [11].

Cow's milk cheese is produced all year round, while goat's milk cheese production is seasonal. Since the production period is not long, a suitable preservation method for semi-hard cheeses is extremely important to increase their availability for a longer period of time without altering their sensory characteristics [12].

Traditional cheesemakers on the Croatian islands of Brač and Krk, preserve cheese in olive oil, while in southern Croatia—in the city of Dubrovnik and on the island of Mljet—cheese is usually preserved in a mixture of locally produced olive oil and commercial refined sunflower oil for up to two years. However, the time of immersion of the cheese and the duration of cheese ripening in the oil are not standardized. For example, cheeses from Dubrovnik and Mljet are immersed in oil after seven days of ripening in air [13,14]. On the other hand, cheeses from the islands of Brač and Krk continue to ripen in oil after at least two months of ripening in air. Similarly, Manchego, a Spanish hard cheese made from sheep's milk, is also often placed in olive oil after three months of ripening in air, where it is usually kept until consumption [15,16].

The ripening conditions such as temperature and relative humidity in the ripening chamber and the ripening media (e.g., oil, animal skin, plastic or stone containers, brine, or spices) influence the biochemical processes of glycolysis, proteolysis, and lipolysis, which can consequently lead to the development of specific sensory characteristics of the cheese [15–19]. Thus, cheeses ripened in animal skin (e.g., Sir iz mišine, Tulum, Darfiyeh, and Bouhezza) have a unique and piquant smell, taste, and aroma, which is due to intense lipolysis and proteolysis during ripening conditions in the skin [19–21], i.e., lower air permeability of the skin compared to the cheese rind [8], but higher compared to plastic or stone containers, which serve as an alternative ripening medium [22].

Moisture content is one of the most important factors affecting the course of ripening and the development of sensory properties of cheese [17]. For example, oil as a ripening medium prevents moisture loss which influences sensory characteristics of cheese [23]. Also, animal skin has higher water permeability than a plastic container and lower permeability than the natural cheese rind, which affects the dry matter content in cheese and its sensory characteristics [8,24,25]. Semi-hard goat cheeses are usually smaller, which affects their moisture content during air ripening, since the small size of the cheese increases the surface area per unit weight, which favors dehydration [26] and leads to poor sensory characteristics of the cheese, especially texture. Cheese with pronounced dryness can unfortunately only contribute to an increase in food waste because, although it is still edible, it is perceived as relatively undesirable compared to other similar foods because it deviates in sensory perception. This type of cheese is then considered a "suboptimal food" [27].

Texture, as an expression of some rheological properties of food, is one of the most important organoleptic properties. Also, from the consumer's point of view, texture is one of the most important parameters they use to make purchasing decisions [28]. The texture of a cheese is the determining factor for its identity and quality, as it affects the mechanical properties, such as cutting, stretching, mixing, and melting [28–30]. It depends on a variety of factors, from the quality and treatment of the raw material (milk) to the ripening conditions (e.g., temperature) [31,32] and duration, the type of cheese and its manufacturing technology (including the type of salt used) and the moisture content [33]. The complex structure of cheese leads to differences in texture, even within the same type of cheese, depending on the ingredients and how they change during ripening. The storage conditions of cheese also have a great influence on texture characteristics [34].

Quantitative descriptive analysis (QDA) is a modern technique for qualifying the type and quantifying the intensity of sensory properties immediately after sensory stimulation [35,36], which is recognized as an excellent tool for measuring and optimizing the sensory characteristics of various dairy products [37–39].

Knowledge about the influence of oil on cheese ripening is limited and almost unexplored, except for two studies on the ripening of Manchego cheese in olive oil conducted more than four decades ago [15,16] and our previous research on the influence of ripening

of semi-hard goat cheese in oil on its physicochemical composition and sensory properties [23]. This study was designed to evaluate the effects of ripening in oil on the sensory profile of semi-hard goat cheese. Since texture plays an important role in the overall sensory quality, another objective of this study was to compare the QDA results with the texture analyzer results. Finally, the goal was to determine the optimal duration of cheese ripening in oil in order to develop the preferred sensory characteristics and to extend consumption time during periods when goat's milk is not produced.

2. Materials and Methods

2.1. Semi-Hard Goat Cheese Production

For this study, five batches of semi-hard goat cheese were produced in the pilot plant of the Department of Dairy Science at the University of Zagreb Faculty of Agriculture (Croatia). Each batch was produced from 100 L of raw goat's milk (Saanen goat breed). The milk was collected during evening and morning milking and stored in a cooling tank at 4 °C before cheese making.

The cheese-making process was as follows: (i) The filtered milk (100 L) was heated to 31 °C and then lysozyme (Lysozyme granular, Proquiga Biotech S.A., Spain—5 g of lysozyme dissolved in 1.5 dL of distilled water at room temperature for 15 min), freeze-dried mixed starter cultures (Lyofast MT 096 FEN 5 UC, Sacco Srl, Italy—1352 g; 1/5 of the bag weight for 100 L of milk), and rennet powder (Caglificio Clerici Spa, Italy—4 g of rennet powder dissolved in 1.5 dL of distilled water at room temperature for 10 min) were added according to the manufacturer's procedures and guidelines. (ii) After coagulation (setting time was between 50 and 60 min), the curd was cut into uniform walnut-sized grains with sharp edges using a cheese harp. The curd grains were heated to 39 °C with constant stirring. (iii) When the desired temperature was reached, the cheese grains were stirred for 30 min and then evenly placed in the plastic molds and pressed with weights. (iv) After pressing and turning the cheese at each change of weights (2–3 h process) and reaching a pH of 5.4–5.5, the cheeses were dry-salted, stored overnight in a refrigerator, washed in the morning, and subjected to ripening.

A total of sixty-five cheeses were produced (thirteen per batch: control group—six cheeses, group 2—four cheeses, and group 3—three cheeses). The initial cheese weight was about 800 g and the initial dimensions were 12 cm × 4 cm. Cheeses of the same batch were randomly divided into 3 groups according to the ripening method: (i) ripening in air (control group—group 1) for 60 days, (ii) ripening in oil for 50 days after 10 days of ripening in air (group 2), (iii) ripening in oil for 40 days after 20 days of ripening in air (group 3). The temperature in the ripening chamber was 15–17 °C and the relative humidity was 70–80%. The cheeses of groups 2 and 3 were placed in plastic vats (Figure 1) with lids filled with a mixture of extra virgin olive oil (EVOO) from the island of Mljet and commercial refined sunflower oil (50:50 ratio).

Figure 1. Cheese ripening in oil and in the air.

2.2. Cheese Sampling

For each ripening treatment and for each ripening time, the whole cheese was taken as a sample. To avoid dehydration, cheeses were packed in plastic bags and transported to the laboratory using a mobile refrigerator at a temperature of 4 °C. Cheese samples were labeled and stored in the refrigerator at 4 °C prior to analyses. Before sensory evaluation, the cheeses were tempered at room temperature.

2.3. Quantitative Descriptive Analysis (QDA)

The sensory properties of samples were analyzed on the last day of the 60-day ripening period using QDA by a group of 6 expert assessors (scientific staff: 4 women, 2 men; ages 33–55) trained at the University of Zagreb Faculty of Agriculture, Croatia. The assessors were selected and generically trained according to the ISO 22935-1 [40].

In addition, during the terminology development phase (8 h), the assessors agreed to evaluate 5 groups of attributes—appearance, odor, texture, taste, and aroma. In assessing appearance, the panelists evaluated the external characteristics and cross-section of the cheese. The main descriptors were color (white to yellow) and overall likability, but also the thickness of the rind (more or less than 5 mm). For the odor attribute, the descriptors used were sour, rancid, goat-like, oily, off-odors, and overall likeability. For texture, the descriptors elasticity and stickiness determined by fingers, solubility and crumbliness in mouth, and overall likability were used. To evaluate taste, the descriptors salty, sour, bitter, and overall likability were used. The following descriptors were used to evaluate aroma: buttery, goat-like, oily, fruity, rancid, off-flavor, and persistence.

Following the terminology development phase, panelists were trained in five two-hour sessions on quantification of the selected terms and inter-assessor calibration to improve consistency and reproducibility, evaluating various commercially available cheeses using the descriptive terms developed to describe and quantify the above-mentioned attributes. Sensory analysis was carried out in the sensory laboratory of the University of Zagreb Faculty of Agriculture (room-related technical requirements: relative humidity 50–55%, temperature 20–22 °C, illumination of 4000 K and 500 lux on the working table) according to the ISO Standard 8589:2007 [41]. All attributes were evaluated using a digital questionnaire on a numerical and unipolar intensity scale of 0–9 to assess the intensity of the rated attribute, where zero meant "not detected" and 9 meant "high intensity" or examples were provided to describe the intensity of the descriptor.

Prior sensory evaluation, research was approved by the Ethics Committee of the University of Zagreb Faculty of Agriculture on Sensory Analysis of Agri-food Products and the assessors gave informed consent. Individually coded samples were served at room temperature (3 mm thick slices cut from the center of the cheese to the rind) in sensory booths. Samples were presented in monadic way in a randomized order and 5 min break was considered between samples, and 30 min between sessions of the same day. The assessors used water, almonds, bread, and apples as palate cleansers. In total, five sessions were held over two days, and within each session, three samples and one replicated sample were assessed. Replicated sample was used for the calculation of assessor's repeatability (the calculation is based on the differences in absolute value between the scores assigned to the different descriptors of the sample and its replica) within software for the statistical processing of descriptive sensory analysis tests (Big Sensory Soft 2.0) [42].

2.4. Texture Analysis

The measurement of cheese texture parameters was performed in the laboratory of the Institute of Adriatic Culture and Karst Reclamation in Split by analyzing the texture profile with a texture analyzer (TA Plus; Lloyd Instruments, Bognor Regis, UK) according to the manufacturer's instructions.

Cheese samples for texture measurement were taken with a sterile cork borer (17.40 mm diameter) parallel to the pressing direction of the cheese between the top and bottom sides. Before sampling, the cork borer was lubricated with paraffin oil to facilitate cutting

out the samples. The cheese cores were cut into cylindrical samples (diameter = 17 mm; height = 25 mm) using a cutter with tensioned wire (Figure 2). These samples were wrapped in plastic film, stored at 4 °C, and analyzed within the next 24 h.

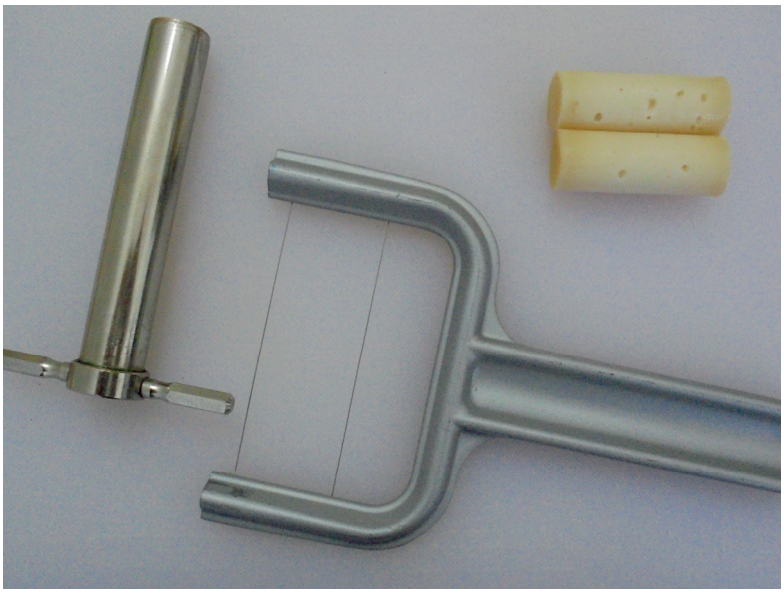

Figure 2. Semi-hard goat cheese samples (control group), cork borer, and cutter with tensioned wire.

Texture measurements were performed at room temperature using the uniaxial compression method with the texture analyzer (TA Plus; Lloyd Instruments, UK) equipped with a 500 N load cell (XLC-0500-A1; Lloyd Instruments) and a round aluminum pressure plate (ST 6/1-50 mm; Lloyd Instruments). Cheese samples were wrapped in plastic film and left until they reached room temperature. Each cylindrically shaped sample was subjected to a break and adhesive test with the pressure plate at a preload of 0.1 N and a constant crosshead speed of 50 mm/min. During the break test, the compression plate moved from the point of reaching preload until the moment the sample fractured and then was retracted to zero position. The adhesion test was performed by moving the compression plate from the moment it reached preload to the moment it reached 30% of strain. The instrument then waited 10 s and the plate was retracted to zero position at the same crosshead speed.

The texture parameters of the cheese were determined using Nexygen Plus 3 software [43] and included three parameters (load at break, adhesion force and elasticity). Load at break is defined as the load at which the sample breaks. Elasticity is calculated as the extension from the preload to the point of break. Adhesion force is defined as the maximum negative force required to overcome the attractive forces between the surface of the cheese sample and the surface of the plate.

2.5. Data Analysis

The procedures of the statistical program SAS Studio [44] were used for the processing of the sensory data. The PROC MIXED procedure with the Tukey post hoc test was used with the ripening treatment as a systematic effect and the assessor as a random effect at a significance level of $p = 0.05$.

Statistical procedures for texture were performed in SPSS [45]. One-way ANOVA and general linear model (GLM) were used to study the significance of textural changes in cheeses subjected to three different ripening treatments during 60 days of ripening. Pairwise comparisons of mean values were performed using the least significant difference (LSD) test. The relationship between the variables was analyzed using Pearson's correlation coefficient.

3. Results and Discussion

Sensory Properties of Air- and Oil-Ripened Semi-Hard Goat Cheese

Figure 3 shows the appearance and cross-section of the semi-hard goat cheese after 60 days of ripening and Figures 4–8 show the mean scores for the attributes of appearance, odor, texture, taste, and aroma of each ripening treatment. Table 1 summarizes all 27 sensory attributes and their reference standards.

Figure 3. Appearance and cross-section of semi-hard goat cheese. From left to right: Group 1 (control group) = cheese ripened in air (60 days); group 2 = cheese ripened in oil for 50 days after 10 days of ripening in air; group 3 = cheese ripened in oil for 40 days after 20 days of ripening in air.

Table 1. Definitions and references of the descriptive terms for semi-hard goat cheese.

Attribute	Descriptor	Low—0 (Not Detected/Like)	High—9 (Very Intensive/Like)
Appearance	External—color intensity	Cottage cheese	Cheddar
	External—overall likeability	0	9
	Cross-section—rind thickness	<5 mm	>5 mm
	Cross-section—color intensity	Cottage cheese	Cheddar
	Cross-section—overall likeability	0	9
Odor	Sour	0	Fermented milk
	Rancid	0	Unpleasant
	Goat-like	0	Goat
	Oily	0	Oil
	Off-odors	0	Barn, basement etc.
	Overall likeability	0	9
Texture	Elasticity determined by fingers	Parmesan	Mozzarella
	Stickiness determined by fingers	0	Cheddar
	Solubility in mouth	Parmesan	Mozzarella
	Crumbliness in mouth	Mozzarella	Parmesan
	Overall likeability	0	9
Taste	Saltiness	Mozzarella	Feta
	Sour	0	Fermented milk
	Bitter	0	Arugula
	Overall likeability	0	9
Aroma	Buttery	0	Butter
	Goat-like	0	Goat
	Oily	0	Oil
	Fruity	0	Nuts, fruits
	Rancid	0	Overripen blue cheese
	Off-flavor	0	Barn, basement etc.
	Persistence	Mozzarella	Parmesan

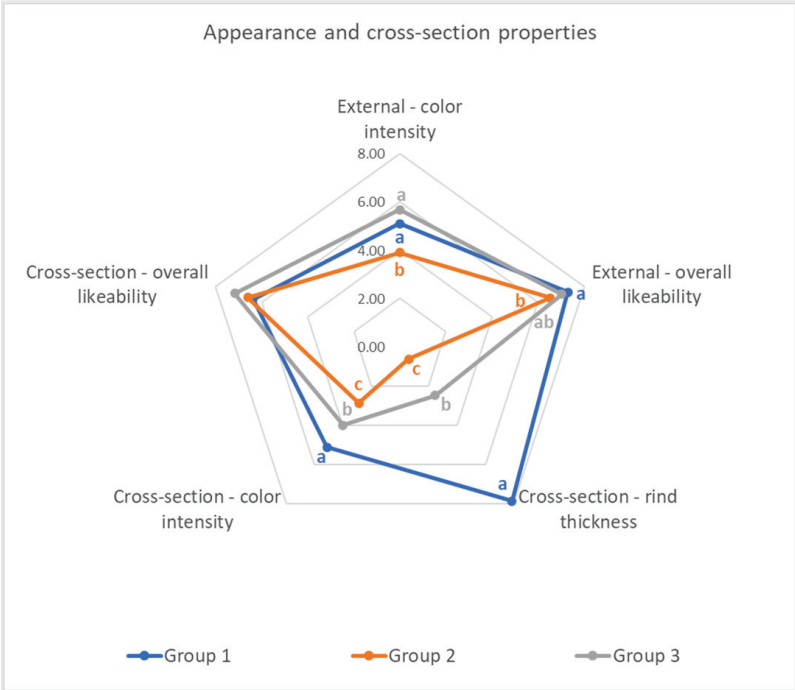

Figure 4. Descriptive sensory scores of appearance and cross-sectional properties of semi-hard goat cheese. Group 1 (control group) = cheese ripened in air (60 days); group 2 = cheese ripened in oil for 50 days after 10 days of ripening in air; group 3 = cheese ripened in oil for 40 days after 20 days of ripening in air. Different letters referring to the same attribute imply significant difference ($p < 0.05$) between ripening treatments.

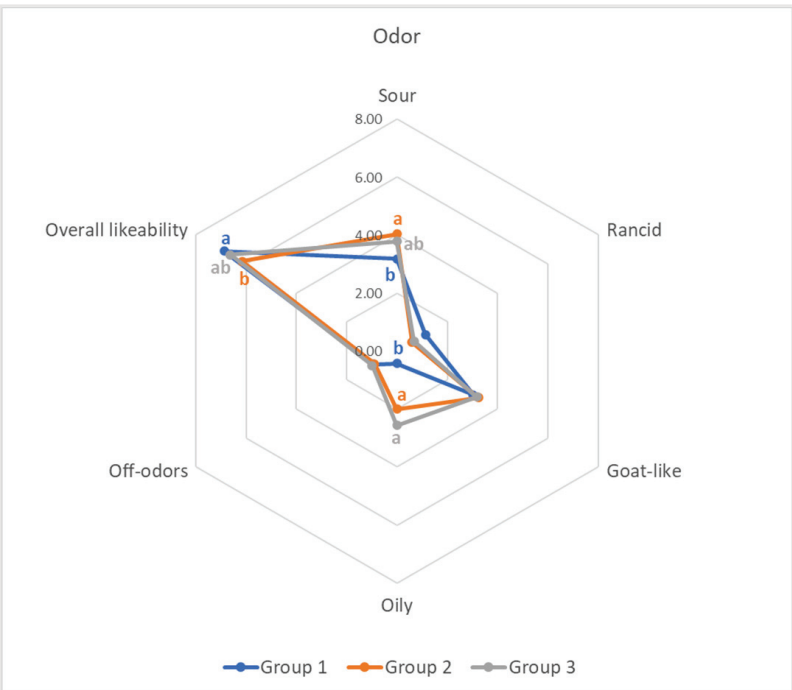

Figure 5. Descriptive sensory scores of the odor of semi-hard goat cheese. Group 1 (control group) = cheese ripened in air (60 days); group 2 = cheese ripened in oil for 50 days after 10 days of ripening in air; group 3 = cheese ripened in oil for 40 days after 20 days of ripening in air. Different letters referring to the same attribute imply significant difference ($p < 0.05$) between ripening treatments.

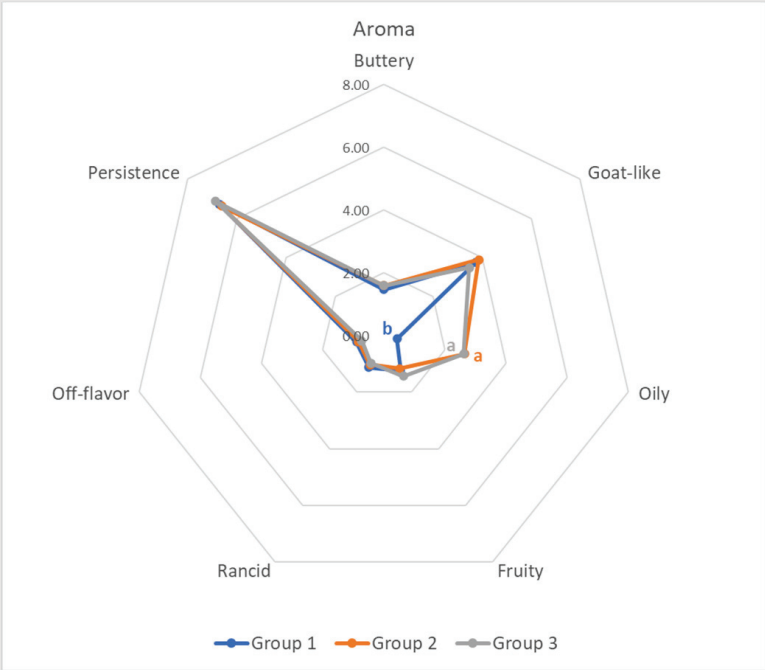

Figure 6. Descriptive sensory scores of the aroma of semi-hard goat cheese. Group 1 (control group) = cheese ripened in air (60 days); group 2 = cheese ripened in oil for 50 days after 10 days of ripening in air; group 3 = cheese ripened in oil for 40 days after 20 days of ripening in air. Different letters referring to the same attribute imply significant difference ($p < 0.05$) between ripening treatments.

Figure 7. Descriptive sensory scores of the taste of semi-hard goat cheese. Group 1 (control group) = cheese ripened in air (60 days); group 2 = cheese ripened in oil for 50 days after 10 days of ripening in air; group 3 = cheese ripened in oil for 40 days after 20 days of ripening in air. Different letters referring to the same attribute imply significant difference ($p < 0.05$) between ripening treatments.

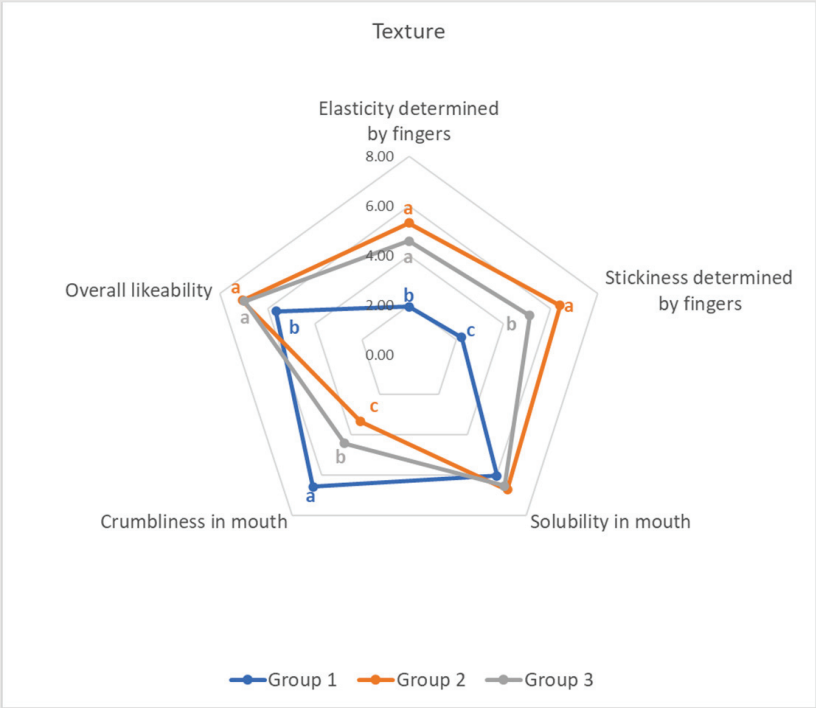

Figure 8. Descriptive sensory scores of the texture of semi-hard goat cheese. Group 1 (control group) = cheese ripened in air (60 days); group 2 = cheese ripened in oil for 50 days after 10 days of ripening in air; group 3 = cheese ripened in oil for 40 days after 20 days of ripening in air. Different letters referring to the same attribute imply significant difference ($p < 0.05$) between ripening treatments.

The longer ripening in oil (group 2) had a negative effect on the overall likeability of the external appearance, as the color intensity of the rind was significantly ($p < 0.05$) lower compared to the cheeses of groups 1 and 3, which can also be seen in Figure 3. This is in accordance with the scores for color intensity in the cross-section and thickness of the rind, which were significantly lower ($p < 0.05$) compared to the cheeses of groups 1 and 3 (Figure 4). Also, this is clearly visible in Figure 3, which shows that the cheeses of group 2 had the lowest color intensity and rind thickness. In addition, the air-ripened cheeses had the highest color intensity in cross-section and rind thickness, which may be due to the fact that these cheeses had the lowest moisture content compared to the cheeses ripened in oil after 10 or 20 days of ripening in the air [23], and it is well known that greatest moisture loss occurs at the beginning of ripening [23,46,47]. In the study of traditional Serbian goat cheese, the most pronounced changes in cheese color (yellowing) occurred after 14 days of ripening, which was due to moisture loss, the microbiological activity of non-starter lactic acid culture, and complex biochemical processes (proteolysis, lipolysis, and oxidation processes) [48]. The results for the color parameters (yellowness) in the study of *Serrana* goat cheese, which was subjected to a particularly long ripening period, were explained by a slight browning effect typical of cheese ripening [49].

Cheese ripened in oil (groups 2 and 3) had a significantly ($p < 0.05$) higher intensity of an oily odor (Figure 5), which was also manifested in the significantly ($p < 0.05$) higher oily aroma attribute (Figure 6). Although the duration of ripening in oil was different, no significant differences ($p > 0.05$) were found in the oily aroma and odor attributes between the cheeses of groups 2 and 3. The values for the off-flavor, off-odor, and rancid odor and aroma attributes were not higher in groups 2 and 3 than in the control group, but the overall odor likeability score (6.17) was lowest for the cheeses in group 2 which is consistent with the results of our previous research. Cheeses from group 2 had the lowest odor score (1.65), compared to the cheeses from group 1 and group 3 (1.88 and 1.79, respectively) [23]. This can be explained by the longer ripening in oil, which resulted in the most pronounced sour odor ($p < 0.05$). In products where the moisture content is not balanced, various defects can

be observed, including excessive sourness [25]. The goat-like odor and aroma, associated with higher levels of short-chain free fatty acids in goat's milk [50], were not affected by the ripening treatment.

Compared to the cheeses ripened in oil, the cheeses in the control group were saltier due to greater moisture loss during ripening (Figure 7). Moisture loss during ripening is a result of microbiological growth, production of lactic acid, and evaporation of water from the cheese [17,24]. A great loss of water is observed, especially in small-sized cheeses, because the surface exposed to the atmosphere is greater, so that the evaporation of water causes the rind to dry out and the water diffuses from the core, leading to the drying of the cheese [26,51,52]. Oil as a ripening medium probably affected biochemical processes in the cheese [23], which improved the overall likeability of the taste (Figure 7). Group 3 had the highest score, which may be related to the greater penetration of the oil into the cheese structure due to the greater water loss caused by the longer ripening time in air before immersion in the oil [23]. This indicates the importance of defining the optimal ripening time in some medium which is also the case for the ripening in the animal skin. A study of Croatian traditional cheese which ripens in a lamb skin ("Sir iz mišine") showed that the optimal ripening time is 45 days, because the intense proteolysis, accumulation of nitrogen fractions, degradation of short-chain fatty acids and accumulation of medium- and long-chain free fatty acids due to the ripening time and specific conditions (high temperatures in the cheese ripening chamber: 16–18 °C; contact material: lambskin) lower sensory scores at longer ripening [8]. Another study showed that the sensory scores of Turkish Tulum cheese started to decrease after 60 days of ripening [53].

The oil-ripened cheeses (groups 2 and 3) were significantly ($p < 0.05$) less crumbly in the mouth than the control group (Figure 8). Table 2 shows that the cheeses of group 1 had significantly ($p < 0.05$) the highest values of load at break parameter. This group had the highest dry matter content [23]. It is known that higher dry matter content can result in protein dehydration and thus a firmer cheese matrix [47]. Comparing the values of load at break between groups 2 and 3, the cheeses of group 3 had significantly ($p < 0.05$) higher values (4.43 and 3.33, respectively), which is in agreement with the scores for crumbliness in the mouth (Figure 8) and can be explained by the fact that a higher moisture content leads to a less firm cheese structure, which was also demonstrated in a study on traditional Majorero goat cheese [47]. Statistical analysis also showed that the sensory perception of crumbliness, the ease with which the cheese breaks down into small particles [54] in mouth, correlated significantly ($p < 0.01$ for cheeses in groups 1 and 2; $p < 0.05$ for cheeses in group 3) with the load at break measured with the texture analyzer (Table 3).

Table 2. Texture parameters of semi-hard goat cheese after 60 days of ripening measured with a texture analyzer.

Parameter	Group			Significance Level
	1	2	3	
Load at break (N)	$45.50^{a} \pm 2.22$	$20.99^{b} \pm 2.20$	$32.50^{c} \pm 2.21$	**
Adhesion force (N)	$-0.31^{a} \pm 0.07$	$-0.86^{b} \pm 0.06$	$-0.54^{ab} \pm 0.07$	*
Elasticity (mm)	$6.94^{a} \pm 0.26$	$9.15^{b} \pm 0.25$	$7.76^{a} \pm 0.26$	**

Group 1 (control group) = cheese ripened in air (60 days); group 2 = cheese ripened in oil for 50 days after 10 days of ripening in air; group 3 = cheese ripened in oil for 40 days after 20 days of ripening in air. Results are expressed as mean ± standard error. a–c means within a row marked with different letter in superscript differ significantly (* $p < 0.05$, ** $p < 0.01$).

The stickiness determined by fingers was also significantly ($p < 0.05$) higher in the oil-ripened cheeses (groups 2 and 3) than in the control group cheeses due to their higher moisture content [23,54]. The cheeses of group 2 obtained significantly ($p < 0.05$) higher scores for stickiness (6.40) determined by fingers than group 3 cheeses (5.10), which agrees with the results for adhesion force measured with the texture analyzer. For the group 3

cheeses, there was a significant positive correlation ($p < 0.05$) between the adhesion force and the stickiness determined by fingers (Table 3).

Table 3. Correlation coefficients between the descriptive sensory scores of texture and the results of the texture analyzer.

	Load at Break	**Crumbliness in Mouth**		
		Group 1	**Group 2**	**Group 3**
Texture analyzer	Group 1	0.801 **	-	-
	Group 2	-	0.613 **	-
	Group 3	-	-	0.513 *
	Adhesion force	**Stickiness Determined by Fingers**		
		Group 1	**Group 2**	**Group 3**
	Group 1	0.405	-	-
	Group 2	-	0.143	-
	Group 3	-	-	0.504 *
	Elasticity	**Elasticity Determined by Fingers**		
		Group 1	**Group 2**	**Group 3**
	Group 1	0.638 **	-	-
	Group 2	-	0.612 **	-
	Group 3	-	-	0.509 *

Group 1 (control group) = cheese ripened in air (60 days); group 2 = cheese ripened in oil for 50 days after 10 days of ripening in air; group 3 = cheese ripened in oil for 40 days after 20 days of ripening in air. Values marked with asterisk have statistically significant correlation (* $p < 0.05$ and ** $p < 0.01$).

The elasticity determined by fingers was significantly ($p < 0.05$) higher in the oil-ripened cheeses (groups 2 and 3) than in the control group cheeses. Group 2 cheeses had the highest elasticity to a significant extent ($p < 0.01$). Significant correlations ($p < 0.01$ for cheeses of groups 1 and 2; $p < 0.05$ for cheeses of group 3) between elasticity determined by fingers and elasticity measured by the texture analyzer were observed in all treatments (Table 3).

The cheeses of groups 2 and 3 had better scores for the overall texture likeability than the cheeses of the control group. There was no significant difference between the cheeses of groups 2 and 3 for the same parameter. These results are consistent with the results of sensory analysis according to ISO methods in our previous study [23].

In rheology, cheeses are classified according to their moisture content in the non-fat substance, which shows the great influence of moisture content on the textural properties of cheese [47,55]. According to the literature, cheese with a higher moisture content is less firm than cheese with a lower moisture content [54,56], which is attributed to the extent of swelling of casein submicelles with the increase in the casein to moisture ratio. In addition, moisture fills the spaces between fat and protein in the cheese structure and acts as a good lubricant due to its low viscosity. The amount of fat trapped in the paracasein matrix and its physical state have a great influence on the textural properties of cheese [54].

The loss of moisture during ripening in air (groups 2 and 3) before ripening in oil led to the formation of a cheese structure that allowed the penetration of oil into the cheese [23]. Water retention and the penetration of oil into the cheese changed the physicochemical composition of the semi-hard goat cheese, thus affecting its textural properties. Oil as a ripening medium showed moisture-protective properties in the cheese and therefore influenced the cheese texture and sensory profile [23].

4. Conclusions

It can be concluded that preserving goat cheese in oil has a positive effect on its sensory properties. Ripening in oil reduced the thickness of the rind and generally improved the

taste, texture, and cross-sectional properties of the cheese. Cheese with a longer ripening time in air before immersion in oil was characterized by a higher level of acceptance in terms of appearance, cross-section, odor, and taste than cheese with a shorter ripening time in air before immersion in oil. Ripening in oil prevented undesirable texture and dryness in the cheese, which not only extends the consumption period when goat milk is not produced but may also prevent excessive food waste. Furthermore, since the correlations between the descriptive sensory scores of texture and the results of the texture analyzer were significant, it can be concluded that the QDA is an excellent tool for the development of cheeses with specific ripening conditions.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the University of Zagreb Faculty of Agriculture on Sensory Analysis of Agri-Food Products (Class No. 114-02/23-03/01; Reg. No. 251-71-29-02/19-23-2).

Informed Consent Statement: All subjects gave their informed consent for inclusion before they participated in the study.

Data Availability Statement: The data are available on request from the corresponding author.

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

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Isotopic Signatures of Nitrogen in Selected Soils from Croatia

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Abstract: The mobility of nitrogen (N) in the environment is conditioned by its cycling between atmospheric, terrestrial, and marine ecosystems. It is a key element for global biogeochemistry, and although isotope analysis has been an integral part of many studies over the past eighty years, the complexity of the nitrogen cycle hinders a correct and detailed understanding of the mechanisms behind its processes. It could be argued that the interpretation of the isotopic signatures of nitrogen in soils is still in its infancy. In Croatia, such research has recently begun and is driven by a need for the comprehensive study of nitrogen isotopes in terrestrial ecosystems. The aim of this study was to compare the abundance of the ^{15}N isotope in soils from continental and coastal parts of Croatia with different types of land use (arable land/crop production, meadows, forests, orchards, ski slopes, urban soil/city roads) and to authenticate the nitrogen origin in soils in relation to different soil management practices. This research was based on 27 soil samples collected at 11 locations in Croatia. The samples differed according to soil type, land use, applied mineral and organic nitrogen fertilization, and climatic condition at each specific location. The determination of $\delta^{15}N_T$ (T—total nitrogen) values in bulk samples was performed in duplicate with the IRMS (Isotope Ratio Mass Spectrometry) method using an IsoPrime100-Vario PYRO Cube (OH/CHN Pyrolyser/Elemental Analyzer). The results reveal that the mean $\delta^{15}N$ abundance in soils according to different land use declines in the following order: crop production (+5.66 ± 1.06‰) > apple orchard (+5.60 ± 0.10‰) > city road (+4.33 ± 0.38‰) > meadow (+3.71 ± 0.85‰) > ski slope (+2.20 ± 0.10‰) > forest (+2.15 ± 1.86‰). The individual values were in the range from 0.00 ± 0.10‰ in the forest soil in continental Croatia to +7.19 ± 0.07‰ in the vegetable garden (crop production) soil in coastal Croatia. Among the investigated soil properties and weather conditions, PCA analysis identified close correlations between P_2O_5 content and $\delta 1^{15}N$ abundance in arable soils, as well as between soil reaction (pH) and mean annual temperatures, while high C/N ratio values explained the isotopic distribution in non-arable soils (city roads and forests). Despite the long-term application of mineral nitrogen fertilizers, the results represent nitrogen of organic origin in the arable soils (crop production), which partly confirms the sustainable management of those agroecosystems.

Keywords: ^{15}N; nitrogen origin; arable land; mineral nitrogen fertilization; meadow; forest; orchard; ski slope; urban soil

1. Introduction

The use of stable isotopes to understand the biochemical cycle of carbon (C), nitrogen (N), sulfur (S), oxygen (O), and hydrogen (H) in the environment [1–6], along with their applications in food origin and quality assessment [7], forensics [8], drug metabolism [9], athlete doping testing [10], and archaeology and anthropology [11], has been developed over eight decades. Their use started with the development of mass spectrometry after

World War II [12] with the design of the mass spectrometer (gas inlet, ion source, tube, magnet, ion collectors, mercury diffusion pump) and isotope analysis routines by Alfred Nier in 1947 [13]. Today's mass spectrometers are designed for isotope ratio measurements (IRMS method—Isotope Ratio Mass Spectrometry) and use dedicated static magnetic sector fields and multicollection with discrete Faraday cups for the simultaneous quantification of all ion beams with precision in the determination of isotopes in the sub-ppm range [14]. The IRMS analysis determines the stable isotope concentrations in the analyzed sample, which are expressed as the molar ratio of the heavy and light isotope. Due to the fact that the quantified ratio is low, stable isotope abundances are presented relative to an international standard using the following δ notation:

$$\delta X = (R_{sample}/R_{standard} - 1) \times 1000 \quad (1)$$

where δX is the delta value of the sample for element X (N, S, H, O, C, etc.) in parts per thousand (‰) and R is the molar ratio of the heavy (less common) to light (more common) isotope in the sample and in an international standard, respectively [15]. Considering that nitrogen is found in nature as a mixture of two stable isotopes, ^{14}N and ^{15}N, where the isotope ^{14}N comprises 99.64% and isotope ^{15}N 0.36% [16], Equation (1) can be rewritten as

$$\delta^{15}N = (^{15}N/^{14}N_{sample}/^{15}N/^{14}N_{standard} - 1) \times 1000 \quad (2)$$

Atmospheric N_2 represents the reference value of the standard in $\delta^{15}N$ measurements [17] in which the ratio of stable nitrogen isotopes $^{15}N/^{14}N$ (1/272) is 0.0036764 or +3.68‰ [18].

The isotopic signature of nitrogen ($\delta^{15}N$) in terrestrial ecosystems is conditioned by the complexity of the nitrogen cycle, its numerous transformations, and the degrees of isotopic fractionation, along with the mean annual air temperature, annual precipitation, and the content of clay and organic carbon in the soil [19]. $\delta^{15}N$ varies significantly from −20‰ to +30‰ in most terrestrial materials and from −49‰ to +102‰ in natural materials of terrestrial ecosystems [20]. Fifty-nine years ago, in 1964, the first isotopic abundances of nitrogen in USA soils were reported, and $\delta^{15}N$ varied from +1‰ to +10‰ in cultivated soils and from +2‰ to 16‰ in natural soils [21] (Cheng et al., 1964). Recent studies have confirmed very similar ranges of isotopic nitrogen in the soils of the world, from −0.3‰ in forest soils in Germany to 3.59‰ in woodlands in Congo, and up to +9.48‰ in arable soils in Australia [22–24]. The interpretation of soil $\delta^{15}N$ values is very challenging, not only due to the complexity of the nitrogen cycle, but also because of many other factors that influence the nitrogen content in soil. For example, mineralization/ammonification in soil influences the results, with isotopic fractionation abundance ranging from 0‰ to 5‰. Values also vary from 30‰ to 60‰ due to ammonia volatilization, from 15‰ to 35‰ due to nitrification, and from 28‰ to 33‰ due to denitrification, while N_2 fixation depletes soil $\delta^{15}N$ values due to the fact that atmospheric nitrogen has an isotopic value of 0‰ [25,26]. Also, during nitrogen fixation, soil bacteria convert nitrogen into ammonium, a process that itself does not induce a large isotopic fractionation but could lead to a shift from 0‰ to 2‰ [14]. The depletion of the nitrogen isotopic signature in soils can result from the application of mineral nitrogen fertilizers with isotopic values from −4.0‰ to +3.9‰ [27–29], while organic fertilizers (sewage sludge and animal manure) tend to have $\delta^{15}N$ values between +8‰ and +20‰ [14], which can contribute to the enrichment of soil $\delta^{15}N$. Considering all of the above and the fact that $\delta^{15}N$ of organic nitrogen in the soil ranges from +4.0‰ to +9.0‰ [30], the interpretation of the isotopic signatures of nitrogen in soil could be simplified as 0‰ to 2‰—atmospheric, 2‰ to 4‰—mineral, >4‰—organic origin.

Recently, many studies have focused on $\delta^{15}N$ abundance in the optimization of nitrogen fertilizer use [31–33]. Using fertilizers labelled with ^{15}N isotope made it possible to determine crop use efficiency and the optimal application of fertilizer, which will greatly enhance the sustainability of the agroecosystem. However, even without the use of labeled ^{15}N tracking, knowledge of natural $\delta^{15}N$ abundance in soil can even demystify the

negative impact of mineral nitrogen fertilization and provide an insight into the path of nitrogen in soil. This can, in particular, refer to organic N recorded in arable land which is readily available to plants, and can also contribute to the sustainable management of the agroecosystem and to a reduction in fertilizer consumption.

The aim of this study was to compare the abundance of ^{15}N isotopes of soils from continental and coastal parts of Croatia with different types of land use (arable land/crop production, meadows, forests, orchards, ski slopes, urban soil/city roads) and to authenticate the nitrogen origin in the soil regarding the different soil management types.

2. Materials and Methods

2.1. Site Descriptions and Soil Samples

In order to achieve our research goals, we first looked at the utility of soil nitrogen isotopes quantified in selected soils from Croatia and selected 27 soil samples—which had already been the focus of previous research—from the soil archive of the Department of General Agronomy, University of Zagreb Faculty of Agriculture, and enabled the initial database of $\delta^{15}N$ abundance in Croatian soils. The selected soil samples, along with the chosen locations, covered all Croatian agricultural regions. The investigation even included composite soil samples from the only Croatian ski resort where world cup races (FIS Giant slalom) are held. This research included the analysis of soil samples collected—during the period of 2005–2020 as part of scientific research conducted by the employees of the Department of General Agronomy—from 11 locations (L1–L11) in Croatia (Figure 1, obtained via ArcGIS [34] based on the known coordinates of each location).

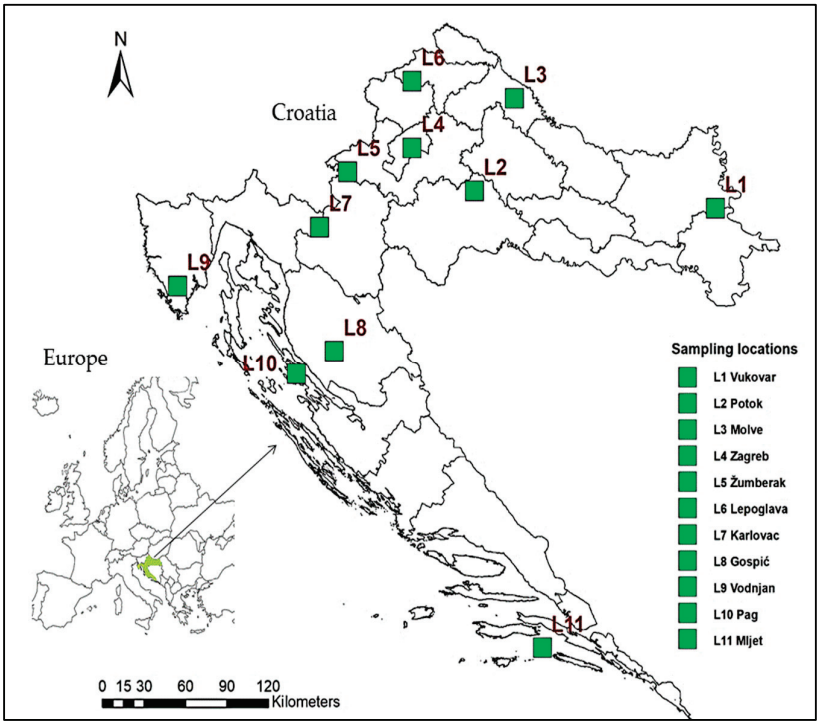

Figure 1. Geographic position of the 11 sampling locations (L1–L11).

The samples were collected at six locations in the Pannonian agricultural region: three soil samples from Vukovar (eastern Pannonian agricultural subregion, L1); three from Potok; five from Molve; five from the area of the city of Zagreb, including the nearby Medvednica Nature Park; one from Zumberak–Samoborsko gorje Nature Park (western Pannonian agricultural subregion, L2, L3, L4, L5); and two from Lepoglava (northwestern Pannonian agricultural subregion, L6). Five samples were taken from two locations in mountainous agricultural regions: two samples from Karlovac (L7) and three samples from Gospic (L8). From the Adriatic agricultural region, three soil samples were selected: one

sample from Vodnjan and one sample from the island of Pag (northern Adriatic agricultural subregion, L9 and L10), along with one soil sample from the island of Mljet (southern Adriatic agricultural subregion, L11) (Figure 1).

Continental Croatia (such as L1, L2, L3, L4, and L6) has temperate continental conditions (Cfwbx" climate) which are modified by the maritime influence of the Mediterranean. Mountainous districts with a higher altitude (L5, L7, L8) have a mountain climate (Cfcbx" climate), while on islands and in coastal areas (L9, L10, L11), an olive climate (Csa) is prevalent [35]. In terms of weather conditions, it is noticeable that, in a twenty-year period among the selected locations, the lowest mean annual temperature (MAT) of 9.3 °C occurred in the peak area of Zumberak, while the highest MAT (17.2 °C) was recorded at the southernmost point of the island of Mljet (L11). Precipitation in Croatia is the consequence of passing cyclones and related atmospheric fronts, and the annual amount of precipitation in continental Croatia decreases from west to east, because the moist air masses from the west lose their humidity on their way eastward [35]. This causes the lowest amount of precipitation (685.8 mm) to occur at the easternmost research location, Vukovar, location L1 (Table 1).

Table 1. Weather conditions at selected locations—averages from 2000 to 2020.

Location		MAT, °C	MAP, mm
L1	Vukovar	12.0	685.8
L2	Potok	12.2	954.7
L3	Molve	11.3	815.3
L4	Zagreb	12.2	867.3
L5	Zumberak	9.3	1229.8
L6	Lepoglava	11.4	891.4
L7	Karlovac	11.5	1135.5
L8	Gospic	10.1	1379.5
L9	Vodnjan	15.2	874.3
L10	Pag	16.2	1111.9
L11	Mljet	17.2	875.9

MAT—mean annual temperature; MAP—mean annual precipitation.

Soil samples differed according to soil type, land use, and mineral nitrogen fertilization (Table 2). All samples were collected from the surface soil layer (up 0.3 m depth). Out of 27 selected soil samples, 11 soil samples were collected from areas with intensive crop production as part of field experiments (L1, L2, L6, and L8). Samples from Vukovar are related to the five-year research on the temporal impact of nitrogen application (150 and 180 kg/ha) on corn yield and the spatial distribution of mineral nitrogen in the soil. The samples from Potok, Lepoglava, and Gospic represent soil conditions after the three-to-seven-year experiments of different liming materials and mineral nitrogen fertilizers (105, 150, 180, 200 k N/ha) on the yield of crops and soil chemical properties. From these four locations, soil samples were also selected from unfertilized plots (0 kg N/ha; CP_N0_L1, CP_N0_L2, CP_N0_L6, CP_N0_L8) in order to confirm the impact of the omission of nitrogen fertilization on the nitrogen isotopic signature. Also, one sample from Gospic was from a plot with solid manure applied at 30 t/ha (CP_SM_L8) (Table 2).

Five soil samples from Molve are related to the long-term monitoring of the environment of Molve central gas station. The sample from location L5 (AO_L5) represents soil from an apple orchard located in Nature Park Zumberak–Samoborsko gorje, and it was part of a study on the influence of different land use in the park on the soil chemical properties and flora distribution. Two soil samples from the Zagreb—M location represent the average soil samples from Nature Park Medvednica collected along the Red Slope at the Sljeme ski resort (SS_L4) and the surrounding forest (F_L4), while three soil samples (CR1-L4, CR2-L4, CR3-L4) from the Zagreb—C location represent soil in the vicinity of city roads. The sample from Pag (F_L10) represents soil from the only deciduous forest on the island of Pag (a mixed forest of pubescent oak *Quercus pubescens* Willd. (Fagales: Fagaceae)

and hop hornbeam *Ostrya carpinifolia* Scop. (Fagales: Betulaceae)), while the soil sample from the island of Mljet (F_L11) is from a forest located in the targeted protection zone of Mljet National Park. Sample CP_N150VC_L9 represents soil from a vegetable garden where tomato was grown with the addition of mineral fertilization (150 kg N/ha) and vermicompost. The samples from Karlovac (M1_L7 and M2_L7) represent *Holcus lanatus* meadows invaded by bracken (Table 2).

Table 2. Site and soil sample descriptions.

Location		Sampling Year	Soil Type *	Land Use	Nitrogen Fertilization **	Sample ID
L1	Vukovar	2016	Calcic Chernozem	Crop production	0	CP_N0_L1
		2016			180	CP_N180_L1
		2015			150	CP_N150_L1
L2	Potok	2016	Dystric Stagnosol	Crop production	0	CP_N0_L2
		2016			150	CP_N150_L2
		2020			180	CP_N180_L2
L3	Molve	2019	Dystric Regosol	Crop production	Unknown	CP1_L3
		2019	Gleyic Stagnosol	Meadow	-	M1_L3
		2019	Stagnic Gleysol	Meadow	-	M2_L3
		2019	Vertisol	Meadow	-	M3_L3
		2019	Dystric Anthrosol	Crop production	Unknown	CP2_L3
L4	Zagreb—C	2019	Humic Leptosols	City road	-	CR1_L4
		2019		City road	-	CR2_L4
		2019		City road	-	CR3_L4
	Zagreb—M	2015	Dystric Cambisol	Forest	-	F_L4
		2015		Ski slope	-	SS_L4
L5	Zumberak	2016	Regi-hortic Anthrosols	Apple orchard	Unknown	AO_L5
L6	Lepoglava	2009	Dystric Cambisol	Crop production	0	CP_N0_L6
		2009			200	CP_N200_L6
L7	Karlovac	2020	Dystric Cambisol	Meadow	-	M1_L7
		2020			-	M2_L7
L8	Gospic	2005	Dystric Cambisol	Crop production	0	CP_N0_L8
		2005			105	CP_N105_L8
		2005			SM 30 ***	CP_SM_L8
L9	Vodnjan	2020	Rhodic Lixisol	Crop production	150 + VC	CP_N150VC_L9
L10	Pag	2015	Rendzic Leptosols	Forest	-	F_L10
L11	Mljet	2016	Humic Leptosols	Forest	-	F_L11

* Soils according to [36]; Zagreb—C: city; Zagreb—M: Medvednica Nature Park; VC—vermicompost. ** Nitrogen fertilization: mineral fertilization in kg ha^{-1}; *** SM 30—solid manure 30 t/ha.

Some basic soil properties have been described in previous studies (Table 3). The pH was detected using the potentiometric method (w/v 1:2.5; 1 mol L^{-1} KCl) [37]; total nitrogen (TN) and total carbon (TC) were detected using the dray combustion method [38,39]; and plant-available phosphorus and potassium were extracted using an ammonium lactate (AL) solution [40] and detected via spectrophotometry and flame spectrometry, respectively. Due to different soil types, the soil reaction (pH) varied from 3.76 in Dystric Cambisol at the L8 location up to 7.70 in Humic Leptosols at the L4 location. Nitrogen supply was between moderate (0.077%) and very rich (0.692%), and on average, soils contained 137.7 mg P_2O_5 kg^{-1} and 234.7 mg K_2O kg^{-1}.

Table 3. Soil chemical properties.

Location		Sample ID	pH_{KCl}	TN, %	TC, %	CN Ratio	P_2O_5, mg kg^{-1}	K_2O, mg kg^{-1}
L1	Vukovar	CP_N0_L1	6.95	0.451	1.86	4.1	143.0	190.0
		CP_N180_L1	6.75	0.505	1.80	3.6	284.0	238.0
		CP_N150_L1	7.28	0.141	1.66	11.8	214.0	265.0
L2	Potok	CP_N0_L2	4.04	0.191	1.01	5.3	203.0	273.0
		CP_N150_L2	3.82	0.211	0.99	4.7	188.0	280.0
		CP_N180_L2	4.53	0.238	1.18	4.9	11.0	188.0
L3	Molve	CP1_L3	4.80	0.692	7.22	10.4	16.0	218.0
		M1_L3	4.70	0.347	4.02	11.6	55.0	200.0
		M2_L3	4.76	0.531	5.46	10.3	40.0	204.0
		M3_L3	4.83	0.983	10.6	10.7	22.0	240.0
		CP2_L3	7.45	0.077	1.23	16.0	262.0	361.0
L4	Zagreb—C	CR1_L4	7.57	0.323	6.35	19.6	113.0	160.0
		CR2_L4	7.43	0.283	4.25	15.0	410.0	207.0
		CR3_L4	7.70	0.233	7.45	31.9	87.0	185.0
	Zagreb—M	F_L4	5.16	0.449	6.32	14.1	44.0	421.0
		SS_L4	7.07	0.228	4.56	20.0	135.0	289.0
L5	Zumberak	AO_L5	5.48	0.261	2.31	8.9	113.0	160.0
L6	Lepoglava	CP_N0_L6	5.58	0.137	1.38	10.1	602.0	207.0
		CP_N200_L6	5.52	0.139	1.43	10.3	87.0	185.0
L7	Karlovac	M1_L7	4.05	0.330	5.29	16.0	16.0	218.0
		M2_L7	4.25	0.242	2.74	11.3	55.0	200.0
L8	Gospic	CP_N0_L8	3.98	0.316	2.57	8.1	40.0	204.0
		CP_N105_L8	3.76	0.393	3.14	8.0	22.0	240.0
		CP_SM_L8	4.15	0.446	2.93	6.6	262.0	361.0
L9	Vodnjan	CP_N150VC_L9	7.43	0.167	3.22	19.3	73.0	243.0
L10	Pag	F_L10	7.28	0.286	6.64	23.2	106.0	209.0
L11	Mljet	F_L11	7.05	0.343	6.23	18.2	116.0	192.0

2.2. Sample Analysis

The selected archived soil samples were already air dried, homogenized, and sieved (<2 mm), so no additional sample preparation was performed. $\delta^{15}N_T$ (T—total nitrogen) measurements in prepared soil samples were performed in 2021 at the Department of Environmental Science, by the Group of Organic Biogeochemistry at Jožef Stefan Institute at Reaktorski centar in Ljubljana. The determination of $\delta^{15}N$ values in bulk samples was performed with the IsoPrime100-Vario PYRO Cube (OH/CHN Pyrolyser/Elemental Analyzer) (IsoPrime, Cheadle, Hulme, UK). Analyses were carried out automatically, where 30 mg of the soil sample was transferred directly into tin capsules, closed with tweezers, and put into an automatic sampler. Analyses were performed in duplicate. The results were normalized against the following international reference materials: USGS61 and USGS65, with $\delta^{15}N = -2.87 \pm 0.04$‰ and $\delta^{15}N = +20.68 \pm 0.06$‰, respectively. They were then calculated according to Equation (2). For independent quality control, international reference materials USGS64 with $\delta^{15}N = +1.76 \pm 0.06$‰ and IAEN-N-1 with $\delta^{15}N = +0.43 \pm 0.07$‰ were used, and the reproducibility of measurements was ±0.02‰.

2.3. Statistical Analysis

The obtained data of $\delta^{15}N$ abundance in soil samples were processed at the level of descriptive statistics (the mean of $\delta^{15}N$ for each selected soil sample and standard deviation), along with calculations of $\delta^{15}N$ means and standard deviations according to different land use (crop production, apple orchards, forests, meadows, city roads, and ski

slopes). Principal component analysis (PCA) was employed to examine important variables in a soil dataset and the relationship between the selected soil variables regarding land use and applied fertilization. Clusters of observations with similar characteristics with respect to measured soil variables and weather conditions ($\delta^{15}N$, pH, TN, TC, C/N, P_2O_5, K_2O, MAT, MAP) were identified [41]. Figures were obtained via Plotly [42]. All the data in the tables and graphs are presented in their original state.

3. Results

The mean $\delta^{15}N$ abundance in soils according to different land use decreases in the following order: crop production (+5.66 ± 1.06‰) > apple orchards (+5.60 ± 0.10‰) > city roads (+4.33 ± 0.38‰) > meadows (+3.71 ± 0.85‰) > ski slopes (+2.20 ± 0.10‰) > forests (+2.15 ± 1.86‰) (Figure 2). According to datasets from Table 3, the mean total nitrogen content observed in the soils decreases in following order: meadows (0.487 ± 0.29%) > forests (0.359 ± 0.08%) > crop production (0.293 ± 0.18%) > city roads (0.280 ± 0.05%) > apple orchards (0.261 ± 0.04%) > ski slopes (0.228 ± 0.06%), the while total carbon decreases in the following order: forests (6.10 ± 0.22%) > city roads (6.02 ± 1.63%) > meadows (5.61 ± 2.97%) > ski slopes (4.56 ± 0.19%) > apple orchards (2.31 ± 0.38%) > crop production (2.26 ± 1.63%). Due to the fact that only one sample was selected from an orchard and one from a ski slope, the mean values represent the results of duplicate measurements for those land uses. Comparatively, the lowest mean δ15N abundance in forest soils (+2.15 ± 1.86‰) is associated with the highest mean amount of total carbon (6.10 ± 0.22%) and a very rich nitrogen supply (0.359 ± 0.08%).

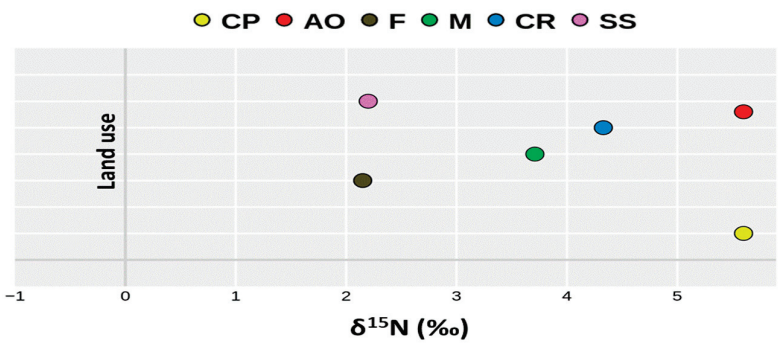

Figure 2. Mean nitrogen isotopic values ($\delta^{15}N$) according to different land use. CP—crop production; AO—apple orchard; F—forest; M—meadow; CR—city road; SS—ski slope.

$\delta^{15}N$ varied from 0.00 ± 0.10 ‰ in the forest soil at the L4 location to +7.19 ± 0.07‰ in the vegetable garden at the L9 location (Table 4). In arable soil with crop production, the lowest isotopic signature was recorded at the L8 location where 105 kg ha^{-1} of mineral nitrogen was applied, while the highest abundance was recorded at the L9 location where a combination of mineral and organic fertilization was applied. The highest isotopic variation among the locations was recorded for forest land use, where $\delta^{15}N$ ranged from 0.00 ± 0.10‰ at the continental L4 location to 3.24 ± 0.08‰ at the coastal L10 location, and varied by 86.6% according to the calculated coefficient of variation. Meadow soils located in the continental part of Croatia differed in $\delta^{15}N$ abundance by 23.0% (from 2.50 ± 0.10‰ to 4.61 ± 0.06‰), while the lowest variation in nitrogen isotopic signature (CV = 8.74%) was recorded among urban soils in the vicinity of city roads in Zagreb (L4 location).

The relationship between PC1 and PC2 for all investigated locations is shown in Figure 3. The variables with the highest loadings are TC and TN in PC1, which explains 31% of the variance, and K_2O and MAP in PC2, which accounts for 28% of the total variance. TN and TC were inversely related to P_2O_5 and $\delta 1^{15}N$, while the MAT and soil pH were related to K_2O and MAP, respectively. Furthermore, the PCA analysis showed that P_2O_5 and $\delta 1^{15}N$, and pH and MAT, were highly correlated. The high negative values of PC2 for pH, MAT, and C/N demonstrate a distinction between non-agricultural land and crop

production areas. Higher values of $\delta 1^{15}N$ are responsible for organic N origin as well as the P_2O_5 content. High C/N ratio values explain the distribution of non-arable land (city roads and forests). K_2O, to a lesser extent, was responsible for grouping fertilized agricultural soils. High TN and TC values in the PC1 plane indicated fertile meadows (M3_L3) and forest soils (F_L4).

Table 4. Variability of $\delta^{15}N$ abundance in soil according to land use and locations.

	Sample	$\delta^{15}N \pm SD$ (‰)		Sample	$\delta^{15}N \pm SD$ (‰)
Arable land/Crop production	CP_N0_L1	6.22 ± 0.07	Meadow	M1_L3	2.50 ± 0.10
	CP_N180_L1	6.28 ± 0.06		M2_L3	4.00 ± 0.10
	CP_N150_L1	4.99 ± 0.09		M3_L3	3.20 ± 0.10
	CP_N0_L2	6.38 ± 0.04		M1_L7	4.25 ± 0.02
	CP_N150_L2	6.59 ± 0.03		M2_L7	4.61 ± 0.06
	CP_N180_L2	6.15 ± 0.12	Forest	F_L4	0.00 ± 0.10
	CP1_L3	4.00 ± 0.10		F_L10	3.24 ± 0.08
	CP2_L3	6.20 ± 0.10		F_L11	3.22 ± 0.07
	CP_N0_L6	6.24 ± 0.13	City road	CR1_L4	4.60 ± 0.10
	CP_N200_L6	6.11 ± 0.09		CR2_L4	4.50 ± 0.10
	CP_N0_L8	4.57 ± 0.03		CR3_L4	3.90 ± 0.10
	CP_N105_L8	3.81 ± 0.17	Ski slope	SS_L4	2.20 ± 0.10
	CP_SM_L8	4.56 ± 0.10			
	CP_N150VC_L9	7.19 ± 0.07			
Orchard	AO_L5	5.60 ± 0.10			

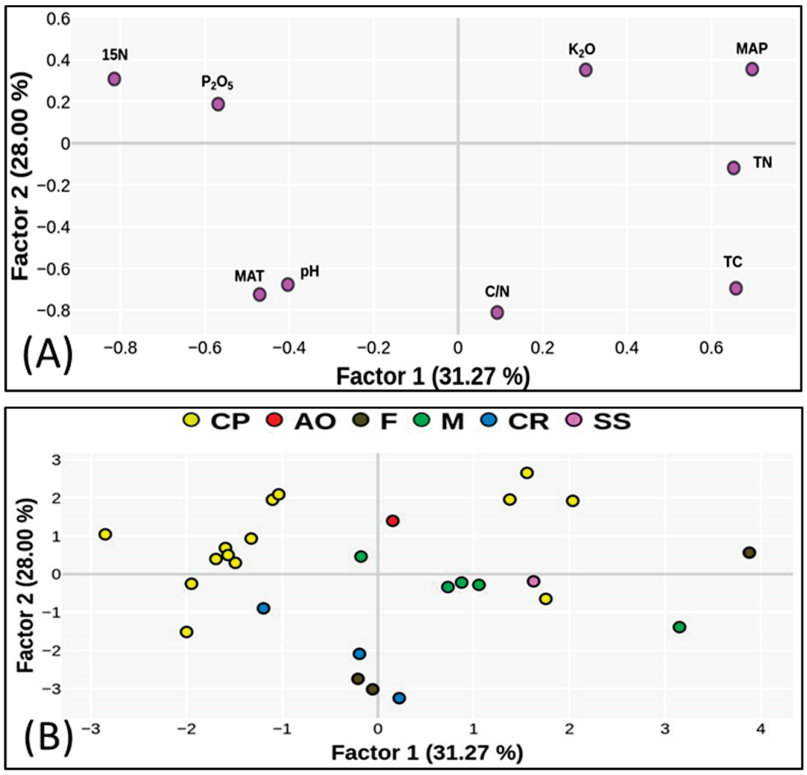

Figure 3. Relationship between factors 1 and 2: (**A**) variables, (**B**) cases. CP—crop production; AO—apple orchard; F—forest; M—meadow; CR—city road; SS—ski slope.

4. Discussion

The recorded value of 0‰ in forests at the L4 location can be associated with atmospheric nitrogen, i.e., with moist deposition or nitrogen fixation. The isotopic composition

of atmospheric molecular nitrogen is homogeneous and $\delta^{15}N$ in the atmosphere is 0‰ [43]. A similar $\delta^{15}N$ abundance (0.7‰ ± 0.1‰ to 0.9‰ ± 0.2‰) in the forest soils of Mediterranean cork oak, holm oak, and randomly mixed Montados was recorded in the Portuguese Alentejo region [44]. Tomatoes (''St. Pierre'' variety) were grown in the vegetable garden at the L9 location, and in addition to basic fertilization with NPK 5-20-30 fertilizer, 100 g of pure solid vermicompost was deposited in the soil next to the root of each plant. The in-season application of vermicompost was also applied as a solution in a ratio of 1:2 (earthworm/water; v/v). The determined value of +7.19‰ indicates that the nitrogen in that soil originated from the vermicompost. This can be confirmed by the fact that the results of the $\delta^{15}N$ analysis of vermicompost were +7.79 ± 0.10‰. According to several authors, the values of isotopic nitrogen in mineral nitrogen fertilizers range from −2.4‰ (urea) to +2.2‰ (NH_4NO_3) [45], and from −1.7‰ (NPK 15-15-15) to +3.9‰ ($Ca(NO_3)_2$ [28], as well as from −0.96‰ (LAN) to +3.26‰ (NPK 7-20-30) [29]. The values of isotopic nitrogen in organic fertilizers range from +3.5‰ to +16.2‰ [45]; therefore, the $\delta^{15}N$ values of the vermicompost (+7.79 ± 0.10‰), as well as the soil sample (+7.19 ± 0.07‰) from the L9 location, were as expected. The results from the tomato garden in this study are in accordance with the results of $\delta^{15}N$ abundance (5.25‰ to 11.02‰) in the soils of Spanish organic and conventional gardens where zucchini, cucumber, tomato, and pepper were grown [46]. The results from that study also reveal that the $\delta^{15}N$ values of applied vermicompost (4.15‰), manure (8.89‰), and compost (15.38‰) resulted in a higher abundance of isotopic composition in the observed soils [46]. Ref. [47] explains that higher values of isotopic nitrogen in organic fertilizers are the result of several processes in the nitrogen cycle (ammonification, immobilization, nitrification, denitrification, NH_3 volatilization, and leaching) that take place across different stages of manure maturation, and which consequently enrich organic manure with the $\delta^{15}N$ isotope. Conversely, ref. [30] explains that the range of lower values of isotopic nitrogen in mineral fertilizers is caused by the fact that they are produced on the basis of the quantitative processes of the "industrial" fixation of atmospheric nitrogen. This results in low isotopic fractionation, which consequently causes mineral nitrogen fertilizers to have $\delta^{15}N$ values close to zero (0‰).

Following the aforementioned values of isotopic nitrogen in organic and mineral fertilizers, it was to be expected that the values of $\delta^{15}N$ in the soil samples collected from stationary field experiments where mineral nitrogen fertilization was applied would be in the range of −2.4‰ up to +3.9‰. It was thought that this would correspond to the isotopic signature of nitrogen from mineral fertilizers; however, this was not the case for the values of isotopic nitrogen in the soil from the L1 location ($\delta^{15}N$ = +4.99 ± 0.09‰ and $\delta^{15}N$ = +6.28 ± 0.06‰) and the L2 location ($\delta^{15}N$ = +6.59 ± 0.03‰ and $\delta^{15}N$ = +6.15 ± 0.012‰), where 150 kg N/ha and 180 kg N/ha were applied, respectively, as well as in the L6 location with 200 kg ha^{-1} of mineral nitrogen ($\delta^{15}N$ = +6.11 ± 0.09‰), indicating the organic origin of the nitrogen in soil. It is necessary to add that the observed soils were fertilized with mineral nitrogen for three to seven years, and a short period of fertilization could partly cause the $\delta^{15}N$ in the soil to not be identical to the $\delta^{15}N$ in mineral nitrogen fertilizers. A similar study was conducted in central Croatia (Dystric Cambisol), and the results indicate that a twenty-two-year nitrogen application of 300 kg ha^{-1} and crop production led to a $\delta^{15}N$ value of 6.80 ± 0.10‰ [29]. But it was expected that $\delta^{15}N$ values in the samples from unfertilized plots at L1, L2, L6, and L8 (CP_N0_L1, CP_N0_L2, CP_N0_L6, CP_N0_L8) would be >4‰, which was confirmed (6.22 ± 0.07‰, 6.38 ± 0.04‰, 6.24 ± 0.13‰, 4.57 ± 0.03‰, respectively) and, according to ref. [30], indicates organic nitrogen. All of the above leads to the conclusion that observed trends in $\delta^{15}N$ variation under long-term mineral nitrogen fertilization are conditioned by the nitrification process in soil, creating isotopically heavier ammonium and lighter nitrate in the soil. Nitrates were subsequently taken up by crops and removed from the system, resulting in soil with increased $\delta^{15}N$ values in the long term [22]. Also, the $\delta^{15}N$ value of +4.56 ± 0.10‰ determined in the CP_SM_L8 sample (soil with 30 t/ha of solid manure application) indicates nitrogen of organic origin and is in accordance with the ranges of isotopic nitrogen in the organic fertilizers in ref. [45]. This

was confirmed by the PCA analysis, i.e., among all other analyzed soil variables, isotopic $\delta^{15}N$ contributed the most to the clustering of soils with N of organic origin. The $\delta^{15}N$ values observed in arable land, e.g., crop production (+4.00 ± 0.10‰ to +6.38 ± 0.04‰), are in line with the isotopic signatures of arable soils in Europe: +3.7‰ in Germany [23], +5.5‰ in Scotland [48], and from +3.5 to +7.3‰ in France [49].

Furthermore, the determined $\delta^{15}N$ values of +2.20 ± 0.10‰ at the ski slope (SS_L4) and +2.50 ± 0.10‰ in the meadow (M1_L3) indicate the inorganic origin of nitrogen; more precisely, the $\delta^{15}N$ values indicate a signature of NH_4NO_3 fertilizer. As reported by [28] in their example of 27 commercial single-component and complex mineral fertilizers, the isotopic signature of nitrogen in the majority of the tested nitrogen fertilizers ranged from −1.7‰ (NPK 15-15-15) to +1.5‰ $(NH_4)_2SO_4$ with an average value of −0.34‰, although two fertilizers stand out with significantly higher $\delta^{15}N$ values, NH_4NO_3 (+2.50‰) and $Ca(NO_3)_2$ (+3.90‰). The nitrogen signature at the ski slope was as expected, especially due to the fact that, for the production of artificial snow and the preparation of the ski slope, various salts are used, including nitrogen-based fertilizers, namely: urea, ammonium sulfate, and ammonium nitrate [50,51]. Their application as ''snow hardeners'' improves the snow quality with the primary goal of providing fair and safe competition conditions for the FIS Ski World Cup, which also takes place at the L2 location. The inorganic origin of nitrogen in the meadows at the L3 location (+3.20 ± 0.10‰ and +2.50 ± 0.10‰) was unexpected, and those isotopic signatures also correspond to mineral fertilizers. This can be partly explained by the fact that both meadows are located in the vicinity of the arable crop land (more precisely, on the slope below the arable land) where, at the time of soil sampling (May 2019), the maize was in 8–10 leaf development, and in-season fertilization with ammonium nitrate had already been carried out. A certain amount of the applied nitrogen could have reached the meadow soil as a result of surface runoff. The soil from this location was sampled at a shallow depth (0–5 cm). The apple orchard at the L5 location is maintained by being mown twice a year, and the grass is left as mulch on the surface, which must have additionally contributed to the fact that the nitrogen in that location was of organic origin (5.60 ± 0.10‰). In the meadow soil at the L7 location, the isotopic signature of nitrogen (+4.25 ± 0.02‰ and +4.61 ± 0.06‰) indicates the as-expected organic origin of nitrogen, while the forest soils from the islands of Pag ($\delta^{15}N$ = +3.24 ± 0.08‰) and Mljet ($\delta^{15}N$ = +3.22 ± 0.07‰) indicate the atmospheric origin of nitrogen in these soils. The results from the forest soils from coastal Croatia are in accordance with the $\delta^{15}N$ abundance (3.29 ± 0.69‰) determined in Huajiang Grand Canyon in China, an area with a primarily subtropical monsoon climate, an average annual precipitation of 1100 mm, and an annual average temperature of 18.4 °C [52]. The isotopic signatures observed in the meadow soils were similar to those from previous studies of isotopic signatures in meadow and grassland soils, from +2.9‰ to 4.4‰ [48,49,53], and the enrichment of $\delta^{15}N$ can be associated with higher microbial activity in those soils. Ultimately, the results from this research indicate that the origin of nitrogen in soils from land used for crop production; orchards; and meadows is organic ($\delta^{15}N$ > 4‰), just as was reported from southern China, where $\delta^{15}N$ values were in the range of 4.79‰ to 8.01‰ in peach orchard soils, meadows, and soils from land used for paddy, maize, and tobacco production; the maximum $\delta^{15}N$ values were found in the soil surface layer (0–20 cm) of the maize fields [54]. Regarding the $\delta^{15}N$ abundance in forest soils, it must be pointed out that forest soils usually have lower $\delta^{15}N$ values—from −0.3‰ to +2.94‰ [24,55]—compared to arable soils and meadows, and along with N_2 fixation, decreased isotopic signatures can be caused by the decomposition of litter. Higher $\delta^{15}N$ variability in forest soils (0.00 ± 0.10‰ to 3.24 ± 0.08‰, CV = 86.6%) can be associated with the weather conditions in different locations. For example, a lower isotopic abundance (0.00 ± 0.10‰) was recorded in colder locations with more humid atmospheric conditions (8.5 °C and 1321.3 mm), whereas a higher $\delta^{15}N$ value (3.24 ± 0.08‰) was recorded in warmer and less humid locations (16.4 °C and 972.6 mm). Previous analyses have shown that $\delta^{15}N$ soil decreases with a decrease in MAT (mean annual temperature) and with an increase in MAP (mean annual precipitation) [56].

Overall, the results of this study indicate that variations in the stable nitrogen isotope in forests, cultivated areas, meadows, orchards, and urban soil are the result of internal ecosystem transformations, whereas the abundance of the stable nitrogen isotope in the soil of the ski slope was influenced by an external nitrogen source, i.e., the application of mineral fertilizers. It should be added that, although mineral nitrogen fertilization did not affect the isotopic signature of nitrogen in arable soils, it can negatively contribute to the environment. The increasing use of nitrogen fertilizers in food production worldwide has resulted in an increase in N_2O concentration in the atmosphere, where it remains as a greenhouse gas and is 298 times more potent than carbon dioxide [57]. In 2015, 40% of surface waterbodies and more than 50% of groundwater in the EU were affected by nutrient pollution, largely due to N fertilization and manure mismanagement [57]. From an economic point of view, variable doses of nitrogen fertilization can enhance maize grain yield, but after accounting for the costs of N fertilizer and other agricultural inputs, a farmers' personal profit can only reach a maximum of USD 2038 ha^{-1} [58].

5. Conclusions

The results indicate that isotopic signatures in orchard, arable, and urban soils in Croatia are conditioned by organic nitrogen cycling, whereas in forest soils, atmospheric deposition is the main source of nitrogen. In meadow soils, the nitrogen isotopic fractionation is conditioned by the content of total carbon and total nitrogen. The isotopic signature in soils from ski slopes reveals the anthropogenic influence of mineral nitrogen fertilizers in their application as ''snow hardeners" during the ski season and ski races. The long-term application of 150, 180, and 200 kg N/ha, i.e., mineral fertilizers produced via the processes of the "industrial" fixation of atmospheric nitrogen, had a sustainable effect on the enrichment of the soil containing organic nitrogen. Even though this research was only based on 27 soil samples, it represents a valuable initial database and provides an important insight for future studies that will confirm and expand on the knowledge presented in this investigation. In addition, it provides support for continuing the use and research of all land use classes and $\delta^{15}N$ abundance in Croatian soils in future.

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Forecasting Fruit Export Damages and Enhancing Food Safety through Risk Management

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Abstract: This study underscores serious issues in the South African fruit export sector, notably highlighting the persistent fruit damage after 2016 that could boost microbial growth, jeopardising food safety. To enhance the supply chain and safeguard food, identifying and strategising the types of fruit damage during distribution is critical. The data bring to light intricate and varied trends in damage claims across different fruit types and years, indicating a need to understand each fruit type's specific vulnerabilities and adjust handling and farming techniques accordingly to minimise losses after harvest. The analysis reveals key insights into seasonal patterns in fruit damage claims, with notable increases especially in January and February, and clear fluctuations throughout the year. Utilising this knowledge, stakeholders can optimise operations and formulate guidelines tailored to high-risk seasons for fruit handling and transportation. Looking forward, both SARIMA and linear regression models predict an increasing trend in damage claims, highlighting a pressing need for improved planning and risk management strategies. This proactive approach will be crucial in mitigating future damage claims and enhancing food safety amid the growing challenges posed by climate changes and shifting global standards and regulations.

Keywords: climate change events; food safety; forecasting; fruit damage; supply chain risk management

1. Introduction

Climate change stands as one of the most pressing challenges of our time, with its effects reverberating through human and natural systems worldwide. As new insights on this topic emerge daily, it is evident that global disruptions caused by weather extremes will persist well into the future, leaving lasting impacts on physical, biological, human and managed systems [1]. Among the numerous industries vulnerable to these changes, the South African fruit export supply chain and marine cargo insurance face significant impacts. Surprisingly, however, there is a lack of research explicitly examining the effects of climate change on these critical components of global trade.

According to the Intergovernmental Panel on Climate Change (IPCC) estimates, human activities releasing greenhouse gases have caused global temperatures to rise by 1.1 °C since the pre-industrial era (1850–1900). The past decade (2011–2020) has seen a pronounced escalation in this warming trend [1]. This rise in temperatures poses a significant threat to various economic sectors, including the fruit export industry of South Africa [2]. To understand the impact of climate change on the marine cargo insurance industry in South Africa, Du Plessis et al. [3] analysed claims over the last decade. The results were alarming, revealing an increasing trend in weather-related cargo claims and extreme outlier years.

The South African fruit export supply chain plays a vital role in the country's economy, annually exporting fruit valued at over USD 3 billion [4]. With the country's favourable conditions for fruit production, this thriving industry contributes significantly to employment opportunities while strengthening trade relationships with over 100 countries worldwide.

The supply chain, however, operates within stringent guidelines and protocols, especially concerning temperature control, due to the perishable nature of the products. Any temperature break in the cold chain can lead to non-conformance and potential food safety concerns, which can result in damage claims [5,6].

Despite the sensitive nature of the South African fruit export supply chain, a concerning trend emerges from global port statistics. Nearly 50% of ports worldwide currently lack strategies to mitigate the impacts of climate change [7,8]. Such a lack of preparedness, coupled with the known and projected climatic disruptions, creates a highly vulnerable supply chain with low levels of resilience [9].

This research delves into the vulnerabilities of South African fruit exports (as evidenced through damage claims) and its implications for food safety within the maritime supply chain. The main objective of the fruit export industry is to deliver fresh fruit in a safe condition for human consumption. However, when the fruit is rejected due to damages, it goes against this goal and leads to insurance claims. By carefully monitoring these claims for any patterns or trends, one can identify the root causes of these rejections, creating a valuable feedback loop for the industry. Armed with this information, one can take preventive measures to avoid future occurrences of damaged fruit and improve the overall delivery process.

Although there is an existing body of research documenting the implications of temperature fluctuations on fruit damage during distribution [5,6,10,11], what sets this study apart is its unique risk-based viewpoint on fruit exports and food safety through a risk transfer mechanism—which has not been thoroughly explored in previous research. By addressing this critical aspect, the research contributes valuable insights to understanding the complexities and potential solutions for ensuring food safety during the export process.

The structure of the remaining sections is as follows: Section 2 provides a literature review covering three main topics central to this research. Section 3 outlines the methodology and conceptual framework, while Section 4 presents the analysis and results. This is followed by a discussion in Section 5, a conclusion in Section 6 and an overview of potential future work in Section 7.

2. Literature Review

Through a literature overview, this section presents a concise summary of the main topics covered in this article, namely (1) South African fruit exports and food safety, (2) South African ports and (3) maritime supply chain risk management. This section aims to provide readers with a broad understanding of these topics and the theoretical framework supporting the research. Firstly, it delves into the significant impact of weather-related risks on the fresh food system, including the cold chain, and highlights the growing concern over food safety and security. Secondly, it focuses on South African ports, which are vital in the global logistics network [3]. It addresses the vulnerability of these ports to weather-related risks and extreme weather events, leading to disruptions and congestion in the supply chain—further affecting the cold chain. Lastly, this section explores the concept of maritime supply chain risk management, including using marine cargo insurance as a risk transfer mechanism. It outlines a layer model for maritime transportation risk management, incorporating risk identification and evaluation into maritime logistics networks. By the end of this section, readers should have gained a general understanding of the core topics and theoretical framework that set the stage for the subsequent research questions.

2.1. South African Fruit Exports

In South Africa, the fruit industry annually exports approximately 3.2 million tons (or USD 3.3 billion) of fruit [4]. Out of this, only the highest quality surplus fruit, accounting for roughly 70% of the total fresh fruit produced, is exported to nearly 110 countries, creating a thriving industry that provides employment opportunities for many [12–14].

The fruit export industry in South Africa is prospering and witnessing substantial growth. According to the National Department of Agriculture, Forestry and Fish-

eries [15], the agricultural sector (including forestry and fisheries) has experienced an average annual growth rate of 7.6% since 1994, confirming this upward trend. South Africa's favourable conditions make it suitable for fruit production, leading to cultivation in various parts of the country. During the 2018–2019 season, more than 250 million cartons of fresh fruit were exported to major destinations, including the European Union (35.43%), Asia (20.62%), the United Kingdom (14.04%), the Middle East (12.74%) and the Russian Federation (6.89%) [16].

When exporting fruit, it is crucial to control time and temperature factors in the supply chain. Failure to do so can result in the fruit not meeting market requirements, leading to a decline in quality, shelf life and food safety. This, in turn, can lead to price reductions, rejection or loss of market [10,14]. The series of refrigeration steps implemented throughout the supply chain to maintain perishable food at the appropriate temperature is known as the cold chain [17]. Maintaining specific temperatures within the cold chain and continuously monitoring temperature within reefer containers are essential for preserving the quality of the fruit [5,11,18].

Although different types of fruit have distinct cold chain handling processes, the handling process after loading the fruit into the reefer container is the same for all types [6]. The Perishable Products Export Control Board (PPECB), established in 1926 and currently managed by the Department of Agriculture, Land Reform and Rural Development (DALRRD), oversees all South African perishable product exports. They establish export protocols and guidelines, including ideal temperature ranges for each perishable product, and ensure exporters adhere to quality standards.

Research conducted by Goedhals-Gerber et al. [6] examined temperature breaks in the fruit export cold chain at the Port of Cape Town. They found that 41.5% of temperature breaks occurred at the port but did not investigate the specific causes of these breaks. A subsequent study in 2017 revealed that 81% of temperature breaks within the fruit export cold chain via the Port of Cape Town occurred at the Port of Cape Town. Factors such as external ambient temperatures, weather-related delays (e.g., high winds, fog, waves), vessel ranging and strong ocean currents were identified as the dominant causes of these breaks [11].

In 2020, a further study on the export of navel oranges through the Port of Cape Town found temperature breaks during port operations, some lasting over 9 h. While the study did not investigate the root causes of these breaks, it highlighted weather exposure, transportation delays, port congestion and inspection delays as potential reasons [5,19].

Controlling the time and temperature factors throughout the fruit export supply chain is crucial to ensuring high-quality produce comply with country-specific food safety regulations and avoid rejections at the port of import, which leads to potential damage claims. Mutumbo [20] state that rising natural hazards and extreme weather events have led to additional risks in ports and shipping operations, potentially affecting the fruit export supply chain [6]. Many exporters rely on marine cargo insurance to mitigate potential risks, as discussed briefly in the subsequent sections.

Food Safety

Food safety and security is a growing concern, and discussions around it have increased in recent years [21–23]. While progress has been made in fresh food governance through international collaboration and advancements in science and technology, the literature now confirms that climate change has a negative impact on fresh food safety [24]. Globally, foodborne diseases make nearly one out of every ten people sick and cause over 400,000 deaths each year, and climate change is likely to exacerbate this problem [25]. Predictions indicate that climate change events will reduce food production, increase food contamination and contribute to global food price increases from 3% to 84% by 2050, leading to food insecurity and malnutrition [26].

Refrigeration plays a vital role in ensuring food safety [27]. Perishable food, such as fruit, must be maintained in a chilled or frozen state throughout the entire supply chain.

Insufficient refrigeration that fails to keep perishable food within the required temperature range can promote the growth of harmful pathogens and spoilage microorganisms, rendering the product unfit for human consumption [17]. Consequently, when cases of inadequate refrigeration of perishable food are identified and reported, it becomes necessary to reject the food shipment to address concerns about food safety.

Decision makers must consider the direct and indirect impacts of climate change and variability on food safety hazards throughout the entire food chain, including food distribution [25]. Climate change (and unpredictability) can cause food safety hazards at various stages of the fresh food value chain, from primary production to consumption [24]. For instance, rising temperatures, changes in rainfall patterns, drought stresses and extreme weather events can increase the risks of food contamination and the occurrence of foodborne diseases [25]. Transportation and warehousing can also create challenges in maintaining the cold chain due to slow transfers (weather-related delays), disruptions, poor insulation and inadequate refrigeration. This impacts the quality and safety of fresh food [24]. There exists a significant variation in the effectiveness of cold chains among countries; developing nations are generally less equipped to manage potential risks impacting the cold chain [17], a situation compounded by the limited information available on temperature abuse in these countries [28].

In conclusion, the significant impact of climate change events on the fresh food system, including the cold chain, necessitates the involvement of all stakeholders in implementing preventive measures. The risks posed by climate change events extend beyond the safety of fresh food to the entire supply chain, potentially leading to further losses and compromised safety. With food safety (quality) and security (supply) being critical concerns, decision makers must address climate change's direct and indirect effects on food safety hazards throughout the cold chain. This includes identifying sources and mitigating temperature breaches/failures during transportation, which are anticipated to increase due to climate change events.

2.2. South African Ports

The efficient functioning of port cities is vital for the global economy, especially in developing nations [7,8,29]. Ports serve as critical nodes in the global supply chain, facilitating about 80% of trade volume and 70% of trade value through maritime transportation [7]. However, ports face high vulnerability to the impacts of weather extremes due to their geographical location, as demonstrated by the devastating effects of extreme weather events [7,8,29,30]. Climate change directly affects port infrastructure, services and operations [7].

South Africa plays a crucial role in the global logistics network, with its major ports connecting sub-Saharan Africa to other continents. However, the country's logistics network is vulnerable to disruptions caused by extreme weather events, including floods, storms and droughts [20]. On average, South African ports experience one weather-related incident daily, a significant driver of congestion at these ports [31–34].

With 3000 km of coastline, South Africa is home to eight commercial ports operated by Transnet Port Terminals, ensuring efficient connectivity of the country's economy with trading partners [35,36]. Climate change poses potential impacts on these ports, such as rising atmospheric and water temperatures, strong winds, high waves, rising sea levels and heavy rainfall [35]. Port congestion, which leads to supply chain delays, is driven by adverse weather affecting ship and cargo operations, accidents (including strikes), sudden trade demand surges and land-side transport congestion [33]. South African container terminals are located at the Ports of Cape Town, Port Elizabeth, Ngqura and Durban (see Figure 1).

The Western Cape is responsible for almost 80% of all South African fruit exports. In 2022, exports of 4.2 million tons (or nearly 70%) were shipped from the Port of Cape Town. Durban and Port Elizabeth are the other larger export cities, both shipping just under 10% this year [37].

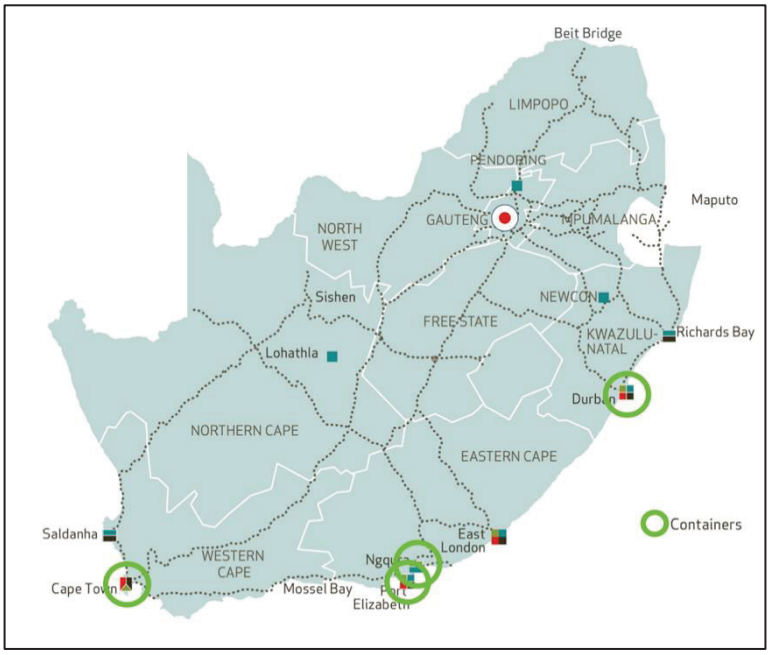

Figure 1. South African container ports. Source: [36].

In their 2021 study, Dube et al. examined flood trends and their impact in the Western Cape over the past 120 years. They found that regions of Cape Town (the 10th most populous city in Africa) are frequently subjected to the detrimental effects of floods. The infrastructure, including railway lines, parking lanes, roads and the power supply and communication systems, are often severely impacted [38].

Fears are mounting that the impacts of these floods could exacerbate due to the rise in sea levels induced by climate change, affecting the city and its surrounding areas [20,38]. There is growing concern about the increased frequency and impact of the El Niño–Southern Oscillation in the Southern Hemisphere. Dube et al. [38] predict that this will likely result in a surge of coastal flooding incidents. Indeed, over the past four decades, flood occurrences have significantly increased compared to earlier periods [38]. Figure 2 shows the statistically significant rise in flood events in the Western Cape during their study period.

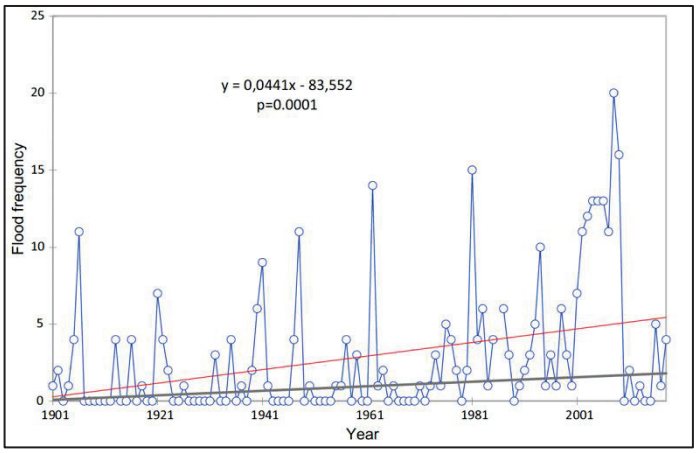

Figure 2. Flooding events in the Western Cape province 1900–2018. Source: [38].

In addition, adverse weather conditions and powerful winds result in significant delays at the Port of Cape Town, and extreme weather conditions account for approximately 15% of the lost time at the Port of Cape Town [34,39,40]. Recent floods, including the 2022 event in Durban, have been attributed to climate change, resulting in significant operational

impacts caused by heavy rainfall. In addition, these ports experience shutdowns of ship-to-shore (STS) gantries when wind speeds exceed 70 km/hour [40,41].

These impacts are not going unnoticed. In its 2020 evaluation, the World Bank ranked the Port of Cape Town notably low in the global container port performance index, obtaining 347th out of 351. The situation saw little improvement by 2022, with the port ranking 344 out of 348 [4,23]. This poor ranking is attributed to ongoing congestion issues at the port caused by outdated infrastructure and equipment, a lack of adequate staff and weather-related disruptions [4].

Climate change's impacts are being felt with increasing severity, particularly in developing countries, such as South Africa [42]. These nations typically lack the necessary resources and infrastructure to effectively adapt to these changes, often resulting in poor responses [38]. Studies forecast increased wind velocity around the Southern African Coast throughout the year due to climate change [43]. In addition, there is a noticeable increase in the frequency and intensity of extreme weather events reported in South Africa by multiple authors [38,44,45].

In summary, South African ports face weather-related risks, resulting in congestion and disruptions in the supply chain. Extreme weather events and higher wind velocities create challenges for maintaining efficient port operations. Moreover, the frequency and intensity of these events are projected to increase, raising concerns about their potential future impact on fresh fruit exports and overall long-term food safety and security.

2.3. Maritime Supply Chain Risk Management

In his 1999 paper on 'Principles of food safety Risk management', Jùrgen Schlundt emphasised the significance of risk management in ensuring food system safety. His steps align with the general process for managing supply chain risks, including risk identification, assessment, mitigation and monitoring/review [46–48]. Guerin [24] further highlights the importance for organisations to understand and effectively engage with these risks by allocating capital toward risk mitigation. This was echoed by Robertson et al. [21] in their holistic risk management perspectives for food safety. The general mechanisms for risk mitigation encompass prevention, reduction (training and education), risk transfer (insurance) and bearing the risk internally by the company itself [49].

Marine cargo insurance is a commonly used method for transferring risk, providing coverage for the physical loss or damage of goods during transportation and storage [50]. Risk managers gain valuable bottom-up insights into risk management by examining marine cargo insurance claims [3]. In their paper on data-driven analytics for cargo loss, Wu et al. [51] presented a 'business analytics for cargo loss severity' framework, which was incorporated and adapted into the conceptual framework for this research in Section 3.

As ports play a crucial role in the global distribution of goods (as evidenced in Section 2.2), it is essential to analyse potential risks in the maritime transportation process. Therefore, Blecker and Kersten [49] developed a layer model for maritime transportation risk management to integrate risk management procedures into maritime logistics networks. This model focuses on risk identification and evaluation, comprising four layers, and forms the theoretical foundation of this research (see Figure 3).

The layers are described as follows:

- Layer 1. Disruptive factors: This layer identifies and defines the events that initiate a chain of events, which can be internal (known and prepared for) or external (a combination of known and prepared for and known and unprepared for).
- Layer 2. Processes: Relevant processes related to the system being analysed are listed in this layer, acting as a link between Layers 1 and 3.
- Layer 3. Basic events: This layer lists non-redundant events, and the occurrence probability is determined by assessing the processes in Layer 2, as defined through the interactions between Layers 1 and 2.
- Layer 4. Consequences: This user-defined layer includes monetary and non-monetary quantifiers to assess the impact of the identified events.

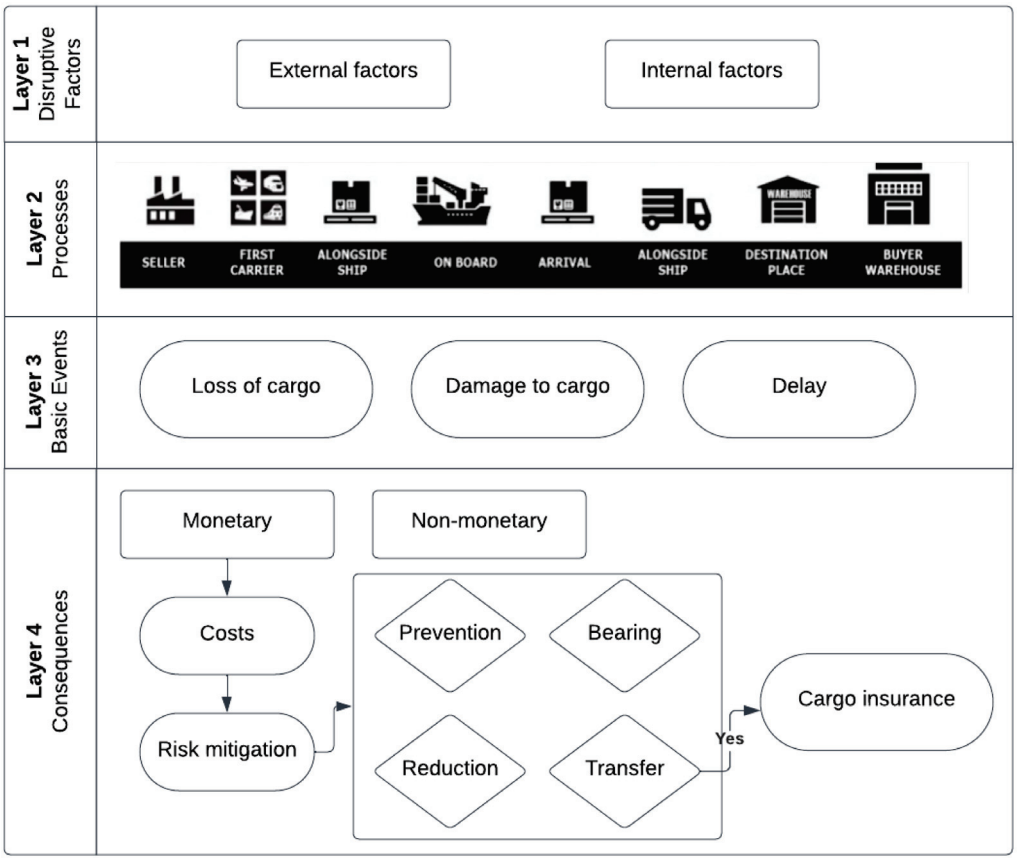

Figure 3. Layer model for maritime transportation risk management (adapted from [49,52]).

This section developed the theoretical background for the risk associated with food safety and security along with the expected future increase in climate change events.

3. Methodology

In 2019, the World Health Organization (WHO) emphasised the importance of obtaining precise quantitative estimates regarding the potential effects of climate change on food safety [25]. They stressed the urgent need for action to minimise predictable hazards.

To respond to these concerns, this research uses the theoretical perspectives from Section 2.3 to investigate marine cargo insurance claims for fruit damage. It focuses on research questions in Table 1, aiming to enhance understanding of distribution factors damaging South African fruit exports and related food safety risk management.

To address the research questions, the authors meticulously studied historical claims data from two major marine insurance companies in South Africa. These companies combined represent approximately 35% of the non-life insurance market and are among the country's top five marine insurance companies. The authors utilised a consolidated, desensitised, original dataset containing 17,727 unique claims over ten years from 1 January 2013 to 31 December 2022. This set of data served as a basis for the analysis.

Datasets included the following information: (1) the date of loss and (2) the description of the loss. The description field's variations (being in an open-text format that allowed free-text descriptions for each claim) led to the use of a keyword analysis formula on the dataset. During the pre-processing phase, a range of keywords such as weather, rain, hail, wind, storm, water, flood, delay, damage, temperature, variation and deterioration were searched. However, due to limited results from certain keywords, the list was refined to: delay, damage and temperature. The keywords with few results were categorised under 'damage'. The subsequent analysis aimed to extract two primary details from the claim

descriptions in the dataset: (1) the type of damage and (2) the type of fruit damaged in each claim.

Table 1. Research questions.

Research Question	Justification and Potential Contribution	Previous Research
1. What type of distribution damage affected fruit over the period under investigation?	By identifying the types of fruit damage during distribution, strategies can be developed to minimise these, enhancing supply chain efficiency and food safety. Fewer damages reduce potential exposure to bacteria or other contaminants, ensuring the fruit stays safe for consumption. Furthermore, intact fruits have a longer shelf life, reducing consumers' chance of purchasing and eating spoiled or nearly spoiled fruit.	A study by [53] shows that reducing physical damage in fruits during transportation significantly decreases the chance of microbial growth, improving food safety.
2. Are certain types of fruit more vulnerable to distribution damage than others?	Recognising more vulnerable types of fruit allows farmers and cold chain operators to adapt their practices to minimise damage, enhancing food safety. Reduced fruit damage means less exposure to contaminants and a lower risk of spoilage. This leads to safer, healthier food reaching the consumer, and the increased shelf life also reduces the likelihood of the consumer unknowingly purchasing and consuming spoiled fruit.	Research by [54] has shown that understanding the unique vulnerabilities of different fruit types and modifying farming and handling practices accordingly can significantly decrease post-harvest losses and enhance food safety.
3. Is there a seasonal pattern in fruit damage claims?	A better understanding of seasonal patterns can help ensure food safety by allowing for better resource allocation during high-risk seasons, reducing potential damage and contamination. This could also lead to formulating policies or guidelines regarding handling, storing and transporting fruits during these seasons, further safeguarding food quality and safety.	The Food and Agriculture Organization of the United Nations [55] has demonstrated that recognising and responding to seasonal trends in agricultural yield and associated damage claims can notably boost food safety and overall quality. Farmers, processors, distributors and consumers can effectively plan ahead by leveraging this understanding of seasonal variations. This optimises resource utilisation and mitigates risks, ultimately leading to increased profits. This proactive approach grounded in seasonal trends significantly contributes to advancing food safety standards and improving quality in the agricultural sector.
4. How can historical damage claims data be used to forecast future damage claims?	Accurate forecasting enables better planning and preparedness, thus minimising potential disruptions to the supply chain that could compromise food safety. For instance, early actions can be taken to ensure supply continuity and food quality preservation if there is an anticipated shortage or issue. Moreover, having a predictive model enables more robust risk management strategies to mitigate potential food safety risks.	A study by [56] has shown that predictive modelling based on historical data can effectively enhance food safety by enabling proactive measures and comprehensive risk management strategies.

After collecting and organising this data, a master dataset was created as the foundation for analysing the research questions. It consisted of 441 unique damage claims related to fruit. A sample post-processed master dataset is provided in Table 2, and Table 3 shows the ratio of fruit damage claims to overall claims. This trend is further examined in Section 4.

This study's conceptual framework, illustrated in Figure 4, was developed using the discussion from Section 2.3. This framework guided the analysis and interpretation of the findings.

Table 2. Sample master dataset.

Date of Loss	Description	Damage	Fruit
1 February 2013	Vehicle overturned—glassware—Veh reg:XYZ123	-	-
2 March 2014	Damages to cntnr XYZ—oranges as result of delay/congestion at port—severe storms ex vessel XYZ	storm; delay; damage	orange
3 April 2015	Damages to fresh oranges and lemons in cntnrs ABC&XYZ—delay in transit ex vessel ABC	delay; damage	orange; lemon

Table 3. Fruit damage claims as a percentage of Company A + B's total claims (data and heat map).

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
All claims	1693	1762	1836	1622	1729	1759	1759	1686	2042	1839
Fruit damage claims	7	17	14	9	36	49	125	59	52	73
Percentage of claims	0.4%	1.0%	0.8%	0.6%	2.1%	2.8%	7.1%	3.5%	2.5%	4.0%

Key: Green = lowest; Yellow = lower-middle; Orange = upper-middle; Red = highest values.

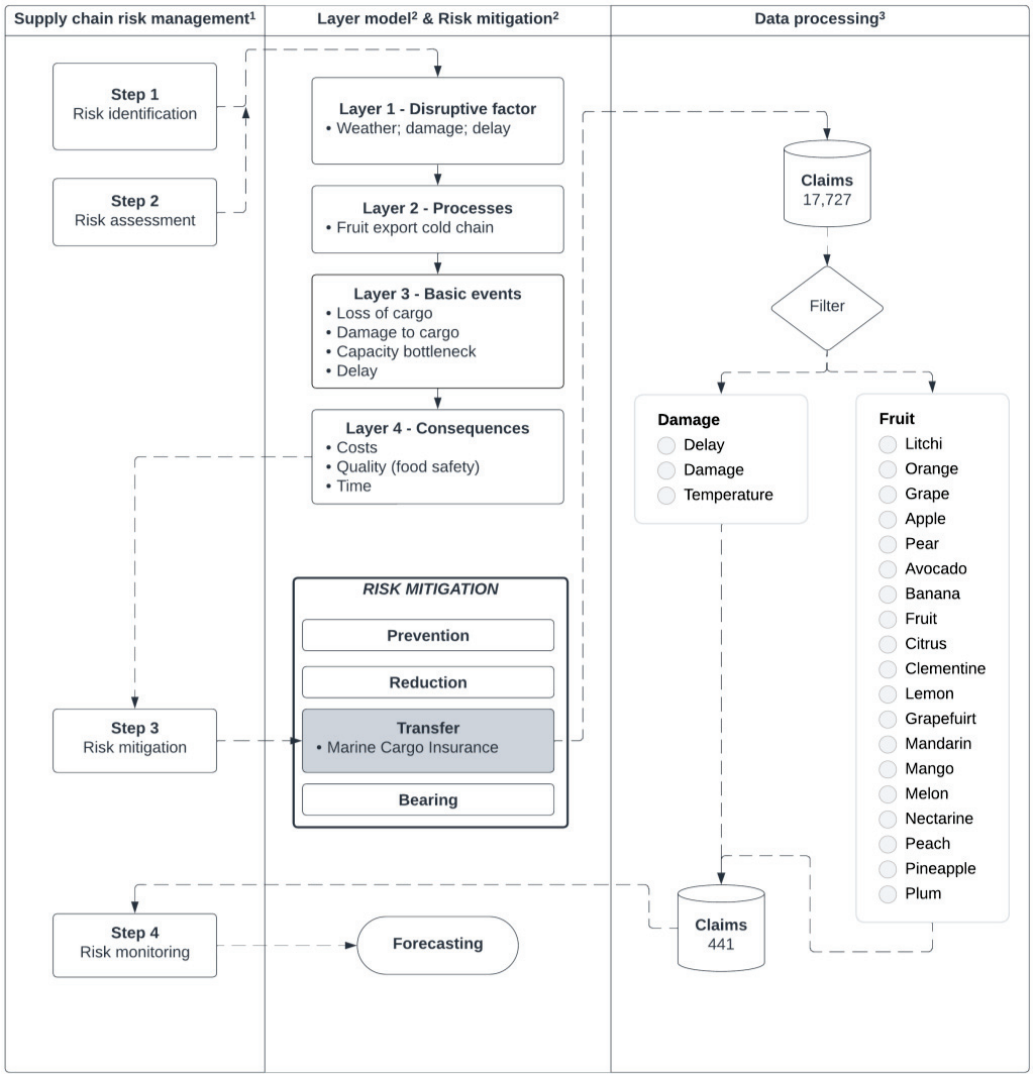

Figure 4. Conceptual framework of the research. Source: Authors' own creative. [1] [46,47,49], [2] [49], [3] [51].

The master dataset was analysed using Excel® to address research questions 1, 2 and 3. For research question 4, which focuses on forecasting future damages, assistance was provided by Stellenbosch University's Centre for Statistical Consultation, employing Statistica 14.

4. Analysis and Results

This section presents the analysis and results corresponding to each research question in Table 1, Section 3.

4.1. Research Question 1—What Type of Distribution Damage Affected Fruit over the Period under Investigation?

This section examines the variations in fruit damage during transport, essential for devising strategies to mitigate harm and boost supply chain efficacy and food safety. Mitigating physical damage, proven by Rolfe and Daryaei [53] to also diminish contaminant exposure, extends shelf life and underscores the need for meticulous handling and cold chain maintenance to deliver fruit in peak condition to consumers.

To analyse research question 1, the master dataset was filtered and categorised into three main groups: *damage*, *delay* and *temperature*. Each claim was examined using keyword filters to determine the best-fitting group. In cases where a more specific description was unavailable, the claim was assigned to the *damage* group by default. Due to the nature of agricultural practices, output volumes can vary from season to season or due to orchard renewal programs. To ensure validity of the research outcomes, some compensation for large-scale volume fluctuations should be included. To normalise for volume changes over the years, each year's total fruit export volume was indexed to the volume of the base year, 2013. The percentages indicated are calculated using the annual number of claims per category divided by the total claims for that category and then adjusted using the normalisation factor. This indicates the distribution of claims across the years examined. The results of this analysis are presented in Table 4 as a heat map, and visual representations can be found in Figure 5.

Table 4. Indexed distribution of claims by category over the years (data and heat map). Source: SARS (2023).

Number of Claims	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total Claims by Type
damage	4	14	11	8	22	38	99	42	33	49	320
delay	2	1	1	1	4	5	10	6	8	15	53
temperature	1	2	2	0	10	6	16	11	11	9	68
Annual total	7	17	14	9	36	49	125	59	52	73	441
Factor to normalise for volume	100	104	107	107	117	121	150	130	145	150	-
Heatmap (after normalization)	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	
damage	1%	4%	3%	2%	6%	10%	21%	10%	7%	10%	-
delay	4%	2%	2%	2%	6%	8%	13%	9%	10%	19%	-
temperature	1%	3%	3%	0%	13%	7%	16%	12%	11%	9%	-
Annual total %	2%	4%	3%	2%	7%	9%	19%	10%	8%	11%	-

(Green = lowest; Yellow = lower-middle; Orange = upper-middle; Red = highest values).

Focusing on *damage*-related claims, which fluctuated throughout the years, these claims notably exceeded the average of the category in 2018 (10%), 2019 (21%), 2020 (10%) and 2022 (10%), which indicates a changing situation. The sharp surge in 2019 could reflect particular challenges faced in transportation mechanisms or quality controls during that year. Subsequent years, while showing a decline from the peak, remained high, indicating that challenges with *damage* persisted.

The *delay* category started at 4% in 2013, considerably below the average. However, from 2018 onwards, every year exceeded the average, culminating in a significant peak of 19% in 2022. This consistent rise over the latter part of the decade might point to recent challenges in transportation logistics or increased sensitivity in detecting and reporting delays.

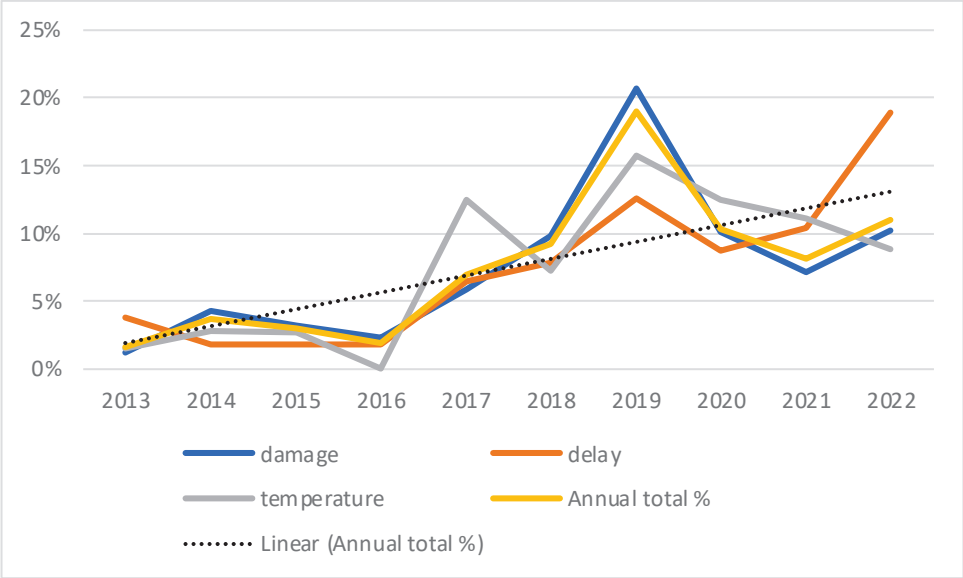

Figure 5. Indexed claim distribution by category: 2013–2022.

Temperature-related claims experienced an irregular pattern. Years that experienced notable increases include 2017 (13%), 2019 (16%), 2020 (12%), 2021 (11%) and 2022 (9%). The pronounced fluctuations may hint at periodic challenges with maintaining the cold chain's temperature, possibly due to changes in the temperature control equipment (or related challenges), transportation routes, or handling practices during these years.

During the study period, fruit distribution damage trends raised concerns. The heatmap visually confirms significant changes post-2016, with persistently high figures suggesting continued fruit damage problems. However, it is essential to consider additional factors, such as the impact of weather conditions in specific years and any other potential factors that could influence the number of claims in a particular year. Rolfe et al. [53] emphasised that such damages increase microbial growth risks, affecting food safety.

4.2. Research Question 2—Are Certain Types of Fruit More Vulnerable to Distribution Damage Than Others?

This section explores the varying susceptibilities of different fruits to damage (and potential spoilage). Recognising these vulnerabilities could enable farmers and cold chain operators to adapt their methods to minimise harm, leading to safer, fresher produce. Research by the Food and Agriculture Organization of the United Nations underscores the importance of understanding these specificities, as modifying practices accordingly can substantially reduce post-harvest losses and increase food safety [54].

The dataset was filtered and then categorised into the different fruit groups, as discussed in Section 3. Each claim was examined using keyword filters to determine the fruit group. In the few cases where more than one type of fruit was detected, the claim was assigned to the *other fruit* group by default. To again account for volume variations year-on-year, each fruit group's export volumes were indexed to the base year, 2013. The percentages indicated in Table 5 and Figure 6 are calculated using the annual number of claims per fruit category divided by the total claims for that fruit category for the year and then adjusted through the normalisation factor. This indicates the distribution of claims across the analysed years.

Table 5. Indexed distribution of claims by fruit group over the years (data and heat map). Source: [57].

Number of Claims												
Group	Fruit	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Group total
citrus fruit	citrus; clementines; grapefruits; lemons; mandarins; oranges	2	6	4	2	13	12	66	17	6	4	132
grapes	table grapes	1	2	2	0	3	9	13	20	27	50	127
other fruit	litchis; mangos pineapples; other	4	3	3	2	11	16	40	15	10	16	120
pome fruit	apples; pears	0	1	4	5	6	10	5	7	5	2	45
stone fruit	nectarines; peaches; plums	0	5	1	0	3	2	1	0	4	1	17
Annual total		7	17	14	9	36	49	125	59	52	73	441
Factor to normalise for volume												
Group	Fruit	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	
citrus fruit	citrus; clementines; grapefruits; lemons; mandarins; oranges	100	100	102	97	109	123	120	140	147	146	-
grapes	table grapes	100	96	116	139	150	177	126	149	153	192	-
other fruit	litchis; mangos pineapples; other	100	201	187	168	220	111	730	41	225	111	
pome fruit	apples; pears	100	92	100	108	108	103	106	122	118	155	-
stone fruit	nectarines; peaches; plums	100	104	102	99	100	90	81	85	133	152	-
Heatmap												
Group	Fruit	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	
citrus fruit	citrus; clementines; grapefruits; lemons; mandarins; oranges	2%	5%	3%	2%	9%	7%	42%	9%	3%	2%	-
grapes	table grapes	1%	2%	1%	0%	2%	4%	8%	11%	14%	21%	-
other fruit	litchis; mangos pineapples; other	3%	1%	1%	1%	4%	12%	5%	31%	4%	12%	-
pome fruit	apples; pears	0%	2%	9%	10%	12%	22%	10%	13%	9%	3%	-
stone fruit	nectarines; peaches; plums	0%	28%	6%	0%	18%	13%	7%	0%	18%	4%	-

(Green = lowest; Yellow = lower-middle; Orange = upper-middle; Red = highest values).

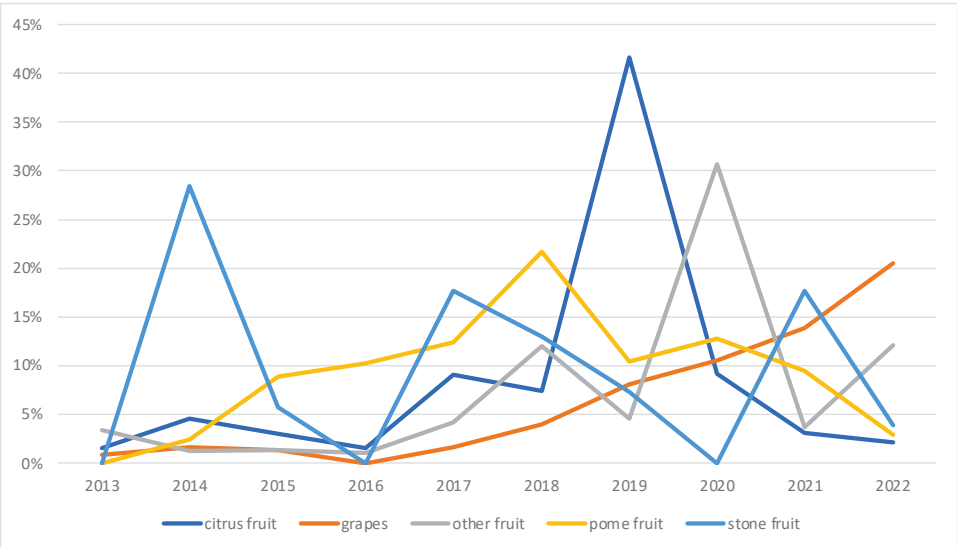

Figure 6. Indexed claim distribution by fruit group: 2013–2022.

The dataset, adjusted for volume increases, presents an insightful analysis of fruit damage claims between 2013 and 2022, categorised into *citrus fruits, grapes, pome fruits, stone fruits and other fruits*. Over this period, *citrus fruits*, which include varieties like clementines and oranges, had notable variations in the claim rate. The year 2019 was particularly concerning, registering a claim rate of 42%—far exceeding the average. Similarly, the claim percentages for 2017 and 2020 were above average. Over the past decade, *grapes* had a stable claim rate between 2013 and 2016. However, starting from 2018, there has been a steady increase in claims, culminating in 14% in 2021 and reaching a high of 21% in 2022. *Pome fruits*, mainly apples and pears, consistently surpassed the average between 2017 and 2020; the highest being 22% in 2018. *Stone fruits* like nectarines and peaches recorded elevated claims in 2014 and 2017 at 28% and 18%, respectively, which stood out. Lastly, the category of *other fruits*, encompassing litchis, mangos and pineapples witnessed higher-than-average claims in 2018 and 2020 at 12% and 31%, respectively. Please see Section 7 for suggested future work on this topic.

4.3. Research Question 3—Is There a Seasonal Pattern in Fruit Damage Claims?

Understanding seasonal patterns in fruit damage claims can reveal potential risk factors like handling, transportation and weather-related influences that affect food quality and safety during specific times of the year. Recent studies, such as the Food and Agriculture Organization's 2021 report, emphasise recognising seasonal trends to optimise resources, mitigate risks and increase profits [55]. This section analyses the master dataset from 2013 to 2022, identifying key monthly seasonal patterns in fruit damage claims. It is important to note that the input data reflects the reported date of loss associated with the claim. This analysis aims to inform strategies and policies to enhance food safety and quality during high-risk seasons, contributing to the overall resilience of the agricultural sector.

The dataset is presented in Table 6, and a graphical representation in Figure 7. The percentages indicate the monthly proportion of fruit-related claims out of Company A + B's total claims for that month. This highlights the monthly trends over the years in fruit claims development. The researchers would have preferred to normalise for total claims variations across all insurance companies to balance any long-term trends in other insurance markets; however, this data was not available to the researchers.

Table 6. Seasonal trends in claims as a percentage of Company A + B's total claims (heat map).

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Jan	0%	0%	1%	0%	0%	2%	2%	3%	4%	7%
Feb	0%	1%	0%	1%	2%	1%	4%	3%	6%	11%
Mar	1%	1%	0%	0%	1%	4%	2%	7%	11%	4%
Apr	1%	1%	0%	0%	0%	0%	3%	4%	2%	1%
May	0%	0%	1%	1%	2%	3%	4%	4%	3%	2%
Jun	0%	1%	1%	1%	1%	3%	7%	4%	0%	1%
Jul	1%	1%	3%	1%	8%	4%	8%	5%	1%	3%
Aug	1%	2%	0%	2%	6%	7%	19%	5%	1%	2%
Sep	0%	1%	1%	1%	3%	6%	22%	5%	1%	1%
Oct	0%	0%	1%	0%	1%	1%	12%	0%	0%	0%
Nov	0%	1%	1%	0%	1%	1%	3%	2%	0%	4%
Dec	1%	3%	1%	0%	1%	1%	2%	4%	3%	2%

(Green = lowest; Yellow = lower-middle; Orange = upper-middle; Red = highest values).

The dataset analysis reveals several key insights regarding seasonal patterns in fruit damage claims as a percentage of total claims for that month from the original dataset. The first notable observation is an increasing growth trend in damage claims over the years, most noticeably in January and February. This increase might indicate specific fruit type vulnerabilities, changes in handling, transportation, weather conditions impacting the freshness or quality of the produce, increased demand leading to quicker and potentially

rougher shipping methods, variations in packaging materials or techniques, fluctuations in quality control measures or changes in regulations or standards.

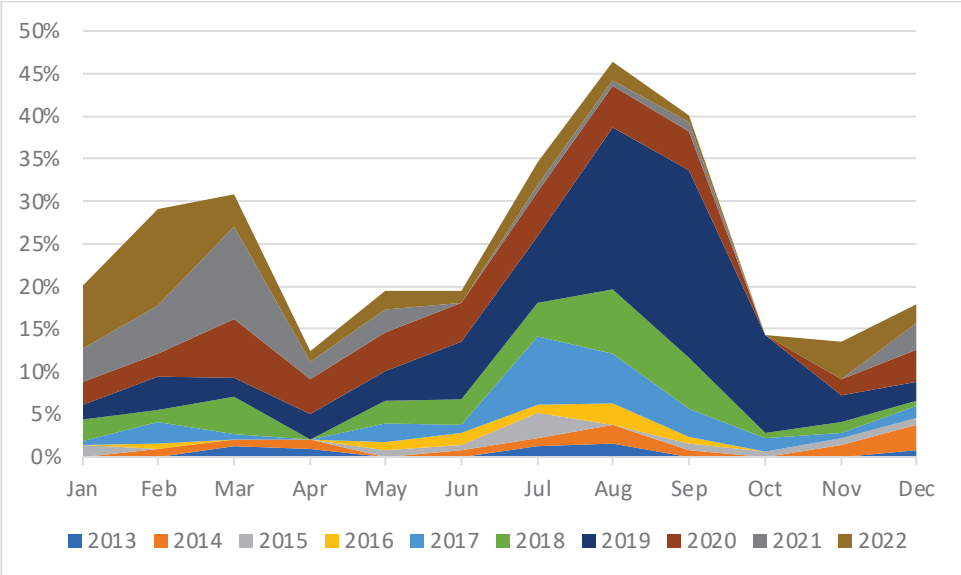

Figure 7. Seasonality in fruit damage claims: 2013–2022.

Secondly, there are evident seasonal fluctuations throughout the years. June to September tends to have escalating claims, with substantial peaks observed in August and September across several years (e.g., 19.1% in August 2018 and 22.1% in September 2019). Equally, December to February initially saw relatively low claims, but a consistent increase is noticeable in later years, notably in February 2022 at 11.3%. March to May generally sees moderate damage claims, with minor variations year-on-year, suggesting a relatively stable situation in this period. A spike in claims was anticipated in April 2022 due to the Durban storms. However, two factors affected this: (1) As mentioned in Section 2.2, in 2022, 70% of fruit was exported via the Port of Cape Town, and (2) general storm damage claims in Durban would have largely overshadowed any fruit-related claims. A final important insight is the presence of sudden, significant fluctuations in certain months, such as August 2019 (19.1%) and September 2019 (22.1%). Interestingly, there are declines in certain months, specifically October and April, where the number of claims has reached zero in several instances.

4.4. Research Question 4—How Can Historical Damage Claims Data Be Used to Forecast Future Damage?

In food safety, accurate forecasting is a powerful tool for risk mitigation and, thus, the integrity of the cold chain. The potential to predict future damages allows for early interventions, preserving food quality and ensuring a continuous supply. The application of predictive modelling, using historical data as illustrated by a study by Rejeb et al. [56], effectively enhances food safety.

Two primary statistical techniques were explored to address the third research question of whether historical data can be employed to forecast future situations. Section 4.4.1 delves into using the seasonal autoregressive integrated moving average (SARIMA) model. Following this, Section 4.4.2 focuses on regression analysis, a different approach that provides additional insights into the relationships between the variables.

4.4.1. SARIMA Forecasting

To forecast monthly damage claims to fruit, one needs a model that can use time series data to forecast these potential liabilities. The model should be able to predict the volume

of claims and consider the seasonal volatility inherent to the type of monthly claims. The seasonal autoregressive integrated moving average (SARIMA) model offers this solution.

This model is an extension of the ARIMA (autoregressive integrated moving average) model, which considers seasonality in the data, as evidenced in research question 3. SARIMA is particularly useful for time series data exhibiting trend and seasonality [58]. It can handle trends and seasonality, making it versatile for real-world time series data.

SARIMA has several components. The AR (autoregressive) component captures the relationship between an observation and its previous ones. The integrated (I) component involves differencing observations to make the time series stationary, ensuring consistent mean and variance. Differencing over a lag of 1 means subtracting the prior observation from the current one. The MA (moving average) component relates an observation to the residual error from a moving average model applied to past data. In addition, SARIMA has seasonal counterparts to these components: seasonal autoregressive (SAR), seasonal integrated (SI) and seasonal moving average (SMA), emphasising periodic patterns in the data and residuals.

To apply a SARIMA model, one needs to identify and then specify the order of each component (p, d, q) for the non-seasonal part and (P, D, Q, S) for the seasonal part, where:

- *p*: order of AR term.
- *d*: number of differencing required to make the series stationary.
- *q*: order of the MA term.
- *P*: seasonal order of the AR term.
- *D*: seasonal differencing.
- *Q*: seasonal order of the MA term.
- *S*: number of observations in each season.

The order of the data are the months in sequence and the analysis of damage prediction started with a data transformation phase. Due to the variance instability of the damage for prediction purposes (see Figure 8), a log transformation was applied, a commonly used method for stabilising variance and making the data more suitable for linear modelling (see Figure 9).

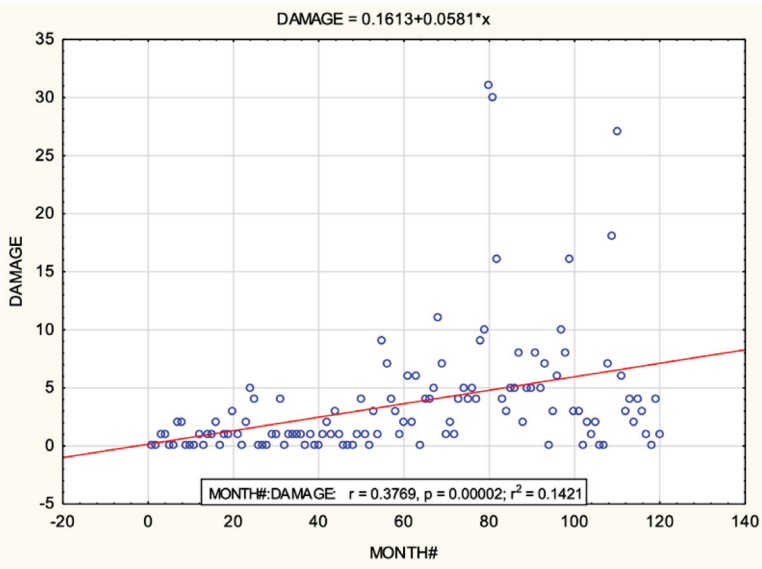

Figure 8. Two-dimensional scatterplot of fruit damage claims.

The rough regression on the monthly data summary suggested a decent level of predictability for the model with an R-Square value of 0.2384, meaning the regression model explains 23.84% of the variation in the data. The F-Statistic ($F(1,118) = 36.944$) and the corresponding *p*-value ($p < 0.00000$) demonstrated that our model is statistically significant.

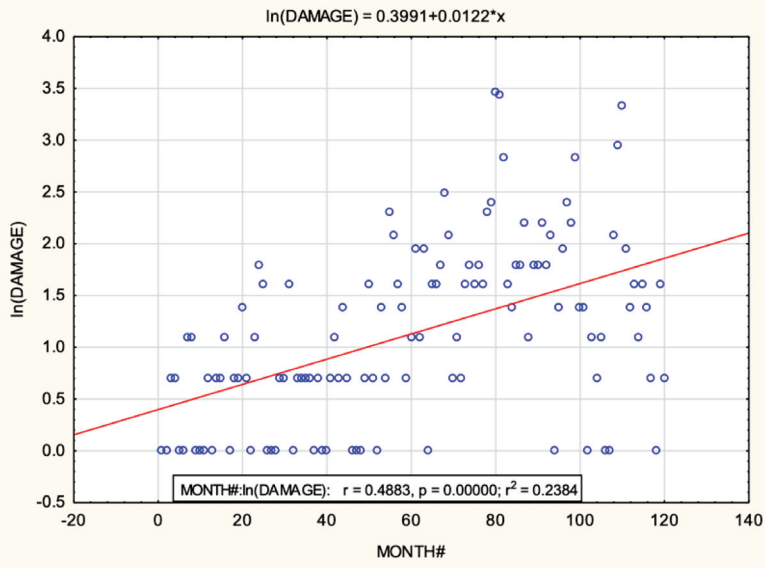

Figure 9. Two-dimensional scatterplot of fruit damage claims after transformation.

Following the regression analysis, several diagnostic tests were performed to check the validity of the model assumptions. The normal probability plot of residuals suggested that the residuals can be assumed to be normally distributed according to the Shapiro–Wilk test with a *p*-value of 0.827. The *p*-value is much larger than the significance level of 0.05, suggesting no evidence to reject the null hypothesis that the residuals are normally distributed (see Figure 10).

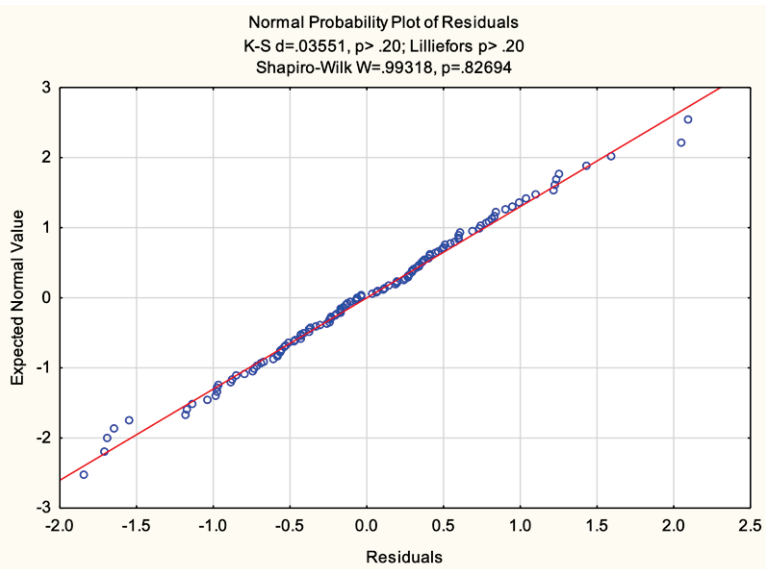

Figure 10. Normal probability plot of residuals.

The Durbin–Watson test showed a result of 1.086, indicating positive autocorrelation in the residuals, a conclusion echoed by a serial correlation estimate of 0.455, which shows that the residuals are seriously autocorrelated at lag 1. This, coupled with the Breusch–Pagan test pointing to heteroskedasticity with a *p*-value of 0.00, lends weight to the consideration of a model addressing these serial correlations. Both tests suggest SARIMA's potential to address the observed concerns in the residuals.

The next step was to address zeros in the damage data. The transformation ln(Damage + 1) was used. Refer to the resultant plot of variables in Figure 11. To control for the non-stationary nature of the data, a first-difference transformation (where 'd' is substituted by

the differencing order) was executed before performing the spectral analysis (see Figure 12). This transformation helped eliminate any potential trends in the data, which could have otherwise led to misleading results in the spectral analysis.

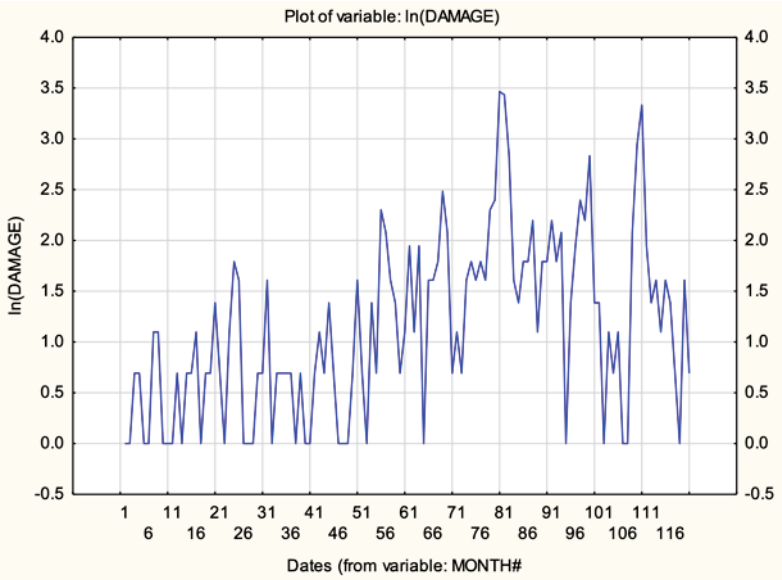

Figure 11. Plot of variables.

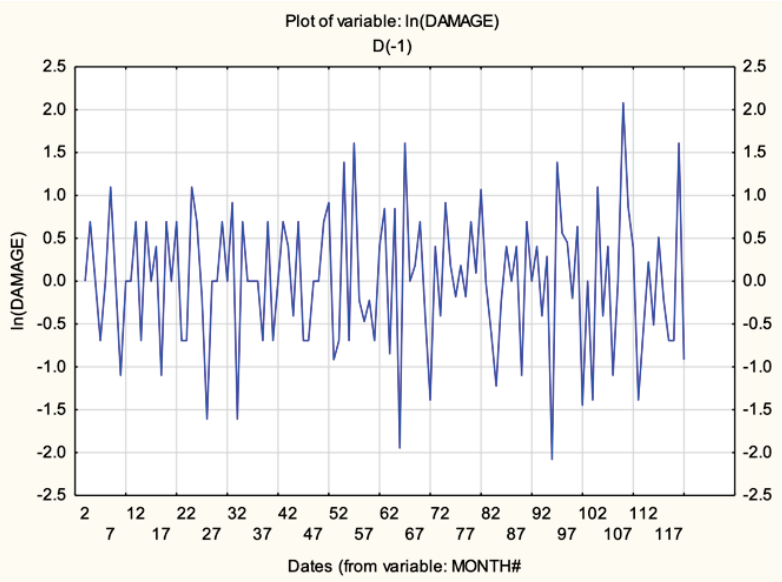

Figure 12. Plot of variables after first order differencing.

Moreover, the stationarity of the series was tested using the augmented Dickey–Fuller (ADF) test. For the original logarithmically transformed series, the ADF test statistic was −1.11 with a *p*-value of 0.26 at four lags without considering an intercept, failing to reject the null hypothesis of a unit root and indicating non-stationarity. Consequently, after applying first-differencing the ADF test yielded a test statistic of −9.12 with a significant *p*-value of 0.01 at three lags, allowing us to reject the null hypothesis and affirming that the differenced series is stationary and suitable for SARIMA modelling.

Autocorrelation (Figure 13) and partial autocorrelation plots (Figure 14) suggested seasonality. The periodogram analysis further affirmed this, which detected a 6-month seasonality, enhanced by Parzen weights for clarity (see Figure 15).

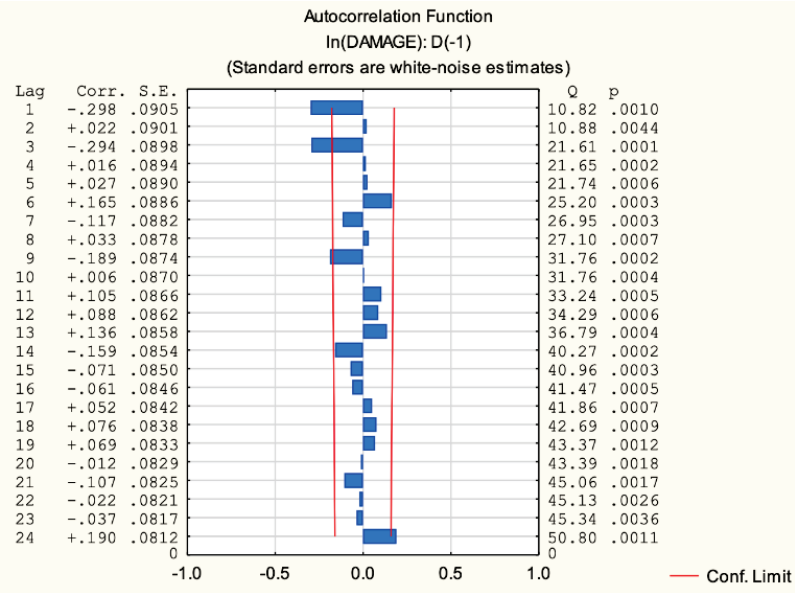

Figure 13. Autocorrelation function.

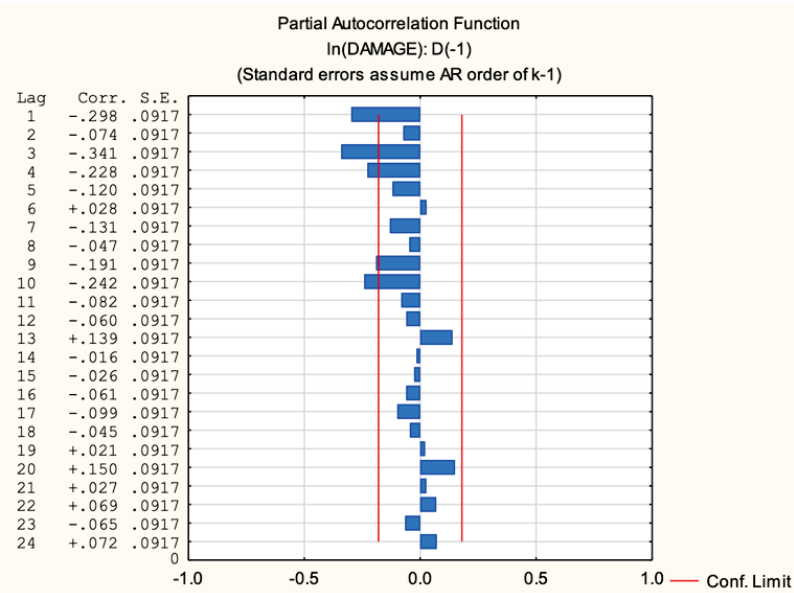

Figure 14. Partial autocorrelation function.

In light of the detected seasonality and serial correlation, a SARIMA model was fitted to the monthly data, specifically a SARIMA $(1,1,1)(1,0,0)_6$ model. The model fit revealed a mean square residual of 0.47404. Each of the model's parameters, p(1) and q(1), were statistically significant (see Table 7). While not statistically significant, the Ps(1) coefficient has a small *p*-value. This model is the best fit found for the monthly logged data.

Table 7. Sarima $(1,1,1)(1,0,0)_6$ model fit results.

Paramet.	Param.	Asympt. Std.Err.	Asympt. t (116)	p	Lower 95% Conf	Upper 95% Conf
p(1)	0.420922	0.099966	4.22333	0.000048	0.223521	0.618323
q(1)	0.924597	0.037381	24.73419	0	0.850558	0.998635
Ps(1)	0.155226	0.101211	1.53369	0.127828	−0.045235	0.355687

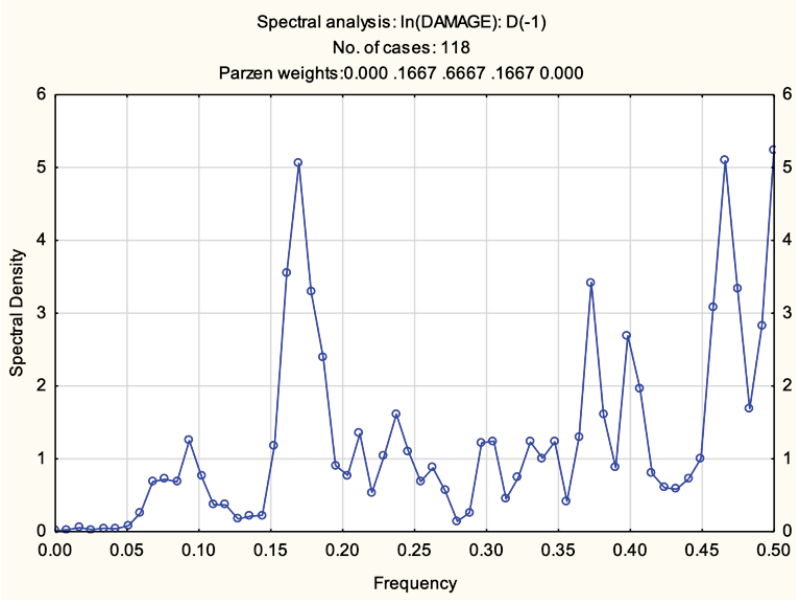

Figure 15. Spectral analysis after Parzen smoothing.

Upon reflecting on potential outliers and their impact on the model, an intervention analysis was conducted considering a possible outlying observation at time 82 as a spike in the data or abrupt, temporary intervention. Despite the discernible presence of this spike, the intervention analysis demonstrated it to be non-significant, thereby not necessitating an explicit model in the SARIMA context. Consequently, the forecasts derived from the SARIMA(1,1,1)x(1,0,0)$_6$ model remain reliable and are not significantly affected by this non-significant intervention.

After the model fit, the residuals were analysed by inspecting their autocorrelation function (Figure 16) and partial autocorrelation function (Figure 17). The Ljung–Box–Pierce portmanteau Q-test on the residual autocorrelations and the tests on the partial autocorrelations indicate that the residuals can be assumed to be white noise.

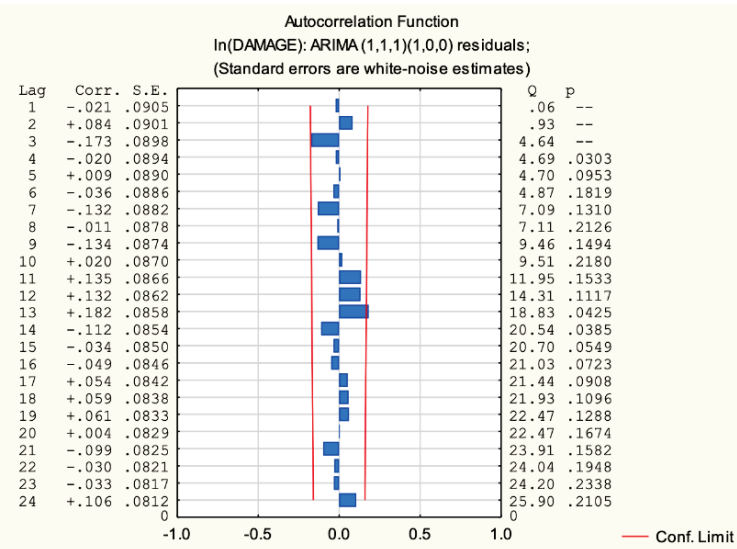

Figure 16. Autocorrelation after model fit.

Finally, the SARIMA model was used to forecast 'Damage' for the next two years (see Figure 18). These forecasts provide insights into future patterns and help with planning and decision making.

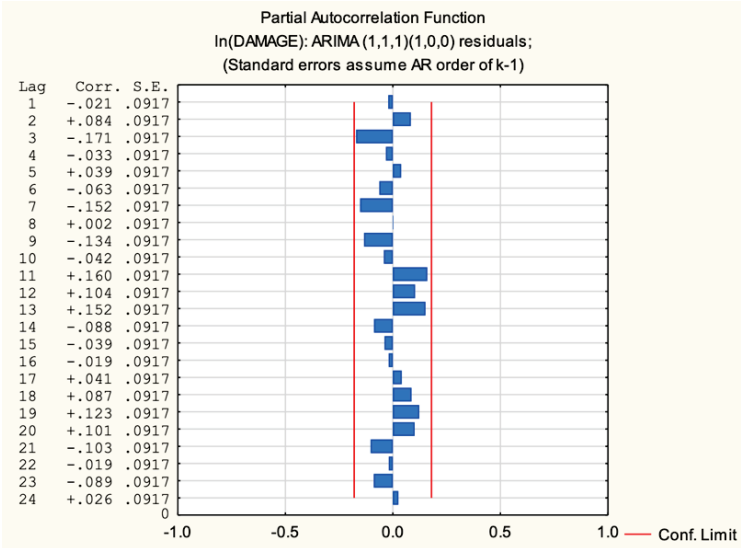

Figure 17. Partial autocorrelation after model fit.

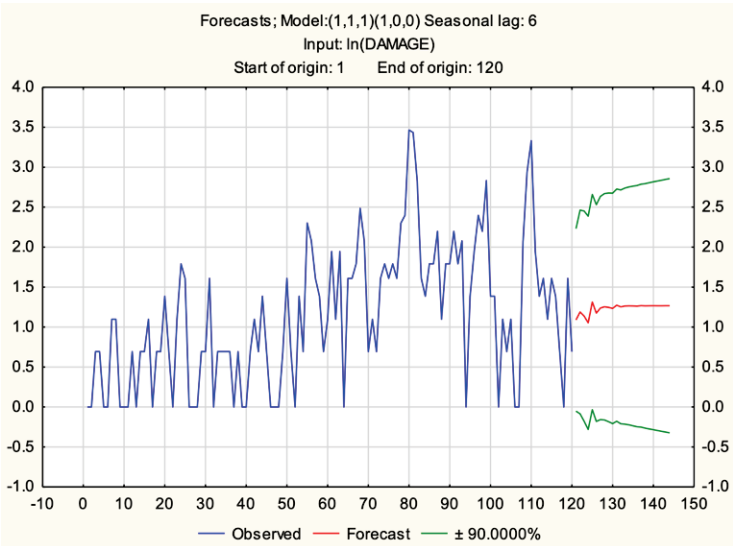

Figure 18. SARIMA forecasting.

The model predicts damage values, captured in the 'FORC DAMAGE' column (see Table 8), ranging approximately from 3.87 to 4.72 over the forecast period (cases 121 to 144). This provides a forecasted range of potential damage magnitudes that can be expected. The damage values in 'FORC DAMAGE' are calculated using X = exp(Y) − 1, where Y is the ln(DAMAGE + 1). This transformation helps in interpreting the forecasts in their original scale.

To check the forecasting accuracy of the SARIMA model, the data was cut-off at time point t = 108 (December 2021) and the same model fitted to the shorter series. The last twelve months is then forecasted. The forecasted ln(DAMAGE + 1) series until t = 120 yield a MAE of 0.9233, an RMSE of 0.7687 and a MAPE of 47.47%, indicating reasonable average accuracy, control over prediction errors and a robust initial framework, respectively. This groundwork provides substantial potential for enhancing predictive accuracy in future research and iterations of fruit damage forecasting.

In summary, the SARIMA model predicts a consistent uptrend in damage over the forecasted cases with slight fluctuations. The transformed 'FORC DAMAGE' values provide monthly actionable forecasts that can be more directly used for planning and risk management regarding fruit damage claims.

Table 8. SARIMA forecasts of fruit damage claims.

Case No.	Forecast	Lower 90.00%	Upper 90.00%	Std.Err.	Forc Damage
121	1.089763	−0.051843	2.231369	0.688504	3.97357031
122	1.188694	−0.08579	2.463177	0.768643	4.28279004
123	1.137321	−0.177845	2.452486	0.793178	4.11840216
124	1.053391	−0.280497	2.387279	0.80447	3.86735794
125	1.313179	−0.032775	2.659134	0.811747	4.71797542
126	1.17514	−0.180502	2.530781	0.817589	4.23859528
127	1.23847	−0.157086	2.634026	0.841662	4.45032979
128	1.254569	−0.161292	2.670431	0.853908	4.5063278
129	1.246908	−0.183012	2.676827	0.862386	4.47956587
130	1.234011	−0.207651	2.675673	0.869469	4.43497983
131	1.274392	−0.178063	2.726848	0.875978	4.57652776
132	1.252988	−0.209833	2.71581	0.88223	4.500789
133	1.262829	−0.213618	2.739275	0.890447	4.53540793
134	1.265332	−0.222754	2.753417	0.897467	4.54426883
135	1.264144	−0.234753	2.763041	0.903987	4.54006227
136	1.262143	−0.247187	2.771473	0.910279	4.53298519
137	1.268412	−0.251155	2.787979	0.916453	4.55520148
138	1.265089	−0.264594	2.794773	0.922554	4.54340948
139	1.266617	−0.273588	2.806821	0.9289	4.54882629
140	1.267006	−0.283392	2.817403	0.935047	4.55020557
141	1.266821	−0.293595	2.827238	0.94109	4.54955122
142	1.266511	−0.303817	2.836838	0.947067	4.54844881
143	1.267484	−0.312675	2.847642	0.952996	4.5519033
144	1.266968	−0.322952	2.856888	0.958883	4.550072

4.4.2. Regression Analysis

Regression analysis is a powerful statistical method widely used in time-series datasets for forecasting [59]. In a time-series context, the goal is to analyse sequential data points, ordered by time, to identify underlying patterns or trends. Regression analysis models the relationship between a dependent variable (the variable to be predicted) and one or more independent variables (the predictors) that are believed to influence the dependent variable.

A linear regression analysis was conducted to investigate the relationship between the year and the total number of fruit damage claims and provide insights into potential future damage claims. Figure 19 presents the scatterplot of fruit damage claims over ten years, and Table 9 the regression summary statistics.

Table 9. Regression summary statistics. * = standardized beta coefficient.

Regression Summary for Dependent Variable: TOTAL FRUIT DAMAGE CLAIMS R = 7.1600293 R^2 = 5.1266020 Adjusted R^2 = 4.5174272 F(1,8)=8.4157 p < 0.01986 Std.Error of estimate: 27.040						
N = 10	**b***	**Std.Err. of b***	**b**	**Std.Err. of b**	**t(8)**	***p*-Value**
Intercept	−3.4000	18.4721	−0.18	0.86		
Year#	0.72	0.25	8.6364	2.9771	2.90	0.02

The regression model demonstrated a strong positive correlation (R = 0.716) between the year and the claims, accounting for 51.3% of the variability (R^2 = 0.513). Statistically significant results (F(1,8) = 8.4157, p < 0.0199) support the validity of the relationship, indicating it is likely not a result of random chance. Figure 20 presents the predicted versus the observed values at a 0.95 confidence interval.

In practical terms, this translates to an average increase of 8.6364 units in fruit damage claims per year. Forecasted data are presented in Table 10. The standard error indicates the typical deviation from the regression line, and the confidence interval for the slope adds further assurance to these conclusions.

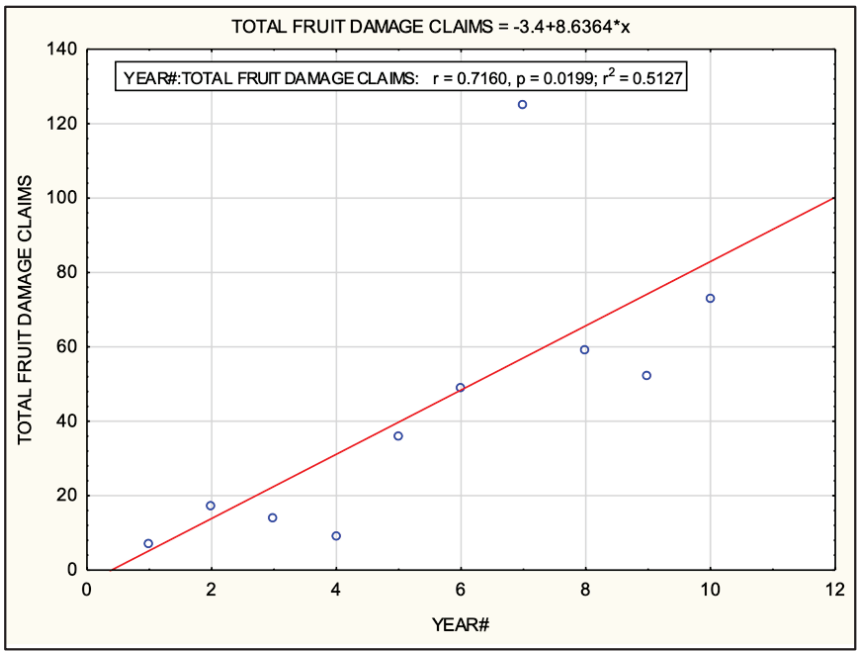

Figure 19. Fruit damage claims scatterplot.

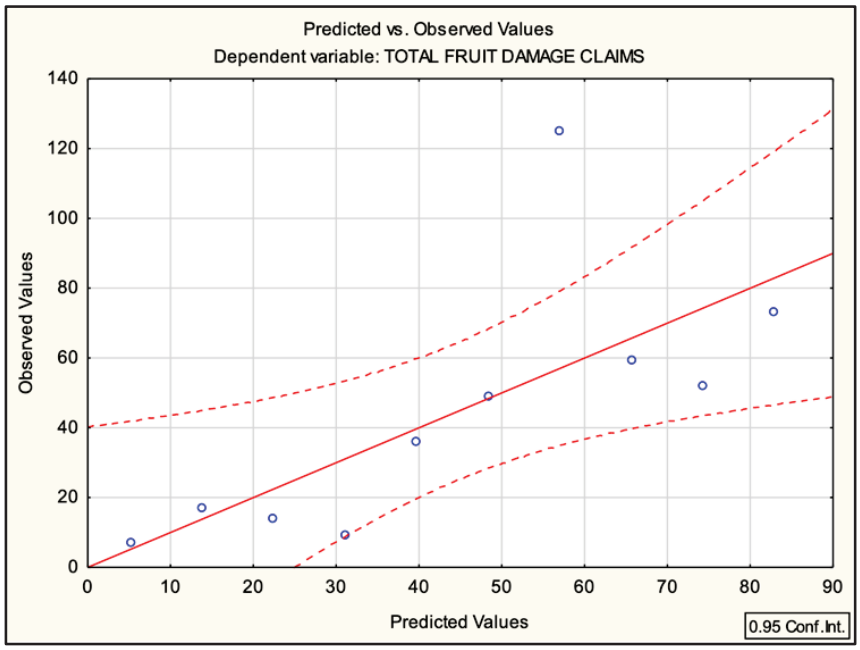

Figure 20. Predicted versus observed values.

The model's statistical significance at the 95% confidence level, coupled with a *p*-value of 0.0199, strongly suggests that the observed relationship is substantive and not due to random fluctuations. To ensure the reliability of these findings, tests were conducted to verify key assumptions of linear regression, such as the independence and constant variance of residuals. Specifically, the Durbin–Watson statistic (1.912180) found no significant autocorrelation and the Breusch–Pagan test (BP = 0.45, $p = 0.50$) detected no heteroskedasticity, validating the model's robustness.

In conclusion, the insights from both SARIMA and regression, in line with the recommendations by Rejeb et al. [56], can be adeptly integrated into planning and risk management. This proactive approach aids in mitigating fruit damage claims, further enhancing food safety.

Table 10. Forecasted fruit damage claims.

Year	Damages	Type
2013	7	Observed
2014	17	Observed
2015	14	Observed
2016	9	Observed
2017	36	Observed
2018	49	Observed
2019	125	Observed
2020	59	Observed
2021	52	Observed
2022	73	Observed
2023	94	Forecasted
2024	102	Forecasted
2025	111	Forecasted
2026	119	Forecasted
2027	128	Forecasted

5. Discussion

Climate change's impact on various global systems and industries constitutes a complex and pressing issue, with the South African fruit export supply chain and marine cargo insurance sectors facing significant challenges that affect food safety. This study examined these vulnerabilities through a unique risk-based perspective.

International research findings highlight that human activities have led to a rise of 1.1 °C in global temperatures since the pre-industrial era, with a marked escalation in the past decade. This warming severely affects South Africa's economy, particularly its vital fruit export industry, which contributes over USD 3 billion annually and employs a significant portion of the workforce. Du Plessis et al. [3] revealed an alarming increase in weather-related cargo claims in South Africa, including extreme outlier years, indicating the marine cargo insurance industry's vulnerabilities. Similarly, the International Union of Marine Insurance has reported a rising trend in such claims worldwide.

Discussions covered climate change, South African fruit exports, food safety and an analysis of marine insurance claims for fruit damage. Nearly half of the world's ports lack strategies to mitigate climate change impacts, resulting in a highly vulnerable and low-resilience supply chain [7]. According to industry experts, South Africa experienced significant logistical challenges in 2019 due to a surge in fruit exports, with increased demands for cold storage and refrigerated trucks, further exacerbated by port congestion from extreme weather damage, labour slowdowns and container buildup, ultimately harming fruit quality, safety and sales (M Marais 2023, personal communication, 02 August) [4]. This aligns with the overall trend revealed in the analysis of fruit damage during distribution from 2013 to 2022, showing increased damage claims after normalising for volume, peaking at 21% in 2019. Concurrently, the table grape industry was recovering from the 2018–19 drought's impact on quality, which saw increased damage claims (M Marais 2023, personal communication, 02 August). In South Africa, the agricultural sector is significantly impacted by climate variations, affecting crop yields, quality and food safety. The repercussions of climate change on food production, agricultural livelihoods and food security have emerged as top national policy concerns, with unstable conditions elevating risks of contamination and spoilage [55].

The complexities deepened further In 2022 when the EU made abrupt changes to the importation requirements for South African citrus, including mandatory cold treatment

at short notice for implementation (M Marais 2023, personal communication, 02 August). This coincides with a spike in delay-related claims in 2022. In addition, the forecast for South Africa's orange production in 2022–23 has been reduced by 1% to 1.63 million metric tons, reflecting weather-related damages and the varying impact of weather conditions on different regions (M Marais 2023, personal communication, 02 August) [37].

From 2017 to 2022, claims related to temperature showed significant deviations above the average, indicating that weather-related events could have affected the fruit export supply chain. This observation aligns with Du Plessis et al.'s [3] findings, which also reported a similar upward trend in weather-related marine cargo insurance claims during this timeframe. The findings emphasise the importance of properly handling and transporting fruit to minimise damage and enhance supply chain efficiency and food safety. These insights emphasise the vital interaction among weather conditions, logistical difficulties and regulatory alterations, accentuating the necessity for a supply chain that is both adaptive and resilient to particular weather conditions and shifting international standards. Consequently, recognising types of fruit damage during distribution enables the enhancement of strategies, amplifying supply chain efficiency and food safety. Fewer damages translate to a safer product for consumers.

The analysis of fruit damage from 2013 to 2022 categorised the claims into five key groups: citrus fruits (30% of total claims), grapes (29%), other fruits (27%), pome fruits (10%) and stone fruits (4%). Citrus fruits had the most significant portion due to a higher market volume. After normalising for volume, the trend was relatively moderate for most of the years except for 2019, which witnessed a significant surge. The damage rate for table grapes after normalising for volume has steadily increased over the years, especially from 2019 onwards, with a peak of 21% in 2022. The different fruit groups exhibited varied patterns, suggesting complex and multi-faceted influences on damage susceptibility. The dataset revealed intricate and varied trends in fruit damage claims across types and years, potentially reflecting factors from susceptibility variations to industry practices. Acknowledging the unique vulnerabilities of each fruit type is paramount, as validated by research from the Food and Agriculture Organization of the United Nations [55]. Understanding specific fruit vulnerabilities and adapting farming and handling methods can significantly reduce post-harvest losses, thereby minimising fruit damage and ensuring safe food products for consumers.

The analysis of fruit damage claims from 2013 to 2022 reveals key seasonal patterns that may inform risk mitigation and quality enhancement strategies. An increasing trend in fruit claims, relative to all claims, is noted, particularly in January and February, possibly reflecting changes in handling or transportation. There are apparent seasonal fluctuations, with June to September experiencing escalating fruit-related claims, peaking in August and September. December to February initially had low claims but showed consistent growth in later years, which coincides with the growth in table grape claims. The months of March to May maintained moderate and relatively stable levels. Sudden spikes were observed in particular months like August 2018 and September 2019, with corresponding declines in October and April over time. Some of these patterns align with Cape Town's winter storms from June to August due to cold fronts and low-pressure systems and the area's intense wind conditions that persist for days during the summer months (December to February) [34]. By accurately allocating resources during perilous seasons and potentially devising season-specific fruit handling, storage and transport guidelines, stakeholders can optimise operations and mitigate risks, with these findings proffering a crucial comprehension of the seasonal dynamics in fruit damage claims, thereby fortifying the agricultural sector's resilience and enhancing overall food safety.

In the forecasted cases 121 to 144, the SARIMA model predicts values between approximately 3.87 to 4.72 per month, a notable uptrend. Concurrently, the linear regression analysis revealed a strong positive correlation between years and total fruit damage claims and predicted a statistically significant increase of 8.6 units in claims annually. Both the SARIMA and regression models indicate an ascending trend in damage claims. These

insights can be effectively harnessed for improved planning and risk management. This proactive stance can help mitigate fruit damage claims, enhancing food safety.

Our findings emphasise the urgent need for targeted policies, preventive strategies and comprehensive investigation into the underlying causes to minimise future damage claims. Attention must be directed towards developing resilience strategies in the maritime supply chain and implementing risk management practices to ensure the continued success and safety of South Africa's fruit export industry in the face of escalating weather-related challenges.

6. Conclusions

Our marine insurance claims data analysis reveals an uptrend in fruit damage reports over the past decade. While our dataset does not enable a direct linkage in every instance of this growth to particular causes, owing to limitations in the description of claims, it is noteworthy that this trend correlates with the period of escalated climate change impact, as documented in various studies [1,38,60] and the troubling rise in weather-related cargo insurance claims in South Africa, as detailed by Du Plessis et al. [3].

Global climate change has been associated with increased temperatures and unpredictable weather patterns, which can harm fruit quality during farming operations, transportation and storage, directly affecting food safety [53]. Furthermore, there are reports of increased port operation disruptions due to extreme weather events, which could potentially affect the handling and storage of perishable goods [20,31,33,34,38].

While climate change presents a compelling potential explanation for the observed increase in fruit damage claims, we acknowledge that other contributing factors could also be at play. These might include changes in agricultural practices, new fruit varieties more prone to damage or even changes in the insurance industry's reporting or claim assessment practices. Therefore, further research is necessary, using more detailed datasets, to isolate the specific factors contributing to this trend.

This study underscores the necessity of a comprehensive approach to managing risks in the fruit supply chain, which may increasingly need to include mitigation and adaptation strategies for climate change. Such measures are paramount to ensuring food safety and maintaining a consistent, quality food supply.

7. Future Work

Based on the extensive findings concerning the interplay between climate change, South African fruit exports, marine cargo insurance and food safety, there is a pressing need for targeted future work to reduce fruit damage and enhance food safety. The key areas to explore and the corresponding actions include:

1. Investigating climate change impact: The observed 1.1 °C increase in global temperatures and its effects on weather-related cargo claims calls for in-depth studies to understand how climate change directly affects fruit damage. This includes assessing extreme weather events, temperature fluctuations and their impacts on transportation, handling and storage. Collaboration with meteorological agencies and climate experts will enable more accurate predictions and adaptive strategies.
2. Developing resilience strategies in maritime supply chains: Nearly half the world's ports lack climate change mitigation strategies. Research must be directed towards innovative solutions and technologies that bolster port and transportation resilience against extreme weather events. This involves creating guidelines, tools and risk management practices applicable globally and then tailored to specific regions.
3. Analysing fruit categories and damage susceptibility: The categorisation of damage claims across different fruit types highlights the need for tailored preventive measures. Further investigations into each fruit category's specific vulnerabilities, market volume and handling practices can lead to targeted strategies to minimise future damage.

4. Enhancing data collection and forecasting models: SARIMA and regression models predicted an upward trend in claims. Future work must focus on continuous data collection and annual updates to enhance accuracy and insights for insurers and the supply chain sectors. In addition, the quality and level of detail included in the claim descriptions should be addressed.
5. Evaluating handling and transportation practices: The detailed analysis of fruit damage claims has shown clear patterns and seasonal fluctuations. Future work should conduct audits and on-site evaluations of handling and transportation practices to identify areas for improvement, implement best practices and use new technologies to enhance supply chain efficiency and food safety.
6. Interdisciplinary research to isolate contributing factors: The complex interplay between climate change events, agricultural practices, fruit varieties and insurance practices requires an interdisciplinary approach. Engaging experts across fields will allow for a nuanced understanding of the contributing factors and the development of comprehensive solutions.
7. Applying FAR models to supply chain management: Investigate the utility of Functional AutoRegressive (FAR) models, proven effective in short-term traffic flow forecasting [61], for predictive management in fruit export logistics. Focus on leveraging FAR models to anticipate maritime transport conditions, optimise logistics and enhance decision making across the supply chain, with an eye toward reducing climate-related damage of exported fruits.

In conclusion, the significant uptrend in fruit damage reports over the past decade, correlated with escalated climate change impacts, demands a multi-faceted and proactive approach. The above future work suggestions aim to foster a comprehensive and targeted response to this complex issue, safeguarding South Africa's vital fruit export industry and contributing to the global goals of food safety and climate resilience.

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Mulch and Grass Cover Unevenly Halt Runoff Initiation and Sediment Detachment during the Growing Season of Hazelnut (*Corylus avellana* L.) in Croatia

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Abstract: Hazelnut orchards are popular for cropping on sloped sites, which are often highly erodible. This study aimed to assess the impact of soil management and season in a hazelnut orchard on soil properties and hydrological response. Three treatments (Tilled, Straw, and Grass) were established in Munije (Croatia) on Stagnosol. In Spring, Summer, and Fall, a rainfall simulation was performed (intensity of 58 mm h^{-1} for 30 min). Results reveal higher water stable aggregate values were observed for the Straw treatment in all seasons. Higher soil organic matter (SOM) content was noticed for the Grass treatment in all seasons, while lower values were recorded for the Tilled treatment. Sediment loss in Summer was up to 650% and 1300% higher for the Tilled treatment compared with the Straw and Grass treatments. This study strengthens the comprehension of utilizing a permanent ground cover in hazelnut orchards as a sustainable practice, contributing to the mitigation of soil erosion processes and the improvement of soil properties. The Straw treatment is a viable option since it increases soil stability and SOM, consequently preventing high soil erosion.

Keywords: ground cover; rainfall simulation; hydrological response; permanent plantation; soil management

1. Introduction

Soil represents an essential resource to all terrestrial life through numerous functions and ecosystem services [1]. The most crucial role of the soil in ecosystems is food production [2]. In addition, soil regulates and filtrates water, regulates climate, remediates contaminants, controls flooding, erosion, and pests, increases biodiversity, and ensures energy supply [3,4]. Since the human population is growing continuously, so is the need for greater food production. Intensive agricultural production helps to ensure food security. However, it can cause soil degradation [5], i.e., soil/water pollution, soil erosion, loss of organic matter and nutrients, crust formation, soil compaction, salinization and acidification, loss of biodiversity, and greenhouse gas emissions. Soil degradation represents a severe global problem [6], which covers up to 30 percent of the global land area and exposes more than 3 billion people to declining ecosystem services [7]. Establishing soil conservation measures is essential [8,9] to halt and reverse the negative impacts of conventional practices.

Soil erosion by water is the most widespread physical soil degradation process, which covers more than 56% of the total degraded land caused by human activity [10]. Typically,

soil water erosion appears on sloped areas, primarily vineyards and orchards [11]. Agriculture activities like conventional tillage, continuous machinery trafficking, or agrochemicals are the main drivers of soil erosion by water [12,13]. Intensive tillage and the removal of surface cover leads to direct exposure of the soil to external factors and decreases the soil organic matter (SOM). Low SOM content usually deteriorates soils' physical, chemical, and hydraulic properties and increases vulnerability to erosion [14–16], often causing on-site and off-site problems [17,18]. Some on-site problems are reduced soil effective depth, organic matter and nutrient loss, low yield, and poor soil structure [19]. In contrast, flooding and water and soil pollution represent off-site problems on a larger scale [20]. In the long term, degraded areas are abandoned. Therefore, it is crucial to adopt climate and soil-friendly practices to ensure farmers' productivity and income and to mitigate soil erosion and degradation.

Proper soil management, establishment of plant cover, use of different mulches, and reduced machinery trafficking (combined operations) significantly affect soil properties and soil erosion [17,21–23]. In the previous literature, soil water erosion has been measured in various permanent plantations: vineyards, olives, avocados, citrus, almonds, and figs [24–28], while research performed in hazelnut plantations was only recently conducted by Telak et al. [29]. Based on the mentioned research [29], it is not possible to determine a realistic erosion rate through the hazelnut vegetation season, since the study was performed only on one occasion. Furthermore, the research was conducted in one location, so more comparison information must be provided. The European hazelnut (*Corylus avellana* L.) is an important crop in Croatia and worldwide [30], and the areas under cultivation constantly increase over the years. Data from 2021 show that the harvested area in Croatia during the 20 years grew from 147 to 6.710 ha and globally from 506.283 to 1.051.684 ha [31]. Hazelnuts usually cover sloping terrain and require more intensive agrotechnical and pomo-technical care during cultivation, including pruning, multiple plant protection applications, several weed management interventions, and harvest, making it a culture suitable for high soil erosion rates [29].

In this research, three different types of soil management were observed. Tillage is the most common practice used in permanent plantations and a known accelerator of soil erosion, while permanent grass cover and straw mulch are two soil conservation measures. Furthermore, this research is carried out over three seasons to determine which treatment can mitigate the adverse effects of intensive management on soil properties and erosion during the hazelnut growing season. Usually, measurements during several seasons in rainfall simulation experiments are missing [11,17,23,24,29] and are often identified as a study limitation, supporting present work as novel and justified. We hypothesize that soil tillage will degrade soil physical properties and enhance the overland flow, while permanent grass cover conserves the soil and water and enhances structure stabilization. Moreover, the straw treatments with surface cover will mitigate the soil erosion but will have lower soil quality in addition to grass treatment. This research aims to expand knowledge about soil erosion in hazelnut plantations and find an adequate measure for its mitigation with a favorable long-term impact on soil properties and hazelnut plantations. Moreover, there are three specific objectives of this paper: (1) to evaluate the impact of various management practices in hazelnut orchards on soil properties, considering different seasons; (2) to identify the most effective sustainable soil management practice for permanent plantation; and (3) to establish a relationship between the soil properties and hydrological response.

2. Materials and Methods

2.1. Study Area and Climate

The study was carried out in central Croatia (Munije: 45°68′ N; 17°29′ E, 296 m a.s.l) in a hazelnut orchard (Figure 1) at an average elevation of 185 m a.s.l and an average slope of 10%. The orchard was planted with a spacing of 5 m between rows and 4 m within rows. The landscape of the studied area was dominantly hilly. The parent material is loess, while the

soil is classified as Stagnosol [32]. According to Köppen climate classification, the climate is moderate continental with a Cfwbx description. The annual precipitation (2020) was 856.6 mm (Figure 2), ranging from a minimum of 11.9 mm (April) to a maximum of 158.1 mm (October). The mean annual temperature for 2020 was 12.1 °C, where January is the coldest (0.7 °C) and August is the warmest (22.3 °C) [33]. Cropland is the dominant land use in this region. However, vineyards and orchards cover the slopes in the study area.

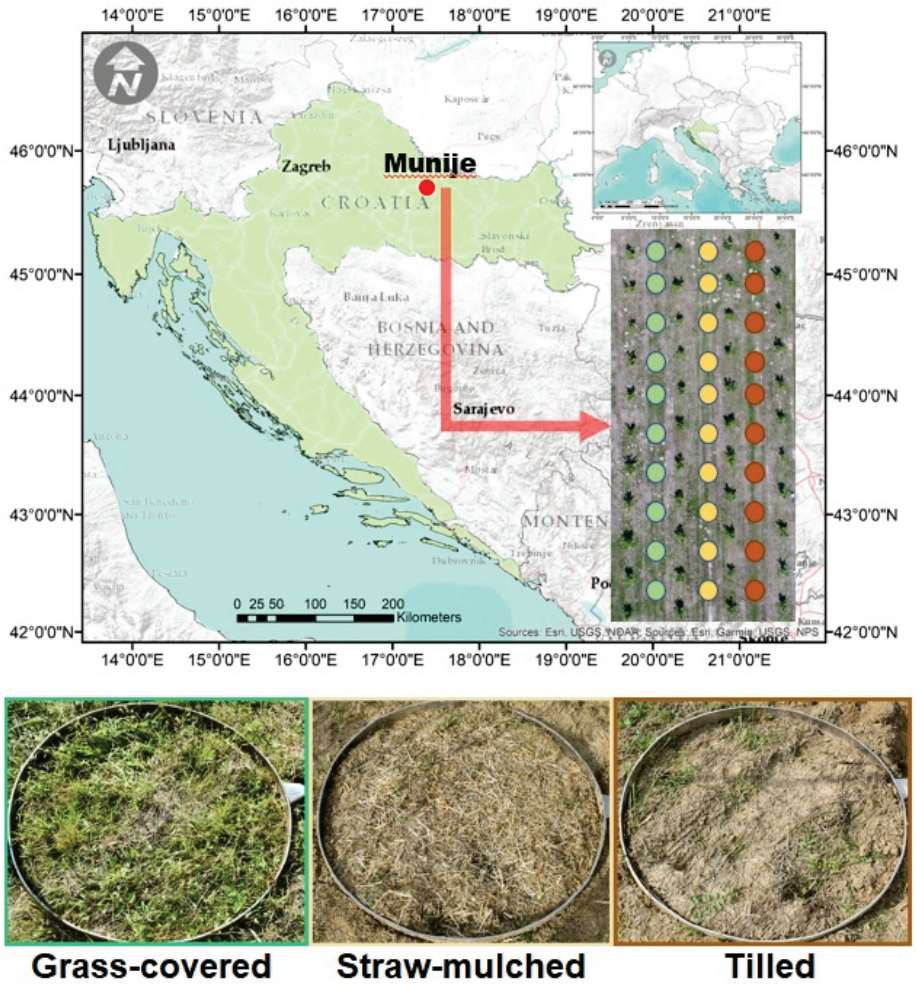

Figure 1. Study site and treatments. Green, yellow and red dots indicate positions of rainfall simulations for grass covered, straw-mulched and tilled plots, respectively.

2.2. Fieldwork

Three different treatments were studied at the location: grass-covered hazelnut orchard (Grass)—natural grass cover; tilled hazelnut orchard (Tilled)—tillage was conducted four times during the experiment (with the use of rotary tiller); and Straw mulched hazelnut orchard (Straw)—Straw was applied every time before the rainfall experiment was conducted at a dosage of 2.5 t ha^{-1}. The grass-covered treatment was mowed five times per year. Each treatment represents an interrow with a length of 40 m. Ten plots were selected for each treatment to conduct the rainfall simulation experiment and to sample the soil using core and additional undisturbed samples. A paired plot strategy was used to ensure similar geomorphological conditions. Ten rainfall simulations with a ring-to-ring distance of approximately 3 m were performed in every treatment. Rainfall simulation experiments were carried out during Spring, Summer, and Fall. In total, 90 rainfall simulation experiments were carried out (3 seasons × 3 treatments × 10 repetitions). Over each plot, a rainfall simulator (UGT Rainmaker, Müncheberg, Germany) [34] was placed to ensure a rainfall at 58 mm h^{-1}

for 30 min. Each plot was enclosed by a metal ring (1 m diameter; 0.785 m^2). Before each simulation started, soil core samples (0–10 cm) and undisturbed soil samples (0–10 cm) were collected near the metal ring to determine soil properties. After the rainfall simulation started, the plastic canisters were connected to the faucet on the metal ring to catch the overland flow. Time to ponding (TP) and time to runoff (TR) were measured with a chronometer (CASIO HS-6-1EF chronometer, Tokyo, Japan) during the simulation.

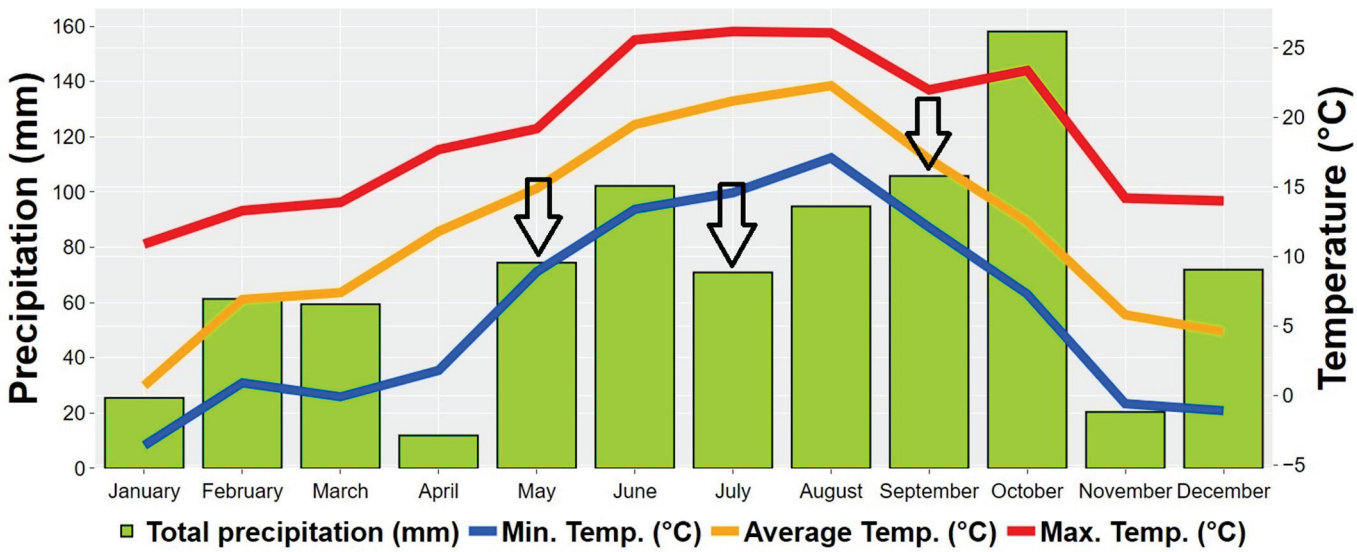

Figure 2. Monthly precipitation and temperature throughout the time of experimenting. The arrows indicate the time when the measurements were conducted.

2.3. Laboratory Work

Bulk density (BD) and soil water content (SWC) were determined using soil core samples. Weighing was carried out before and after capillary wetting and after drying at 105 °C for 48 h, after which they were calculated according to the gravimetric method:

$$\mathrm{BD} = \text{dry sample}/\text{soil volume} \tag{1}$$

$$\mathrm{SWC} = \left(\frac{\text{sample with field water content} - \text{dry sample}}{\text{soil volume}}\right) \times 100 \tag{2}$$

Undisturbed soil samples were prepared by hand, following the method of Diaz-Zorita et al. [35]. Samples were air dried for one week in the laboratory at room temperature (25 °C) and dry sieved in a sieve shaker for 30 s [36] to obtain particular aggregate size fractions (<0.25, 0.25–0.5, 0.5–1.0, 1.0–2.0, 2.0–4.0, 0.4–0.5, and 0.5–0.8 mm) and calculate mean weight diameter (MWD) using the following formula for calculation after weighting each aggregate size:

$$\mathrm{MWD} = \sum_{i=1}^{n} \mathrm{xi} \times \mathrm{wi} \tag{3}$$

where xi is the mean diameter of any particular size range of aggregates separated by sieving, and wi is the weight of aggregates in that size range as a fraction of the total dry weight of soil used. Eijkelkamp's wet sieving method derived from Kemper and Rosenau [37] was used to determine water-stable aggregates (WSA) with Eijkelkamp's wet sieving apparatus on all previously dry sieved samples in the particle size range 1.0–2.0 mm. The percentage of WSA was calculated with the following equation:

$$WSA = \frac{\mathrm{Wds}}{\mathrm{Wds} + \mathrm{Wdw}} \times 100 \tag{4}$$

where WSA is the percentage of stable water aggregates, Wds is the weight of aggregates dispersed in dispersing solution (g), and Wdw is the weight of aggregates dispersed in distilled water (g).

Sediment yield was determined after air drying at room temperature (25 °C) for two weeks and the weighting of the filter paper. Sediment concentration (SC) was calculated by dividing the sediment mass by the overland flow mass. The mass of the sediment loss (SL) was given from the mass of overland flow to obtain the runoff [24]. After determining MWD and WSA, all the undisturbed samples were milled and sieved through a 2 mm sieve so the samples could be prepared to determine SOM following the digestion method of Walkley and Black [38].

2.4. Statistical Analysis

Before further data analysis could be performed, the Shapiro–Wilk test ($p > 0.05$) was used to assess the normality of the data and homogeneity of variances. Since some variables did not follow the normal distribution (except for BD and WSA), some were normalized with SQRT, natural logarithm, and Box–Cox transformations (SOM, TR, SWC, SC). The two-way ANOVA and Kruskal–Wallis tests (MWD, TP, runoff, and SL) were performed to assess the impact of soil management and season on soil properties and soil hydrological response. For results that did not show significant differences at a $p < 0{,}05$, Tukey's LSD post hoc test was performed. Based on the correlation matrix, principal component analysis (PCA) was applied to determine the association between variables. For this purpose, were used Box–Cox transformed data. Data analyses were carried out using Statistica 12.0 [39] for MS Windows. Figures were drawn with Plotly [40]. The original data set was used to create all tables and graphs.

3. Results

3.1. Soil Properties

The statistical analysis showed a significant difference in BD for the Tilled and Straw treatment, where lower values were observed during Spring than in Summer and Fall. Unlike the Tilled and Straw treatments, the Grass treatment showed no significant differences for BD across seasons (Table 1). As for differences in season, significantly higher BD values were recorded for the Grass treatment during Spring compared to Tilled and Straw. BD did not differ between the treatments in Summer and Fall, although the Grass recorded the highest compaction level. The SWC values for the Grass treatment were significantly lower in Summer compared to Spring, while the values in Fall did not differ significantly from those observed in Summer and Spring. Significant differences in SWC values between treatments were observed only in Summer, where the Grass treatment had significantly lower values than Straw.

Table 1. Results of two-way ANOVA analysis considering soil properties (mean ± standard error). Different letters after mean values in the columns represent significant differences at $p < 0.05$. Capital letters show statistical differences in treatment between seasons. Lowercase letters show statistical differences between treatments in season. Abbreviations: BD, bulk density, SWC, soil water content, MWD, mean weight diameter, SOM, soil organic matter.

Treatment × Season	BD (g cm^{-3})	SWC (%)	MWD (mm)	WSA (%)	SOM (%)
Tilled (Spring)	1.08 ± 0.30 Bb	29.69 ± 1.93 Aa	3.67 ± 0.53 Aa	66.27 ± 1.46 Ab	1.81 ± 0.46 Aa
Straw (Spring)	1.09 ± 0.31 Bb	28.58 ± 1.89 Aa	3.45 ± 0.55 Aa	75.67 ± 2.22 Aa	1.80 ± 0.44 Aa
Grass (Spring)	1.49 ± 0.26 Aa	31.86 ± 1.76 Aa	3.52 ± 0.41 Aa	67.12 ± 1.99 Ab	1.95 ± 0.35 Aa
Tilled (Summer)	1.37 ± 0.32 Aa	30.35 ± 2.18 Aab	2.78 ± 0.47 Bb	61.21 ± 1.62 ABb	1.50 ± 0.48 Ab
Straw (Summer)	1.33 ± 0.29 Aa	30.86 ± 1.42 Aa	2.8 ± 0.38 ABb	71.82 ± 2.22 Ba	1.91 ± 0.44 Aa
Grass (Summer)	1.44 ± 0.34 Aa	25.31 ± 1.89 Bb	3.53 ± 0.43 Aa	63.39 ± 2.03 Ab	2.08 ± 0.52 Aa
Tilled (Fall)	1.29 ± 0.34 Aa	31.92 ± 1.50 Aa	2.68 ± 0.50 Bb	59.32 ± 1.96 Bb	1.42 ± 0.53 Ab
Straw (Fall)	1.32 ± 0.34 Aa	32.21 ± 1.22 Aa	2.59 ± 0.61 Bb	69.47 ± 1.74 Ba	1.83 ± 0.61 Aab
Grass (fall)	1.36 ± 0.25 Aa	29.25 ± 2.23 ABa	3.49 ± 0.38 Aa	68.63± 2.10 Aa	1.93 ± 0.76 Aa

Statistical analysis showed significantly higher MWD values for the Tilled treatment in Spring compared to Summer and Fall. Straw treatment showed significantly lower MWD values in Fall than in Spring (Table 1). The highest MWD value in Spring was for the Tilled treatment, which was followed by the Grass treatment and the Straw treatment. During Summer, MWD values were significantly higher in the Grass treatment compared to Tilled and Straw. The same pattern was noticed in the Fall (Table 1). The WSA values for the Tilled treatment were significantly lower in the Fall than in the Spring. Straw treatment showed significantly lower WSA values during Fall and Summer compared to Spring. As for intra-seasonal differences, the Straw treatment had significantly higher WSA values across all seasons than the Tilled and Grass treatments (Table 1).

SOM did not show significant differences in treatment through the seasons (Table 1). During the Summer, Straw and Grass treatments had significantly higher SOM values than the Tilled treatment. The Grass treatment in Fall had a significantly higher SOM value compared to the Tilled.

3.2. Hydrological Properties

Soil hydrological response showed significant differences for treatment and season (Table 2). Time to ponding values for the Tilled and Straw treatments were the lowest in Fall and the highest in Spring, and there were no statistically significant differences among seasons. Grass treatment also shows the highest TP value in Spring, which is significantly higher than in Fall. Between treatments, in the Fall, the TP value is significantly lower in the Grass treatment compared to the other two treatments. Straw treatment had a significantly higher value of TR in Spring than in Fall, while Grass treatment showed significantly lower values for TR in Fall compared to Summer and Spring. Tilled and Straw treatment during all seasons showed significantly higher TR values than Grass treatment. Furthermore, Straw treatment in all seasons had the highest values for TR (Table 2). Runoff did not show significant differences for any treatment during the seasons, while significant differences between the treatments occurred in each season. The Grass treatment in Spring had significantly higher runoff values compared to the Tilled and Straw treatments. Significantly higher runoff values were observed in the Grass treatment in Summer and Fall compared to the Straw treatment. Sediment concentration for the Tilled treatment was significantly higher in Summer compared to Spring. Straw treatment recorded a significantly lower SC during Spring than in other seasons. The SC values in the Grass treatment increased from Spring to Fall, and no significant differences in results were recorded between seasons. In Spring, the lower SC value was in the Grass treatment compared to the tilled, while the Straw treatment did not show a significant difference compared to the other two. During the Summer, there was a significant difference between all three treatments. The tilled treatment recorded the highest value of SC, which was followed by the Straw and Grass treatment. Sediment loss for the Tilled treatment was significantly higher in the Summer and Fall periods than in Spring. The Straw treatment followed the same pattern as Tilled, with the highest value of SL in Summer and the lowest in Spring. SL values increased from Spring to Fall for Grass treatment, and no significant difference existed between seasons (Table 2).

Table 2. Results of two-way ANOVA analysis considering hydrological properties (mean ± standard error). Different letters after mean values in the columns represent significant differences at $p < 0.05$. Capital letters show statistical differences in treatment between seasons. Lowercase letters show statistical differences between treatments in season. Abbreviations: TP, time to ponding; TR, time to runoff; SC, sediment concentration; SL, sediment loss.

Treatment × Season	TP (s)	TR (s)	Runoff (m^3 ha^{-1})	SC (g kg^{-1})	SL (kg ha^{-1})
Tilled (Spring)	192 ± 7.87 Aa	582 ± 12.24 Aa	19.71 ± 3.63 Ab	4.86 ± 1.56 Ba	87.15 ± 7.81 Ba
Straw (Spring)	288 ± 15.37 Aa	996 ± 20.51 Aa	2.47 ± 1.63 Ab	2.96 ± 1.81 Bab	11.97 ± 4.22 Ba
Grass (Spring)	198 ± 9.22 Aa	348 ± 8.89 Ab	160.24 ± 4.42 Aa	0.73 ± 0.62 Ab	118.08 ± 8.26 Aa

Table 2. *Cont.*

Treatment × Season	TP (s)	TR (s)	Runoff (m^3 ha^{-1})	SC (g kg^{-1})	SL (kg ha^{-1})
Tilled (Summer)	144 ± 7.11 Aa	462 ± 12.45 Aa	90.15 ± 5.77 Aab	18.79 ± 2.25 Aa	1742.84 ± 29.99 Aa
Straw (Summer)	180 ± 8.32 Aa	606 ± 10.71 ABa	45.78 ± 6.09 Ab	5.64 ± 1.25 Ab	268.4 ± 15.15 Aab
Grass (Summer)	120 ± 5.32 ABa	342 ± 9.22 Ab	159.31 ± 6.63 Aa	0.83 ± 0.54 Ac	133.2 ± 8.52 Ab
Tilled (Fall)	120 ± 7.00 Aa	444 ± 12.77 Aa	70.64 ± 6.15 Aab	11.57 ± 2.93 ABa	850.23 ± 25.94 Aa
Straw (Fall)	156 ± 8.02 Aa	484 ± 12.77 Ba	35.75 ± 6.83 Ab	11.53 ± 4.43 Aa	204.07 ± 15.65 Aa
Grass (Fall)	86 ± 6.87 Ba	225 ± 11.25 Bb	194.62 ± 6.41 Aa	2.67 ± 2.48 Ab	406.42 ± 29.30 Aa

3.3. Principal Component Analysis

The PCA revealed two major factors that explain 51.45% of the total variance: Factor 1—27.30% and Factor 2—24.16%. Figure 3 shows the projection of the variables for the relation between two major factors. Factor 1 showed a strong negative connection between BD and runoff with TP, TR, and WSA. While Factor 2 explains a positive relation between SC and SL, there is also a negative correlation between SOM and MWD with SWC (Figure 3). Differences are more clearly distinct for treatments than for seasons. The Tilled treatment is more closely related to negative variables, such as SC and SL.

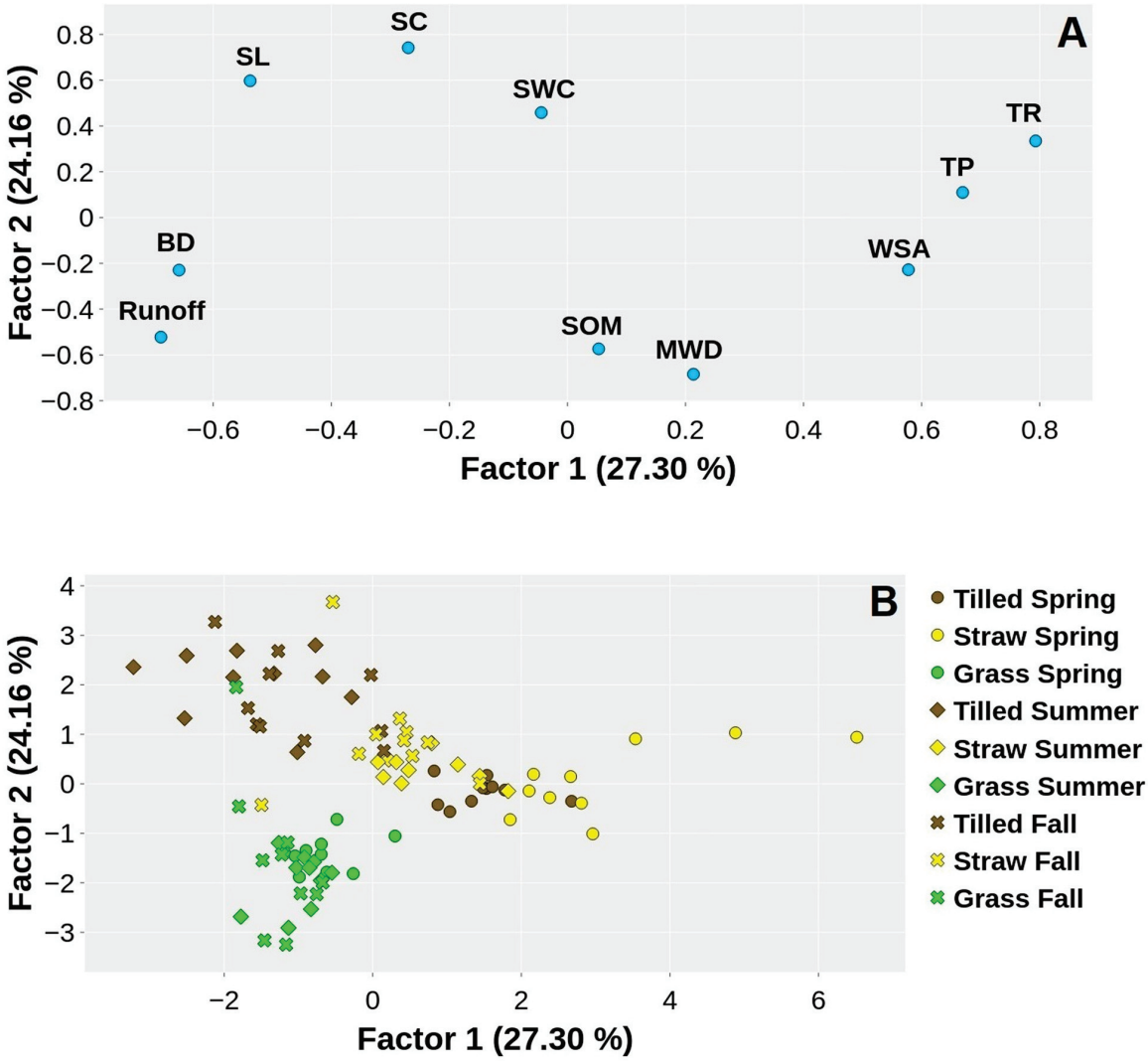

Figure 3. Relation between Factors 1 and 2 (**A**) variables and (**B**) cases. Bulk density (BD); soil water content (SWC); mean weight diameter (MWD); water stable aggregates (WSA); time to ponding (TP); time to runoff (TR); sediment concentration (SC); sediment loss (SL).

4. Discussion

4.1. Soil Properties

The higher BD values were recorded for the Grass treatment compared to Tilled and Straw in all seasons. This behavior was expected, since tillage was conducted for the Tilled and Straw treatment. Tillage loosens the topsoil layer and modifies soil structure [21,41], while greater compaction for the Grass treatment occurs due to natural settling and machinery trafficking, as observed previously [42–45]. There were no differences in SWC in Spring due to similar conditions between the treatments since the tillage and straw application were carried out where Grass was grown. In the Summer and Fall periods, lower SWC values were recorded for the Grass treatment compared to Tilled and Straw. This could be explained by high rainfall throughout the vegetation season (Figure 2), which ensures high SWC in all treatments. Partial consumption of SWC for the Grass treatment decreases the moisture in addition to other treatments. In this context, the Tilled and Straw treatments did not have vegetation consumption of water, while straw application additionally conserved soil moisture [46,47] through the high-temperature period in Summer and early Fall (Figure 2). Although SWC differences in treatments occur, the high SWC enables hazelnut water needs.

The MWD in Summer and Fall recorded higher values for the Grass treatment compared to Tilled and Straw due to (1) higher machinery-induced compaction [48,49], (2) absence of tillage for the Grass treatment, and (3) short period of straw decomposition to affect soil aggregation [50]. The Tilled and Straw treatment recorded higher MWD values in Spring than in Summer and Fall because of (1) frequent tillage events for the Tilled treatment later in the season [51], (2) lack of time for the soil to form aggregates [21], and (3) straw application, which enabled natural conditions to affect the soil, because the straw layer served as a physical barrier [52]. The Grass treatment did not show any significant differences in all seasons since the grass cover is well known for its established root system, which will contribute to stable aggregates by promoting root growth and the secretion of organic compounds [53,54]. The WSA in Spring and Summer recorded significantly lower values for the Tilled and Grass treatment. As Straw protects against the impact of raindrops, preventing soil particles from being dislodged and reducing soil crusting [55], it contributes to preserving soil aggregates. Likely, this affected the higher WSA values observed in the Straw treatment. As the SWC data highlight, the straw cover shields the soil from direct sunlight and wind, reducing the evaporation rate. This helps maintain a more consistent moisture content in the soil [56], supporting aggregate stability. Moreover, the straw cover creates a conducive environment for root growth [57], which aids in binding soil particles and enhancing aggregate stability. In Fall, lower values of WSA were noticed for the Tilled treatment compared to Straw and Grass. This pattern follows the values of SOM in that period, since SOM is most responsible for binding soil particles into larger and more stable aggregates [58]. Tilled treatment through seasons recorded lower WSA values in Fall, when the effect of frequent tillage was noticeable, because of soil disturbance and air exposure, which led to a decrease in SOM, thus directly affecting aggregate stability [59]. The Grass treatment showed no significant differences for WSA between seasons, since the permanent grass cover and well-developed root system secured aggregate stability through seasons. This is achieved when the root system binds soil particles together, thus enhancing aggregate stability [60]. On the other hand, grass plants shed organic material through roots, shoots, fallen leaves, and mowed grass, so this organic matter serves as a food resource for microorganisms. This activity will produce a substance that acts as natural glue that binds soil particles into aggregates [61]. In Summer and Fall, the Tilled treatment had lower SOM values than Grass and Straw, as observed elsewhere [62–66]. This phenomenon occurred due to (1) accelerated decomposition under high oxygen levels [67], (2) disruption of soil structure due to constant tillage events [58,68], and (3) a lack of vegetation cover, which plays a vital role in protecting the soil from erosion (loss of SOM by erosion) [69,70]. The Tilled treatment has higher SOM values in Spring than in other seasons, which is very

likely due to soil loss between investigated periods, as presented in Table 2. Also, organic matter mineralization can explain lower SOM values in later periods [71].

4.2. Hydrological Response

The Tilled and Straw treatment did not have any significant differences in TP between seasons because of the lower soil compaction, thus increasing the infiltration rate due to frequent tillage [45,72] and straw application, which served as a physical barrier, thus slowing the formation of surface ponds [52]. Time to runoff was low in the Grass treatment through all three seasons, as noted in other works [73–75]. The TR values were slightly higher for the Straw treatment than for the Tilled treatment during each season. So, the straw application contributed to reducing TR, as it served as a surface cover that acted as a physical barrier between raindrop impact and soil surface cover [76,77]. Straw, like grass, also absorbs moisture, thus postponing surface runoff [78]. The Tilled treatment recorded no significant differences between seasons for TR. In contrast, the Straw treatment had higher TR values in Spring because the first straw application successfully reduced TR. Later in the season, during Summer, Straw was slowly incorporated into the soil surface, thus losing its initial capability of reducing TR [79]. In Fall, TR was significantly lower on the Straw treatment compared to other seasons since (1) the Straw decomposed in time, thus increasing TR, (2) vegetation growth in Fall was lower and made soil prone to erosion [80], and (3) the absence of Straw contributed to crusting during the Fall period; because of decomposition, it can lose its protective qualities and transform into small particles that can clog soil pores [81]. The Grass treatment showed higher TR values in Spring and Summer than in Fall, which are also affected by mowing and the higher surface cover. At the same time, there was no additional cover in Fall, and regular vegetation growth was lower than in Spring and Summer. The runoff followed the behavior of TR. In every season, higher runoff was recorded for the Grass treatment compared to Tilled and Straw. This is attributed to several reasons: (1) higher compaction for the Grass treatment [82,83], (2) lack of surface roughness for the Grass treatment [84], and (3) the Straw treatment had a mulching effect [77,85]. Sediment concentration recorded significantly lower values for the Grass treatment since grass decreases sediment detachment during rainfall because of greater soil structure and a developed root system, which holds the soil particles bonded through root exudates [86,87]. Higher values of SC for the Tilled treatment occur primarily due to tillage, which decreases soil size particles and makes them more prone to soil erosion [88]. The Straw treatment recorded lower SC in Spring and Summer than in Fall due to losing the straw capability through the season and its incorporation into the soil surface [89]. An increase in SC for the mulched treatment is possible when the finer mulch particles are easily transferable during rainfall [90].

In the Summer, a higher SL was identified in the Tilled treatment than in Grass and Straw. This was due to the low SOM, which helps bind soil particles, making them more stable [91,92], and the lower surface roughness because of recent tillage events [88,93]. The Tilled treatment had a significantly lower SL in Spring than in Summer and Fall due to the freshly tilled soil surface, higher infiltration rate, and lower soil compaction [13]. Similar results were found for the Straw treatment, where higher SL was noticed in Summer and Fall when the straw application was insufficient to mitigate soil erosion processes and because of straw incorporation into the soil surface [52,78]. The Grass treatment showed no statistical differences for SL during all three seasons, with a slight increase in Fall, which was probably due to mowing grass residues, which ended up in the overland flow.

4.3. Interrelations between Properties

The PCA results showed that lower soil compaction leads to postponed pond forming on the soil surface layer and the start of the Runoff, which was also observed previously [94–97]. Moreover, the WSA showed a positive relation with TP and TR because of (1) WSA's capability to create channels within the soil that will enable water to infiltrate and move down the soil profile, which will improve the soil's ability

to store more water, thus reducing the water available for runoff [98,99], (2) higher aggregate stability will prevent crusting, since the soil particles are bounded into aggregates that are less prone to soil detachment during the raindrop impact [97,100], and (3) well-aggregated soil had a rougher surface texture due to the presence of clumps and particles, which will enlarge the surface area for rainfall catchment [101]. Another positive correlation was observed between BD and runoff, which can be associated with the previously mentioned statement that BD directly affects TP and TR. Due to higher soil compaction, there will be more time to produce the overland flow, which will enlarge the final amount [102,103]. The BD decreases porosity, resulting in limited storage capacity and lower infiltration capacity [104,105]. Furthermore, compacted soils are more prone to soil crust formation, thus enabling the rainfall drop impact to initiate soil detachment [106,107].

Factor 2 explains a positive relation between MWD and SOM. Soil organic matter acts as a binding agent that holds the soil particles together in aggregates [58,108,109]. Larger aggregates created through organic matter enhanced aggregation and will increase the pore space in the soil, thus enabling water to infiltrate and move through the soil [110,111]. A strong positive relation occurred between SC and SL, meaning SL is directly influenced by the amount of sediment in the overland flow [112,113]. In the case of this study, this statement could not be completely applicable because the Grass treatment in Spring recorded higher SL than the other two treatments, therefore not having the highest SC under higher runoff rates (Table 2). Similar findings were observed in Römkens et al. [93]. Finally, a positive correlation was observed between SWC, SC, and SL. This relation was expected because higher SWC will lead to pore clogging, thus decreasing the soil infiltration capacity [113]. On the other hand, it will also expedite the time to runoff, thereby increasing overland flow mass and with that increasing SL. Another vital thing to mention is the SWC's effect on hydraulic conductivity, where wetter soil can lead to rapid surface runoff, carrying away more sediment than in drier conditions [113].

This research yields valuable insight with significant implications and recommendations that can arise from it. However, some issues need to be mentioned. The timing of practices should be considered since the research showed the effectiveness of grass cover use, and as such, it could be crucial to emphasize and maintain the grass cover before the rainy season starts. Long-term research is necessary to obtain more appropriate information for identifying the practices that offer the most effective protection against soil loss. With that in mind, implementing practices that enhance soil structure to mitigate erosion must be broadened and applicable to this location and other endangered areas. Further investigation of the impacts of conservation practices is recommendable to minimize erosion events, thus mitigating sediment transport, which can lead to the pollution of soil and waterways. These practices must be emphasized long term to contribute to soil health, erosion prevention, and environmental conservation. Unfortunately, the rainfall simulator has shortcomings, such as a need for standardized methods and equipment. An experiment conducted on a small-scale area is unsuitable for large-scale modeling and needs to provide accurate data under natural climate conditions. One of the essential things that needs to be mentioned is the use of surface cover, whether it will be a permanent cover or just a temporal cover such as Straw. Straw use will mimic permanent grass cover in some percentage. However, its most significant advantage lies in its availability, cost-effectiveness, and immediate soil conservation, thus enhancing soil properties and hydrological response.

5. Conclusions

This study presented significant results regarding how different soil management and seasons affect soil properties and hydrological response. The Grass treatment was the most sustainable, as it enhanced soil properties, such as increasing SOM and WSA while decreasing BD, and effectively mitigated erosion processes to the bare minimum. Conversely, the Tilled treatment exhibited shortcomings, disrupting soil properties by decreasing MWD, SOM, and WSA while increasing runoff, SC, and SL. Meanwhile, the Straw treatment showcased its positive aspects, notably improving

soil properties by decreasing BD, increasing WSA and SOM, and having a beneficial impact on mitigating sediment movement downslope. The primary seasonal effect was observed in the hydrological response, with higher TR and TP in Spring and increased runoff rates, SC and SL in Fall across treatments. Conservation management must be deeply implemented into agricultural practices since it can reduce and slow down further degradation processes in endangered areas, such as permanent plantations characterized by wide rows and lack of surface cover, as a weeding practice. The Grass and Straw treatments demonstrated their sustainable and dependable practices, enhancing soil properties and minimizing potential degradation in hazelnut plantations.

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Value Chain Digitalisation and Adoption Intention by Proactive Land Acquisition Strategy (PLAS) Farmers in the Eastern Cape Province, South Africa

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Abstract: Digital technologies disrupt agricultural value chains, thereby facilitating enhanced connectivity among various players. This contributes to the development of resilience and sustainability within farms. This study examined behavioural factors that influence farmers' intentions to adopt value chain digital technologies available in South Africa. A simple random sample of 100 Eastern Cape PLAS farms was chosen. Data was collected using a semi-structured questionnaire. The data was analysed in R and STATA statistical packages using the unified theory of acceptance and use of technology (UTAUT) and structural equation modelling (SEM). The results indicated a significant relationship between performance and effort expectancy and the intention to adopt value technologies. Furthermore, male farmers had a higher expectation of performance and effort. Prioritising performance demonstrations and trainings on the utilisation of these technologies is crucial in efforts to enhance their adoption. This contributes to the existing body of literature on the deployment of value chain technologies.

Keywords: digital technologies; value chain digitalisation; land reform; proactive land acquisition strategy; behavioural factors; adoption intention

1. Introduction

The agricultural sector of South Africa carries the historical legacy of apartheid, which contributed to the country's dualistic agricultural landscape. As documented by Greyling and Vink [1], entrenched dualism can be traced back to apartheid-era land confiscations. Although this dualism has perpetuated inequality in the sector, the land reform programme was designed to facilitate transformation [2]. The primary intervention of the land reform programme is the provision of land to establish black commercial farmers. The government identifies commercial land, acquires it, and leases it to previously disadvantaged aspiring black farmers through the Proactive Land Acquisition Strategy programme (PLAS), the current strategy for implementing the redistributive land reform program.

Despite efforts to address inequalities in South Africa's agrarian sector via redistributive land reform and various government support programmes, criticisms persist, including concerns about land market distortions, delayed progress, and a lack of transformative impact [1,2]. Budgetary constraints and institutional capacity limitations have added to the complexity of implementing the land reform programme [3]. These complexities render the PLAS programme ineffective in addressing the dual nature of agriculture in South Africa and promoting inclusive development. The emergence of agricultural digitalisation, which involves the incorporation of contemporary digital solutions into agriculture [4]

presents a promising opportunity to advance inclusive development in the South African agricultural sector. South African farmers participating in PLAS have access to various digital value chain options, which they can customise to meet the specific needs of their agricultural operations. Furthermore, these digital solutions possess a synergistic quality that enables farmers to utilise multiple applications, thereby facilitating their integration of value chains [5]. The technologies relevant for digitalisation in the value chain include mobile applications, online digital platforms, and blockchain technology for online commerce and the tracking of agricultural products. For example, HelloChoice is a prominent South African online marketplace that connects sellers and consumers of fresh produce. Nevertheless, there are no studies that have investigated the behavioural factors that affect the adoption intention of PLAS farms in the Eastern Cape Province of South Africa.

Literature has investigated the topic of PLAS from various perspectives, including factors associated with the success of redistributed land reform farms [6], beneficiary selection procedures [7], and the determination of viable land sizes to improve performance on redistributed land reform farms [8]. Some studies have attempted to estimate the impact of digitalisation on performance metrics such as financial performance, productivity, and profitability [9,10]. The parameters to be considered when devising an agricultural digitalisation policy and the implications for the land reform programme have also been analysed [5]. However, there is a significant gap in the existing literature regarding the PLAS farmers' adoption intentions for various value chain technologies in the Eastern Cape, as well as the behavioural factors associated with their adoption intentions. Consequently, this study sought to investigate the role of digitalisation and the adoption of value chain digital technologies in advancing these objectives while also examining the factors influencing a higher adoption rate of these technologies.

Therefore, understanding various digital solutions available for agriculture, their associated costs, infrastructure requirements, and technical demands is crucial, as these factors can significantly impact farmers' intentions to implement digital solutions for the value chain. This is important for upstream high-tech firms, as their efforts to develop digital agricultural solutions can be matched with farmers' needs. The absence of scientific evidence regarding the behavioural factors influencing farmers' intentions to implement such technologies may lead to the development of digital agricultural solutions that do not meet farmers' requirements. Behavioural factors include what farmers perceive with regards to the performance, infrastructure requirements, social influence, and effort required to use a particular technology [11]. Farmers have shown limited enthusiasm for most digital agricultural solutions due to a top-down development strategy that frequently disregards their needs [12].

The Eastern Cape Province is mostly rural and one of the major producers of livestock in South Africa. Poor development of digitalisation among Eastern Cape farmers, particularly PLAS farmers, could lead to the digital divide. Consequently, it is critical to understand how digital technologies in the value chain could assist PLAS farmers in becoming integrated into their respective industry value chains, thereby enhancing their resilience and sustainability. Moreover, it is important to provide valuable insights into how behavioural factors and the identification of behavioural factors that affect farmers' intentions to adopt value chain digitalisation are crucial for promoting inclusive digital development and effective in mitigating the digital divide within South Africa's dual agricultural sector. This will ultimately lead to the sector's long-term sustainability.

The Eastern Cape region predominantly comprises rural inhabitants; a significant portion of them reside in the old homelands that were designated for black individuals during the apartheid period. These areas are known for their dependence on subsistence and small-scale agricultural practices [7]. The demographic makeup of the province may be a contributing factor to the restricted advancements in digitalisation within the agricultural sector. This phenomenon can be attributed to the fact that the PLAS programme predominantly recruits participants from the pre-existing population of local farmers. Although the government provides support for PLAS farms [6], the difficulties encountered

by small-scale farmers in the area may have an impact on the performance of PLAS farms, as already evidenced by below-average productivity.

The aim of the study is to determine the behavioural factors that affect the adoption intention of value chain digitalisation by Eastern Cape PLAS farmers. It investigates the way in which the adoption and utilisation of value chain digital technologies are impacted by the perceptions of proactive land acquisition strategy (PLAS) farmers with regards to infrastructure, effort, performance, and social influence. The study begins by reviewing related literature on the concept of digitalisation, a perspective on the digitalisation of the South African agricultural sector, available options for PLAS farmers, and the drivers of value chain digital technologies. The next sections present empirical evidence the methods and procedures for sampling and data collection, as well as the data analysis techniques. The results and discussion follow. Then, the conclusion is presented last.

2. Review of Agricultural Digitalisation Literature

This section summarises empirical evidence of the adoption of digitalisation and its impact on agriculture to provide context and to establish relationships between key concepts and methodologies. Due to the nascence of agricultural digitalisation literature, the scope of this review is international and does not confine itself to agricultural businesses but rather encompasses all businesses. However, to provide context, grey literature on digitalisation strategies in the South African agricultural sector is discussed.

Building on the previous section's definition of digitalisation, this section discusses the similarities and differences between precision agriculture and digitalisation. Second, empirical evidence will be discussed regarding the factors influencing the adoption of digitalisation in agriculture. Finally, the value chain dimensions of digitalisation as well as how agricultural digitalisation ensures long-term sustainability in the agricultural sector of South Africa will be discussed.

2.1. The Concept of Agricultural Digitalisation

The fourth industrial revolution affects all sectors of the economy, including agriculture. This has led to increasing agricultural digitalisation (which is also called agriculture 4.0 or A 4.0) in farms. According to Szalavetz [12], agricultural digitalisation refers to "the infusion of digital technologies in and the consequent transformation of agricultural pre-production, production, production-related support, and post-production activities." There are several technologies that enable agricultural digitalisation and application domains within agriculture that have been identified in the literature [4]. The agricultural digitalisation technologies are the internet of things, data analytics, artificial intelligence and machine learning, image processing, cloud computing–cyber physical systems, unmanned aerial vehicles, geographic information systems, communication technologies, robotics and automation as well as augmented and virtual reality [4,13–15]. Moreover, the relevancy and applicability of these technologies across agricultural-specific domains have also been identified, including but not limited to crop, soil, pest, irrigation, and water management [4,14]. Value chain application domains include storage, logistics, yield, and market demand forecasting, as well as digital marketplaces [4,13,14].

Digitalisation has historically occurred in three stages. The first wave of digitalisation entails the technical digitisation of analogue content and services without fundamentally altering the industry structure. Digitalisation's initial wave makes no major modifications to the tightly connected layer of product architectures. According to Yoo et al. [16], in the second wave of digitalisation, the decoupling of previously tightly tied devices (networks, services, and content) occurs. Digital content and services may now be delivered over a general-purpose IP network and software-enabled devices, resulting in convergence at numerous levels, including network, device, and market. As a result, established divisions between product categories and industries are continually moving. For example, voice service totally becomes device- and network-independent, with the same level of quality offered regardless of whether the customer is using a fixed-line phone, a desktop computer,

or a mobile phone. Similarly, other media services such as music, books, e-mail, and movies can be supplied via a variety of different network types and devices.

The third wave of emerging technologies is distinct from the previous waves. A new fusion of diverse sorts of digital breakthroughs in recent waves of digitalisation is increasingly being witnessed. Likewise, physical and repetitive jobs are being enhanced using rich digital traces and intelligent digitalised tools. In principle, comprehensive digitalisation can incorporate all seven features of digital materiality into every action, behaviour, and activity performed in human daily lives. Digital traces of physical acts, events, and movements in the physical, social, and virtual worlds may be kept, recorded, monitored, analysed, and reprocessed at an unfathomable scale and rate [16].

The process of digitalisation can be easily illustrated using Bukht and Heeks's [17] three-scope approach to the digital economy. The first scope is the digital (IT/ICT sector), comprising hardware manufacture, information services, software, IT consulting, and telecommunications (Figure 1). ICTs have brought tremendous transformation to the agricultural sector. Evidence of ICT utilisation and impact in agriculture is widely documented [18–20]. The ownership of computers, cellphones, etc. is used to measure ICT adoption in these studies. Despite extensive literature on the digital economy, the subtle distinction between ICT, digitisation and digitalisation has not been emphasised. In agriculture, the separate phases of the digital economy remain poorly understood. The second scope is the digital economy, which is based on offering digital services as well as increasing the use of sharing and platform economies. The third and last scope of the digital economy is the digitalised economy, where the technologies of the fourth industrial revolution are integrated within businesses to transform business models. Thus, this three-scope approach distinguishes between the IT/ICT sector, the digital economy, and digitalised economy.

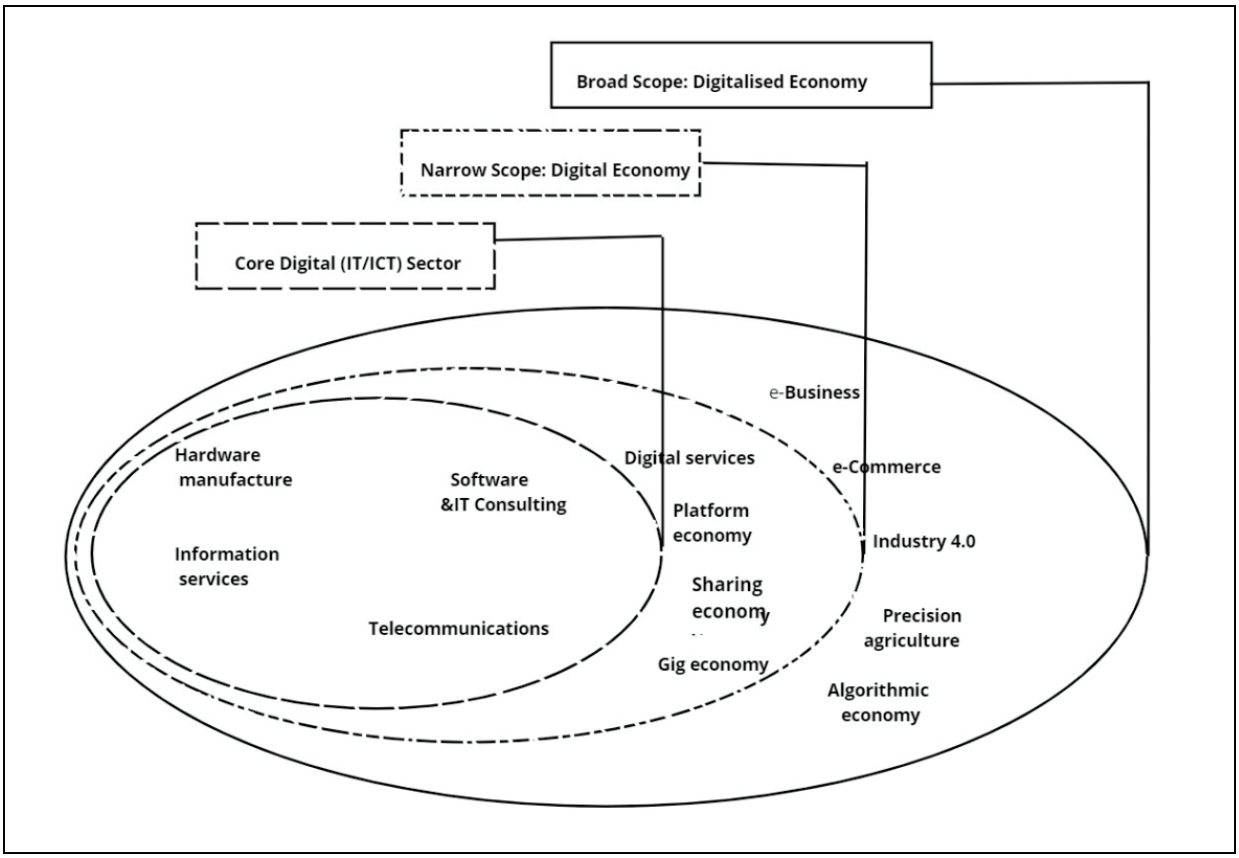

Figure 1. Digital Economy Continuum.— Source: Bukht and Heeks [17].

Digitalisation in agriculture has enabled the introduction of new agricultural digital solutions such as mobile applications, blockchain, the internet of things, drones, and big data into a set of existing precision agricultural technologies (PAT). Adoption of precision agriculture has been on the rise [11]. The economic effect of digitalisation on agriculture is still being debated, but its potential to enhance innovation or create new business opportunities is certain.

Although evidence on the digitalisation of farm processes is still scant, empirical literature on the perspective of IT-enabled organisational capabilities is well established. The IT sector has been around and has been a major focus in literature during the second and third industrial revolutions. The perspectives on IT-enabled organisational capabilities suggest that organisational/process capabilities are a critical mechanism through which IT assists enterprises in creating business value. Organisational learning, knowledge management, talent management, new product development, business agility, and a proactive environment are just a few examples of these intermediate/process (dynamic and operational) organisational competencies. In the literature on the commercial value of IT, this perspective has emerged as the main framework for theoretically and empirically resolving the IT productivity dilemma [10,21,22]. However, questions about the business value of digitalisation remain. Evidence, although still scanty, on digitalisation adoption and impact has emerged.

2.2. Precision Agriculture and Digitalisation

In the agricultural digital solutions adoption literature, Michels et al. [23] have referred to certain agricultural digital solutions such as drones as recent inventions added to PAT. Nevertheless, agricultural digitalisation includes PAT, which makes the digitalisation context broader than precision agriculture (Figure 1). Digitalisation in agriculture focuses on the transformative nature of agricultural digital solutions. Agricultural digital solutions are rendered infrastructural under digitalisation and have the potential to optimise the operational, financial, and marketing decisions of farmers. While adoption of PAT has been skewed towards developed and large-scale commercial farms [24], widespread adoption of agricultural digital solutions is expected even in remote areas of low-income countries because of the rapid expansion of aggrotech.

2.3. Drivers of Digitalisation Adoption

Empirical literature on the drivers of the digitalisation of agriculture takes many different directions. The first one deals with the factors that predict the adoption of agricultural digital solutions. Performance expectancy, effort expectancy, social influence, and facilitating conditions are behavioural factors that are likely to predict adoption of agricultural digital solutions, with exogenous variables such as age, gender, etc. more likely to play a mediating role. Several empirical studies have shown a positive correlation between the intention to adopt digital agricultural solutions and performance expectancy [11,24,25]. There are mixed results on the role that facilitating conditions play in predicting the intention to adopt. While Michels et al. [11] argued that facilitating conditions are only relevant for determining actual adoption, Molina-Maturano et al. [24] found the intention to adopt agricultural apps to be strongly associated with facilitating conditions in Mexico.

Although no significant relationship has been found between effort expectancy and the intention to adopt an agricultural app in Mexico [24], effort expectancy is considered a good indication of the user-friendliness of a particular technology. It is therefore argued to be a strong predictor of the intention to adopt agricultural digital technologies. As these studies are both based on farmers' perceptions, Mexican farmers may perceive overcoming constraints associated with learning digital solutions as important as opposed to German and Chinese farmers, who may enjoy the dynamic capability associated with their advanced economies. Michels et al. [11] reported a positive relationship between smartphone crop protection app adoption and social influence (i.e., the extent to which certain individuals influence the adoption belief of the farmer). Similarly, Sun et al. [25] found that social

influence significantly affects adoption of the internet of things in China. Although Molina-Maturano et al. [24] did not confirm the positive effect of social influence in Mexico, farmers' social networks are important for the adoption of new technologies. Digital solutions such as agricultural apps are still in development and pilot phases in Mexico [24], suggesting the poor role played by farmer networks in predicting adoption.

Other studies that have considered the role that farm and farmer characteristics, besides behavioural factors, play in determining adoption have focused on factors influencing actual use. Michels et al. [23] revealed farm size, age, and literacy on PAT to be the factors that affect the actual adoption of drones by German large-scale farmers. Farmers' age, farm size, knowledge about specific crop protection apps, potential for crop protection, and potential for reducing negative environmental effects have been identified as significant predictors of willingness to pay for crop protection apps in Germany [26]. The evidence produced in these studies is inconclusive and varies by context. They demonstrated that while some factors are significant determinants of digitalisation in some regions, they are insignificant in others. Moreover, the evidence produced is only related to the adoption of one dimension of digitalisation, namely the adoption of agricultural digital solutions. Thus, the need for further research is justified, particularly in the context of South Africa.

The most commonly used framework to study digitalisation adoption is the unified theory of acceptance and use of technology (UTAUT) framework. It was developed after an extensive review of eight theoretical frameworks of behavioural adoption and has been cited as the most comprehensive framework [27]. The basic UTAUT framework considers four constructs: performance expectancy, effort expectancy, facilitating conditions, and social influence [27]. With reference to agricultural smartphone apps for crop protection, Michels et al. [11] used the basic UTAUT framework to assess the factors influencing behavioural intention adoption. Extensions of the basic model with additional constructs exist. The mastery approach, goal orientation approach, trust, and personal innovativeness are the additional constructs considered in the investigation of factors affecting agricultural app adoption intention in Mexico [24]. Exogenous variables are normally included as moderating variables in the model.

Another model that has also been used to understand technology acceptance is the trans-theoretical model of adoption (TTMA). Unlike UTAUT, adoption is viewed as a gradual process under TTMA. In Michels et al. [23], the idea of considering adoption as binary is abandoned, and a measure that accounts for more than two stages of adoption is considered. With the exception of Mikhail et al. [9], who estimated the impact of digitalisation on the financial performance of the agro-industrial complex in Russia, the focus in agricultural digitalisation literature has been on the adoption of specific agricultural digital solutions. There are notable attempts to determine the impact of digitalisation in other fields.

2.4. Perspective on the Digitalisation of the South African Agricultural Sector and Available Options for PLAS Farmers

Agricultural digital solutions applications are dependent on the nature of the job that must be performed. Moreover, their synergistic nature accommodates several applications by farmers promoting value chain integration. With different contributions from various agricultural digital solutions, value chain digitalisation in the South African agricultural sector takes several dimensions, including supply chain optimisation and unlocking finance opportunities.

2.4.1. Access to Markets

Participation by smallholder farmers in global supply chains is often difficult in Africa due to associated high participation costs and low productivity levels. Through initiatives that provide farmers with essential services and market access, unlocking and optimising the supply chain solves the problem of exclusion. The combination of AI-powered platforms with physical warehouses and logistical infrastructure by companies

enables cost-cutting and expansion of operations by the producers through supply chain optimisation [28].

Increased consumer demand for the traceability of products has been associated with digital technologies that improve the transparency of the value chain. Blockchain technology for the tracking of agricultural produce allows farmers to access essential accounting information. Moreover, verification of providers' regulatory compliance is possible through cloud computing technologies. E-commerce offers direct market linkages between the farmer and end-consumers, offering farmers value-proposition opportunities and the exclusion of exploitative intermediaries.

2.4.2. Unlocking Opportunities for Finance

There are several ways in which various government institutions and private commercial banks try to provide funding to South African farmers, particularly smallholder farmers who continue to face start-up or expansion financial constraints. While commercial banks have also attempted to use agricultural data collected by aggrotech companies to provide finance to farmers, a large proportion of farmers remain unbanked in South Africa. Fintech companies are beginning to take advantage of digital technologies such as mobile money to offer unbanked farmers solutions that are related to finance. Crowd farming is one of these solutions and has enabled farmers to access the necessary working capital from people who cannot farm while also giving them an opportunity to own tangible assets such as cows through crowdfunding. Pay-outs are also calculated by the insurance companies based on the satellite information on crops and weather, and this reduces information asymmetries and risk.

2.4.3. Agricultural Digitalisation and Land Reform Sustainability

Technology adoption has always been one of the ways to achieve agricultural sustainability. Particularly, farmers' adoption of sustainable agricultural technology is espoused in the literature. For example, Hatzenbuehler and Peña-Lévano [29] have examined a range of sustainability-focused technologies that are applicable to smallholder farmers in the Global South, emphasising their potential to enhance food availability and stability. Dash et al. specifically emphasise the contribution of the most important technologies, renewable energy and ICT, in achieving sustainable farming practices. In Indonesia, the adoption of sustainable rice farming practices has been associated with positive contributions to farmers' livelihoods and perceptions of change [30]. Thus, literature widely advocates for the adoption of technology to promote sustainable farming practices. In addition, the type of technology that is adopted is important. Hence, literature has also emphasised how the advent of fourth industrial technologies and their adoption would help foster agricultural value chain sustainability.

Various studies have contended that the implementation of the fourth industrial revolution would facilitate efficient and effective value chain processes leading to economic, environmental, and social sustainability. Arvanitis and Symeonaki [31] have underscored the significance of interdisciplinary collaboration and the implementation of cutting-edge technologies to facilitate agricultural production and value chain management, thereby promoting sustainable farm management. The significance of digital transformation in agriculture, encompassing data analysis and process automation, in fostering economic, environmental, and social sustainability in supply chains is underscored in Hrustek [32]. Yahya and Yahya [33] have emphasised the advantages of Agriculture 4.0, including cost reduction and increased yields. However, there are difficulties associated with implementing these technologies to ensure the long-term viability of crop production. In China, the low adoption rate of sustainable agricultural technologies has been attributed to small-scale production and insufficient market demand [34].

Digitalisation of the value chain can assist the South African agricultural sector in achieving long-term sustainability by mitigating the sector's pervasive inequality. The extensive disparities present in the South African agricultural sector have been extensively

documented, often stemming from historical land dispossession during the apartheid era [1]. Efforts to address these inequalities through land redistribution reforms and programmes supporting smallholder farmers in South Africa have yielded limited success [1,2]. The enduring disparity in South Africa's agricultural industry may lead to uneven implementation of digital technology. The existing disparity in the agricultural sector of South Africa has the potential to impede the achievement of the advantages linked to the digitisation of agriculture. However, the implementation of advanced digital technologies to modernise farms would support the long-term viability of land reform. The land reform programme offers an opportunity to address the potential digital divide within South Africa's agricultural sector [5].

The redistributive land reform programme can be used to digitally transform South African agriculture. However, the main objective of the land reform programme in South Africa is to address the issue of inequality within the agricultural sector. It is not widely seen as a strategy for facilitating the digital transformation of the agricultural sector in the country. Mazwane et al. [5] contend that by integrating digital transformation goals into the redistributive land reform policy, it is possible to simultaneously address sectoral inequalities while enhancing efficiency and revitalizing struggling redistributed farms, thereby ensuring long-term agriculture sector sustainability.

Therefore, rising from the historical land dispossession during the apartheid era, attempts to rectify these disparities through land redistribution have yielded limited results. The introduction of advanced digital technologies provides an avenue for the modernisation of farms and the bridging of these gaps, thereby lending support to the enduring viability of land reform in South Africa. By incorporating digital transformation objectives into the redistributive land reform policy, it becomes possible to tackle sector-specific inequalities while simultaneously boosting efficiency and rejuvenating redistributed farms. This, in turn, ensures the long-term sustainability of the agricultural sector. Nevertheless, it is important to consider the adoption intentions of farmers and the influencing behavioural factors thereof.

3. Materials and Methods

A cross-sectional research design was adopted. This means that the time dimension was overlooked in favour of relying on existential differences among farms. Thus, semi-structured questionnaires were used to collect data on farms sampled using multistage and simple random sampling techniques. The list of all active farmers in the selected local municipalities was obtained from the Department of Agriculture, Land Reform, and Rural Development (DALRRD). With respect to ethical considerations that govern the data collection process and results reporting, ethical aspects such as informed consent, respect for dignity, voluntary participation, and confidentiality were adhered to.

3.1. Determination of Sample Size

Several approaches for calculating a sample size exist. The Cochran's approach was chosen and applied for calculating the desired sample size:

$$n = \frac{q(100 - p)z^2}{E^2} \tag{1}$$

where n is the required sample size, p is the percentage of occurrence of a state or condition, E is the percentage of maximum error required, and z is the value that corresponds to the required confidence level.

The adoption of the Proactive Land Acquisition Strategy (PLAS) in 2005–2006 brought about the most important change in land acquisition in South Africa since 1994 [2]. There are about 2000 PLAS land reform farms. The suitable sample size (100) was chosen based on the projected number of PLAS farms, the maximum error (5%), the assumed percentage of digitalisation occurrence on PLAS farms (50%), and a 1.96 z-score equivalent to a 95 percent confidence level. The target population consists of all the PLAS land reform beneficiaries.

The unit of analysis is the farm. PLAS land reform beneficiaries are spread throughout the country, and the implementation of the simple random sampling technique would be costly and time-consuming [35]. However, to ensure that a representative sample was obtained, the Eastern Cape Province was sampled purposefully. The Eastern Cape is a rural province. Not all the districts' local municipalities in the province have the same number of redistributed farms. Thus, stratified random sampling, applied to ensure a representative sample, was drawn from the districts' local municipalities. Consequently, a total of 100 PLAS farms under the local municipalities were sampled and a semi-structured questionnaire was administered.

3.2. Data Collection Instrument and Method

The survey was conducted electronically, telephonically, and through farm visitations. Farmers were contacted first using the list obtained from the Department of Agriculture, Land Reform, and Rural Development (DALRRD) as well as local departments of agriculture and rural development (In instances where contact information for farmers was out-of-date, the database was supplemented with data obtained from local departments) and requested to indicate their preferred choice of completing the survey. Farmers from the following local district municipalities were recruited: Alfed Nzo, Amathole, Buffalo City, Chris Hani, Joe Gqabi, and Sarah Baartman District Municipalities. Farmers with active email addresses and who had indicated email as the preferred choice of contact were requested to complete the questionnaire that was shared via email with frequent reminders. Those farmers who indicated a telephone/phone interview as their preferred choice were contacted at the indicated times, while visitations, with strict adherence to COVID-19 regulations, were paid to farmers who preferred that method. The survey was conducted from January 2023 to February 2023 (which is just after the planting season and before the harvesting season), when farmers were not too busy.

3.3. Data Measures

The concept of farm digitalisation was defined in the literature so that it could be correctly measured. It refers to the use of digital technologies in operating a farm enterprise for the improvement of its value. The items for the value chain dimension that Yu et al. [36] employed to measure enterprise digitalisation were adapted to assess value chain digitalisation and adoption intention of PLAS farmers (see Appendix A). Farmers' perceptions about the value chain dimension of digitalisation were assessed in four areas: usefulness, ease of use, social influence, facilitating conditions, and intention to adopt. A Likert scale method was used to develop items with a 5-level scoring method (one indicates "strongly disagree" and five indicates "strongly agree").

In the context of the current investigation, the term "digital technology" was used to refer to any technology that operates in the digital domain, irrespective of its specific application or use. It functions as an umbrella category for all technologies employing digital components. In contrast, "value chain digital technologies" referred specifically to digital technologies used within the agricultural value chain to carry out the functions enumerated in Appendix C. These are application domains of digitalisation within the value chain. In essence, value chain digital technologies are a subset of digital technologies (including smart technologies) that optimise and enhance various domains of the value chain, such as data analytics, communication technologies, digital sensors, the internet of things (IoT), and digital marketplaces [4,13,15,37].

To aid farmers in comprehending and operationalising the concept of digitalisation of the value chain, a comprehensive picture was presented that detailed how these digital technologies are implemented across the various domains of the value chain. The purpose of this visual aid was to assist farmers in comprehending the practical implications and benefits of integrating digital technologies at various phases of agricultural production and distribution. Subsequently, farmers were questioned about their perceptions regarding the adoption of value chain digitalisation, building on their comprehension of

digital technology applications within the agricultural value chain as depicted in a visual representation.

3.4. Data Analysis and Method of Estimation

Statistical analyses were performed using the lavaan R and SeminR packages and STAT 14. Demographic data were first analysed using descriptive statistics. Then, structural equation modelling (SEM) was conducted to test the models presented in Figure 2. A structural equation model is a set of statistical models that seek to explain the relationships between multiple variables; it was used because it allows the simultaneous analysis of all relationships, combining multiple regression with factor analysis, while allowing for both observed and latent variables to be analysed together [24]. Reflective measurement items were derived from prior research [11,23] and adapted to create five constructs: performance expectation, effort expectation, social influence, infrastructure, and adoption intent. As depicted in Figure 2, the assessment of performance expectancy (PE) relied on items labelled PE1 through PE3, while effort expectancy (EE) was measured by EE1 through EE3. SI1 to SI3 and I1 to I3 were used, correspondingly, to evaluate social influence (SI) and infrastructure. In addition, the adoption intention (AI) of producers was measured using items AI1 through AI3 (also shown in Figure 2). Appendix A contains detailed explanations for each of these measurement elements.

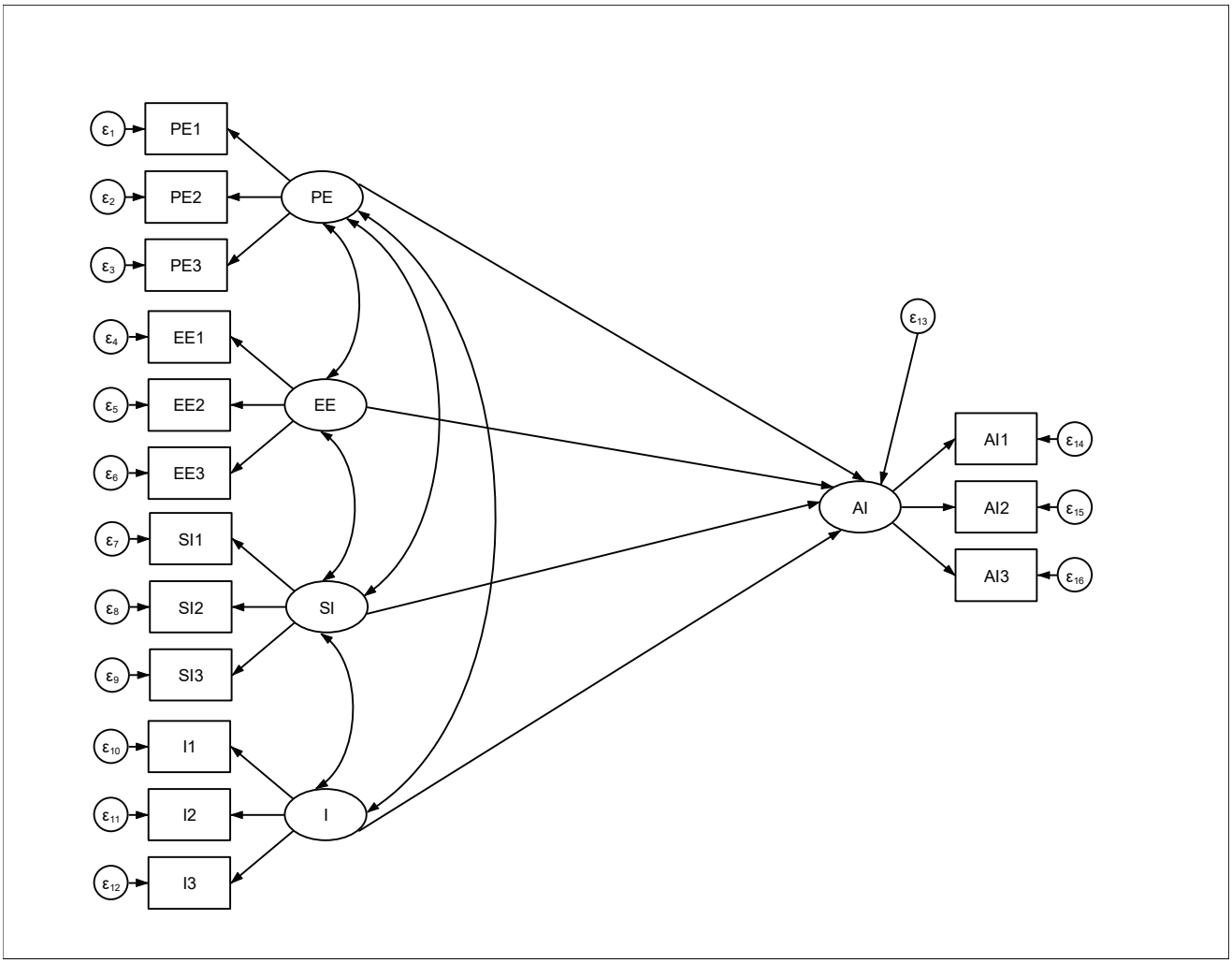

Figure 2. Structural equation model of factors that affect farmers' intentions to adopt. Source: Authors' computation.

There is a lack of a prescribed optimal number of items for measuring a construct in the existing literature. Thus, a set of three items for each construct were used to reduce respondent fatigue and keep questionnaires brief. In addition, Schubert [38] argues that removing one observed variable from reflective measurement models does not alter the construct because these observed variables serve as reflections of the construct itself, not vice versa. STATA allows simultaneous estimation of the structural equation model and confirmatory factor analysis (CFA) using a maximum likelihood estimation. This allows both the evaluation of the reliability and validity of the measurement model and the path analysis of the structural model estimates to test the significance of our hypotheses and the predictive items of the proposed model to be conducted together.

4. Results and Discussion

The descriptive statistics results are shown in Table 1. This includes the important demographic and economic variables of PLAS farmers (see Appendix B for detailed description and measurement type of each variable). The typical Eastern Cape PLAS farms are generally middle-aged, with an average age of 55 years and a standard deviation of 11 years. This is not surprising, as the average farmer's experience in years was 20 years, with a standard deviation of about 12 years. The land reform programme normally selects experienced, emerging black farmers as beneficiaries. This indicates a low probability of selecting a younger farmer. The typical PLAS farmer is educated with an average of 12 years of schooling, which is equivalent to South African matriculation. While the number of years of completed schooling averaged five years with a standard deviation of three years, the family size was large at five people per family. PLAS land reform programme beneficiaries are black South Africans, and African families normally have larger families. Average income and land were R511, 808 and 801 hectares, respectively. The standard deviations were very large: 1051 hectares for land size and R761, 401 for income. This suggested the presence of outliers in both variables. Signal strength in PLAS farms was moderate and averaged at 3 with a standard deviation of 1.5.

Table 1. Descriptive statistics results.

Variable	Mean and Standard Deviation (Sample Size = 100)
Age	55 ± 11
Experience	20 ± 11.8
Number of years of completed schooling	12 ± 3
Family size	5 ± 2
Farm age	10 ± 5
Land size	801 + 1051
Income	R511,880 ($26,821.96) ± 761,401 (39,896.60)
Signal strength	3 ± 1.5

Construct reliability and validity were assessed before inclusion in the path model (Table 2). Cronbach's alpha was used to test for the reliability of the factors. Cronbach's alpha coefficient is the most common tool for assessing the internal consistency and reliability of factors [24]. The Cronbach's alpha coefficients for all the factors (PE, EE, SI, and I) were above the recommended threshold (>0.70). This showed that the scale was reliable, consistent, and stable, and that construct reliability was met. To check if the scale is valid, a Keyser-Meyer-Olkin (KMO) sampling adequacy test and a Bartlett test of sphericity were done. A KMO value of 0.857 and a Bartlett test of sphericity of 1429.937 were obtained from all the indicator variables, indicating the strong validity of the scale. This meant that factor analysis could be performed on the data. This is in line with the findings of Sun et al. [25], who obtained a KMO value of 0.807 and a Bartlett test of sphericity of 2025.270.

Table 2. Reliability test results.

Dimension	Variable	Cronbach's Alpha
Performance expectancy	PE1 PE2 PE3	0.96
Effort Expectancy	EE1 EE2 EE3	0.92
Social Impact	SI1 SI2 SI3	0.97
Infrastructure	I1 I2 I3	0.88
Adoption intention	AI1 AI2 AI3	0.92

4.1. Model Evaluation

The Chi-square, Root Mean Square Error of Approximation (RMSEA), Comparative Fit Index (CFI), Non-Normed Fit Index (NNFI), Tucker–Lewis Index (TLI), and Standardised Residual Mean Square (SRMR) were used to assess the model fit. The model is acceptable, although some of the results suggest otherwise (Table 3). The CFI and TLI are within the recommended ranges. The structural equation modelling technique is a large sample technique ($\geq$100). A sample size of 100 was used to estimate the SEM, and this could be the reason for some of the criteria values falling outside the recommended ranges.

Table 3. Overall model index fitness values.

Indicators	χ^2	RMSEA	CFI	TLI	RSMR
Criteria values		<0.10	>0.90	>0.90	<0.1
Model results	198	0.127	0.929	0.912	0.157

Thus, the first fit of the measurement model that included all the items of the constructs was acceptable, as indicated by the CFI and TLI indices of 0.929 and 0.912, respectively.

The factor loadings for all items were greater than the threshold value of 0.7, confirming the good indicator reliability of the instrument (Table 2). No items needed to be dropped due to low factor loading. The average variance extracted (AVE) was used to test the convergence validity, and all the constructs had an AVE greater than the minimum acceptable value of 0.5, confirming that the convergence validity criterion was met. Thus, the reflectively measured constructs demonstrated reliability and validity and were included in the path model.

4.2. Path Analysis Results

The results of the structural equation modelling are shown in Figure 3. The standardised factor loadings for all the items are greater than the recommended range of 0.7. This shows the good contributions of all items in explaining the respective factors. After assessing the measurement model, the structural model (path analysis) was assessed. The overall model fit for the structural model was good (Table 3). The values for the indices CMIN/DF, CFI, TLI, RNI, SRMR, RMSEA, and AGFI were nearly the same as the measurement model. The path analysis showed that adoption attention is significantly affected by performance expectancy (PE) and effort expectancy (EE) (Table 4). The relationship between adoption intention, performance expectancy, and effort expectancy is positive. This means that the

intention to adopt value chain digital technologies increases because farmers believe that these technologies will perform well.

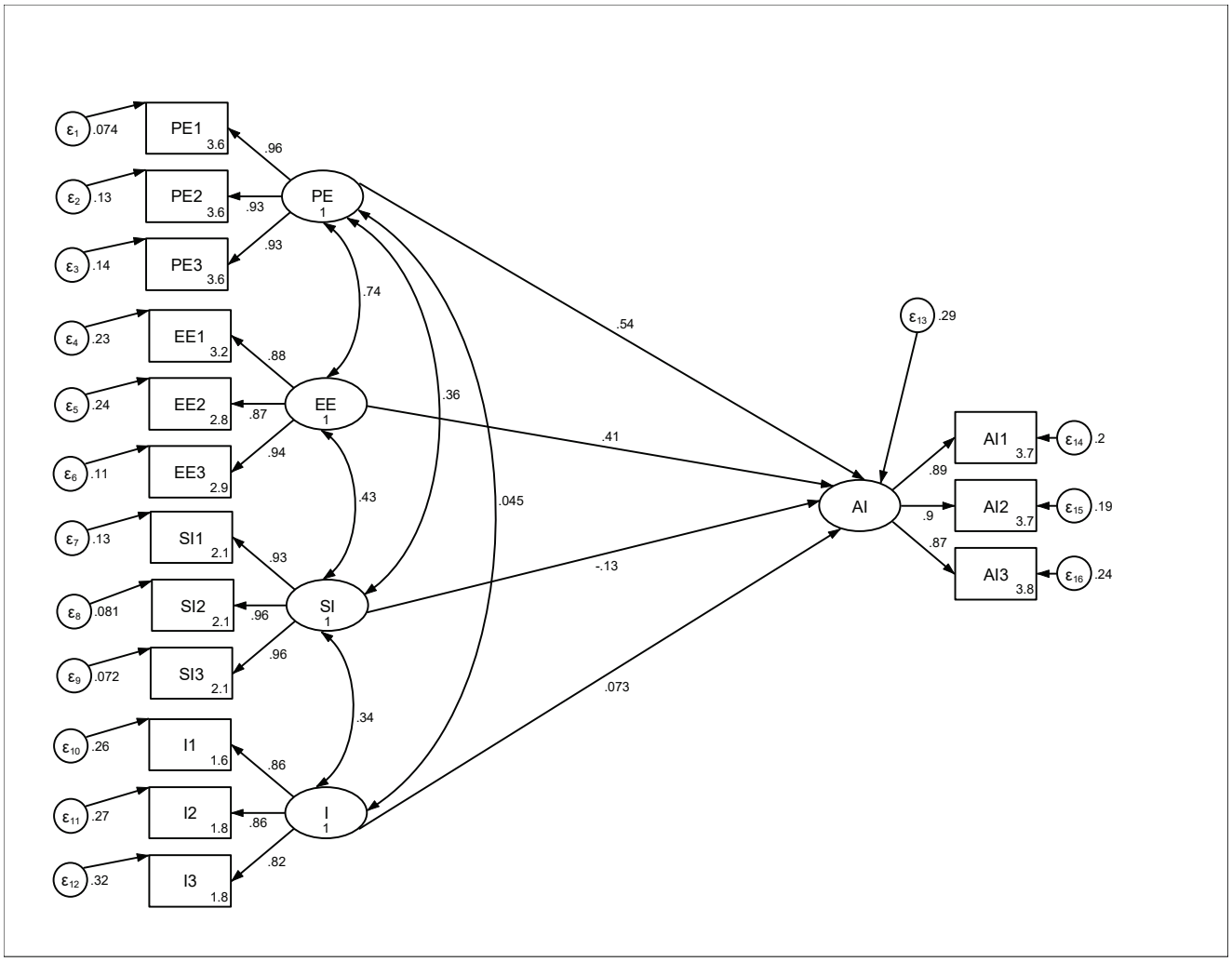

Figure 3. Structural Equation modelling and standardised coefficients. Source: Authors' computation.

Table 4. Path analysis results.

Paths			Directions	Standardised Coefficients
PE	→	AI	+	0.54 ***
EE	→	AI	+	0.40 ***
SI	→	AI	−	0.13
I	→	AI	+	0.07

Note: * indicates $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

The revealed positive relationship between performance expectancy and adoption intention of value chain digital technologies is in line with existing literature on other digital technologies [39,40]. The importance of performance expectancy has been revealed in agricultural studies on decision-support tools, mobile-based communication technologies for agricultural information [41], and SMS agricultural advice. Similarly, high effort expectations are associated with high adoption intentions. The effect of effort expectancy implies that farmers find the effort required to use the value chain digitalisation technologies important in their intention to adopt them. Thus, training may be necessary for farmers to effectively use value chain digitalisation technologies. Although farmers may accept challenges, they may be unfamiliar with the digital platforms, technologies, and apps used

for purchasing farm inputs and selling farm products. This finding is inconsistent with that of Molina-Maturano et al. [24], who discovered that effort expectancy is not important when using agricultural mobile applications. The discrepancy may be because cell phones are widely available, whereas the opposite is true for digital platforms that are used for the purchase and sale of agricultural products.

The relationship between adoption intention and other constructs (social influence and facilitating conditions) was insignificant. This is an indication of poor awareness and digital infrastructure in farming and rural communities. Friends and acquaintances have no influence on the intention to adopt. Although Sun et al. [25] found contrasting results, this is consistent with the findings of Molina-Maturano et al. [24]. The intervention of government through educational awareness programmes and digital infrastructure has been underscored in digitalisation literature [5,42]. The average signal strength for the sample of PLAS farms in the Eastern Cape is 3. This is an indication of poor connection, and digital platforms rely on internet connections. Mabaya and Porciello [43] note high data costs as an indication of poor development of fibre infrastructure.

The sample consisted of 22% of female farmers and 78% of male farmers. This may be indicative of the agricultural landscape in South Africa. While the results are only relevant to the specific sample under investigation, they may raise concern about the gender composition of land reform farms and South Africa's agricultural population. Multigroup analysis was also examined for gender. A multigroup analysis was conducted to investigate potential gender differences in behavioural factors and to determine whether gender influences farmers' perceptions of value chain digitalisation. The multigroup analysis results are presented in Table 5. Performance expectancy was only significant for male farmers (Table 5). This indicates that male farmers will only adopt value chain technologies if they believe that they are effective. Thus, demonstrations of the effectiveness of value chain technologies may be required for male farmers. However, female farmers do not believe that performance is important for the adoption of value chain technologies. This means that females may not need proof of the performance of a particular technology.

Table 5. Multigroup analysis for Gender.

Paths			Male Farmers	Female Farmers
PE	→	AI	0.46 ***	0.23
EE	→	AI	0.77 **	0.32 **
SI	→	AI	−0.18 **	−0.10
I	→	AI	0.20 **	0.064

Note: * indicates $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

With regards to effort expectancy, although both groups of farmers regard effort expectancy as important for the adoption of value chain digital technologies, it is more important for male farmers. This is an indication that increased adoption will be observed in a situation where farmers feel that value chain digitalisation technologies are easy to operate. This may increase the ability of this group of farmers to learn new technologies that are important for their farming operations. Social influence has a negative relationship with adoption intention. It is also less important for male farmers. This is an indication of poor interactions, as males are normally less social compared to females. Facilitating conditions are also more important for male farmers compared to female farmers (Table 5). This is an indication of having the infrastructure and knowledge to utilise value chain technologies and could be an early signal of the digital divide, which has been a concern in the digitalisation literature.

5. Conclusions

A series of value chain disruptions necessitates the use and expansion of value chain technologies. Digitalisation is required for the establishment of resilient and, ultimately, substantiable value chains in the Republic of South Africa. Nonetheless, farmers' willingness to adopt value chain technologies is influenced by their social environment, beliefs,

and the nature of technology. Most farmers are unwilling to adopt value chain technologies, while others show little interest. This necessitated the identification and categorisation of behavioural factors influencing PLAS land reform farmers' willingness to adopt value chain technologies, which increase the resilience of agri-food value chains in the face of disruptions.

PLAS land reform farmers in the Eastern Cape are more likely to adopt value chain technologies. Therefore, performance expectancy and effort expectancy are the influencing behavioural factors. Moreover, the availability of digital technology infrastructure increases the adoption intentions of male farmers. Higher adoption intentions imply greater value chain flexibility. The flexibility of the value chain is critical to the value chain's resilience. Increased information exchanges through value chain technologies such as mobile applications and trading platforms for farm inputs and products increase transparency and collaborations with the value chain, allowing farmers to better prepare for, adapt to, and adjust to value chain shocks.

Furthermore, as consumers become more involved in the value chain, the level of adoption intention demonstrated by farmers is critical for the establishment of sustainability principles. The more actors involved in the value chain, the more positively the value chain will respond to greener operations. Long-term customer and supplier relationships are critical for the development and achievement of social and environmental goals. Thus, agricultural production can be sustained through value chain technologies, as real-time data collection improves operational efficiency across the entire life cycle (planning, production, manufacturing, distribution, and consumption).

The confluence of technology adoption and land reform, with a particular focus on digital transformation, presents a promising route to attaining sustainable agriculture in South Africa and other areas grappling with comparable challenges. This approach not only addresses historical inequities but also positions the agricultural sector for enduring sustainability and prosperity.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due the fact that it is only a portion of a larger dataset from which subsequent publications are expected.

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

Appendix A. Questionnaire Section that Includes Items Used to Evaluate Value Chain Digitalisation Technologies Perception

Section E.1.1: Value-chain digitalisation perception
How do you find digital solutions to optimise the value-chain? Tell me whether you (1) Strongly disagree, (2) Disagree, (3) Neutral, (4) Agree, or (5) Strongly agree with the following statements.
E.1.1.1. I find optimising supply chain useful in my daily life E.1.1.2. Optimising supply chain increases my chances of achieving things that are important E.1.1.3. Optimising supply chain helps me accomplish things more quickly. E.1.1.4. Learning how to optimise supply chain is easy for me E.1.1.5. My interaction with digital tools that are used to optimise supply chain is clear and understandable. E.1.1.6. I find digital tools that are used to optimise supply chain easy to use E.1.1.7. People who are important to me think that I should use digital tools to optimise supply chain E.1.1.8. People who influence my behaviour think that I should use digital tools to optimise supply chain E.1.1.9. People whose opinions that I value prefer that I use digital tools to optimise supply chain E.1.1.10. I have the resources necessary to use digital tools to optimise supply chain E.1.1.11. I have the knowledge necessary to use digital tools to optimise supply chain E.1.1.12. Digital tools to optimise supply chain are compatible with other technologies E.1.1.13. I intend to continue using digital tools to optimise supply chain in the future E.1.1.14. I will always try to use digital tools to optimise supply chain in my daily life E.1.1.15. I plan to continue to use digital tools to optimise supply chain frequently

Appendix B. Descriptive Statistics Variable Description

Variable	Measure/Type	Description
Age	Continuous	Number of years since the farmer was born (years)
Experience	Continous	Number of years since the farmer started farming (years)
Number of years of completed schooling	Continuous	Number of years the farmer has spent in formal education (years)
Family size	Continuous	Number of people in the household
Farm age	Continuous	Number of years that the farmer has occupied the farm through land reform support (years)
Land size	Continuous	The size of the farm (hectares)
Income	Continuous	The income generated from farming activities (rands)
Gender	Dummy	Determines whether a farmer is a male or female
Signal strength	Continuous	The number of network bars that reflected on the cellphone in the farm (ranges from 0 to 5)

Appendix C

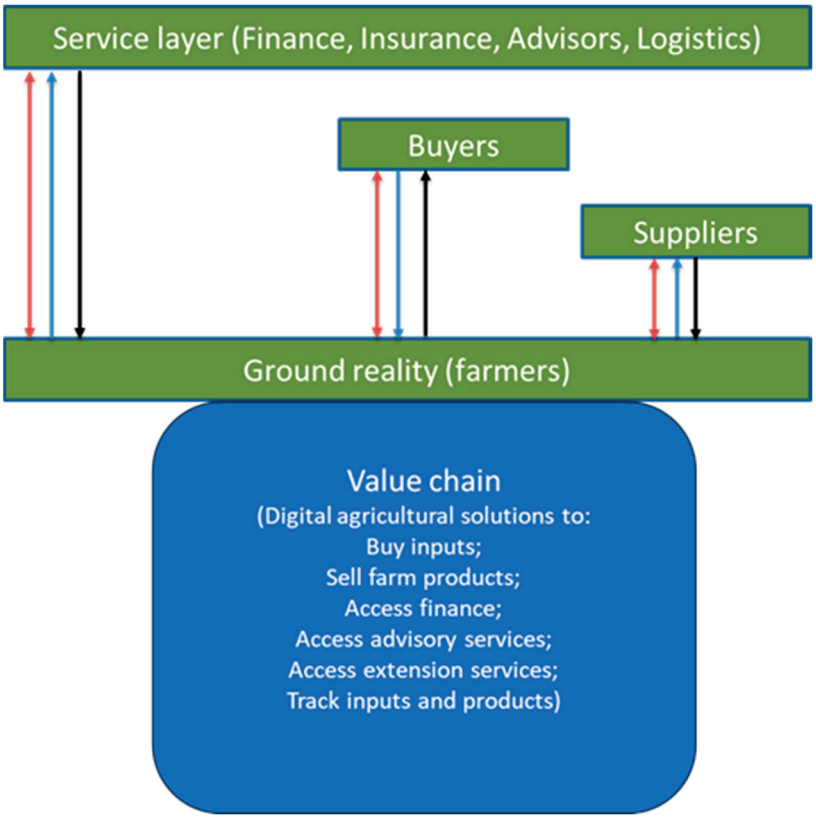

Figure C1. Questionnaire Section that Includes the Application Domains of Technologies That Are Used to Digitalise the Value Chain.

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Switch or Stay? Applying a Push–Pull–Mooring Framework to Evaluate Behavior in E-Grocery Shopping

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Abstract: This study investigates the antecedents of the intention to switch to e-grocery shopping during the COVID-19 pandemic, which is critical in recommending that e-grocery shopping service providers improve their competitiveness by responding to customer expectations. This study proposes a push–pull–mooring framework to describe the influence of dissatisfaction on the physical market, the attractiveness of e-grocery, and switching costs as factors that drive switching intentions. This study surveyed 252 Indonesians aware of the existence of an e-grocery mobile application, and applied structural equation modeling as an analytical method to explain causal relationships between variables thought to influence switching intentions to e-grocery shopping. The results showed that the attractiveness of e-grocery had a significant effect on switching intention. Likewise, switching costs ultimately drive customer intention to switch to e-grocery shopping. However, dissatisfaction is not a driving factor directly affecting switching costs and intentions. Finally, e-grocery services cannot replace the local tradition of Indonesian people who prefer to shop for groceries in physical markets. Nevertheless, these findings provide theoretical and practical contributions to retail grocery businesses that have integrated conventional and digital services as a future strategy that drives business sustainability.

Keywords: switching intention; e-grocery shopping; push–pull–mooring

1. Introduction

The i formation search process is the initial stage of the purchase decision [1]. The era of digitalization exposes consumers to various alternative media to access information about goods and services before making a purchase decision. Statista stated that shopping behavior in the Southeast Asia region in 2025 will switch to digital shopping behavior. Online music and video streaming, online learning applications, e-grocery applications, and food delivery services are new products in an emerging digital market. The emergence of COVID-19 seems to have accelerated the process of technology adoption. Based on e-commerce research from the Central Statistics Bureau in 2021, the demand for grocery and food delivery services has increased rapidly during the pandemic. Even compared to other categories, the number of online shopping transactions for groceries and food reaches 30 percent and dominates all online shopping transactions [2]. The pandemic situation and social restriction policies prompted using mobile applications, such as Tanihub, Sayurbox, Cari Sayur, or Happyfresh, to access online grocery shopping. L.E.K. Consulting stated that among several grocery marketing channels, online marketing channels are considered the most strategic channels to penetrate the market [3]. The penetration rate of e-grocery in Indonesia showed an increase in gross merchandise value of USD 1 billion in 2020, so the growth of e-grocery in Indonesia could reach USD 6 billion by 2025. Based on the increasing intention to e-grocery shop and the projection of the development of e-grocery retail business in Indonesia, this study proposes the following research question:

(RQ1) What are the socio-demographic characteristics of potential shoppers who would be interested in switching to e-grocery shopping?

Outside the pandemic situation, Indonesian consumers tend to shop for groceries in traditional markets because of the fresher product quality, relatively affordable prices, and the feeling of bargaining, which is attractive for some consumers [4]. However, some consumers consider the traditional market conditions to be unhygienic. In addition, the traditional market's low food safety encourages customers to switch to modern markets, supermarkets, and even e-grocery [5,6]. In other words, perceived inconvenience is often the reason for dissatisfaction and potentially encourages switching intentions [7,8]. Many studies examined that perceived price fairness, and the availability of delivery services also increases the e-grocery shopping value compared to physical markets [9,10]. Based on the phenomenon that describes the low level of consumer satisfaction with physical market services and the emergence of attractive alternative e-grocery services that offer a variety of shopping conveniences, the following research question is posed: (RQ2) How can physical market dissatisfaction encourage the intention to switch to using e-grocery services, and is the appeal of e-grocery able to encourage consumers to switch from their old habit of physically shopping e-grocery services?

Furthermore, mobile applications' perceived ease of use and usefulness are what makes e-grocery attractive [11]. Finally, the level of personal innovativeness supported the readiness to utilize technological novelty [12].

Customers have their perceptions about the risks of physical shopping, and these might include that physical shopping accelerates the transmission of the virus, which was especially true during the pandemic [13]. In addition, the abundance of health information circulating in various digital media has increased public health consciousness, triggering the avoidance of crowds in the physical market and switching to e-grocery shopping behavior [14]. As a result, at the beginning of the pandemic, the new phenomena of "panic buying" and "pantry stockers" emerged in many households [13]. The demand for online groceries increased rapidly, encouraged scarcity, and pushed the price level. The characteristics of the groceries that most consumers buy include staple food, instant canned food, processed frozen food, and fresh food, such as beef, chicken, fish, seafood, eggs, dairy products, vegetables, and fruit [15]. Then, to prove the importance of health consciousness and personal innovativeness, this study proposes the following question: (RQ3) How important is the role of health consciousness and personal innovativeness as the moderators in influencing switching intention to e-grocery shopping?

Regarding e-grocery shopping consumer behavior and the potential growth of e-grocery businesses in Indonesia, this study aims to: (1) Identify the characteristics of potential customers of e-grocery shopping services; (2) Analyze the effect of perceived dissatisfaction with the physical market and the attractiveness of e-grocery services on switching intentions toward e-grocery shopping; and (3) Analyze the role of moderation of switching costs, health consciousness, and personal innovativeness in accelerating or inhibiting switching intentions toward e-grocery shopping.

The grocery shopping channel preferences are an exciting topic to explore. Some consumers prefer to shop conventionally in a physical market; however, other consumers with modern lifestyles generally prefer the online market in order to have a practical shopping process. Furthermore, will switching behavior to e-grocery shopping only occur during the pandemic, or will it continue post-pandemic? This study theoretically contributes to identifying e-grocery customers' characteristics and analyzing what factors significantly affect switching intention toward online grocery shopping through the push–pull–mooring framework. In addition, this research also contributes practically to recommending the right strategy for retail grocery businesses to maintain business sustainability in the long term.

2. Literature Review and Hypothesis

2.1. Push–Pull–Mooring Framework

The push–pull–mooring (PPM) framework begins with the law of migration, which explains why a person migrates from the point of origin to the point of destination [16]. Initially, migration studies focused on the concept of aggregate-level push and pull. Push factors are unfavorable conditions that encourage individuals to leave the point of origin, while pull factors are favorable conditions that attract individuals toward the destination point. Then, the researchers considered the possibility of normative and psychosocial variables contributing to migration decisions. So, Moon explained that migration adds to the idea of "mooring", which is then incorporated into the push–pull migration model [17]. The mooring factors are integrated into the push–pull framework to explain migration behavior more thoroughly, where mooring factors can facilitate and inhibit migration behavior. Mooring extends the notion of intervention variables and includes all personal, social, and cultural variables to moderate the migration decision.

Various studies have widely adopted the PPM framework in consumer behavior to analyze the factors that drive consumers to switch to other products (brands) or services. For example, research analyzing switching intention to adopt the food traceability technology has applied the push–pull–mooring framework and integrated it with the DeLone and McLean ISS and TPB Model [18]. The research has found that the integrated model contributes to the relationship quality, encouraging switching intention. Other studies in a similar field highlight willingness to pay a premium price and health consciousness as mooring factors that accelerated switching behavior during the COVID-19 pandemic [14]. This study has found that health consciousness moderates the causality between perceived product quality and switching intention.

Meanwhile, willingness to pay premium price has moderated the causality between perceived risk uncertainty and switching intention, contrary to the research of R. Singh and Rosengren, which analyzed switching intention to online grocery shopping, which focused more on switching costs as a mooring factor in accelerating switching intention [19]. Similarly, research in other fields has highlighted the critical role of switching costs and personal innovativeness in accelerating switching intention [20–24].

2.2. Perceived Dissatisfaction with Physical Market as a Push Factor

Dissatisfaction is a driving factor that affects switching intention. Some things that have the potential to cause dissatisfaction are service quality and perceptions of unfair prices [7]. Specifically, in terms of service quality, customers often complain about the performance of customer service, delivery service, and technical service facilities. The customers' complaints reflect the perceived dissatisfaction, thus encouraging customers to switch to another grocery store in the future [19,25]. The higher the attractiveness of competitors' services, the more likely the intention to switch. In the context of electronic services, the quality of information systems is an essential factor that customers consider when choosing electronic payment services [20,21]. In addition, customer assessment of perceived risk is also why customers choose food delivery services [18]. They consider how much they can afford the consequences of the uncertain risk of food delivery service. Another critical reason customers are loyal is the perception of shopping convenience [22]. Convenience is the customer's perception of the time and effort required to use the service [26]. Convenience reflects how service can efficiently complete customers' tasks [27]. Within online retail shopping, customers need convenience reflecting access to applications and secure electronic transactions [28,29].

Furthermore, Clulow and Reimers [30] stated that the condition of the service location (space) is also a factor that determines convenience in the retail business scope. As Maruyama [6] stated, customers switch from traditional markets to modern markets due to the inconvenience of the unhygienic traditional market environment and product quality that is still below standard. Based on previous research, the hypotheses proposed in this study are as follows.

Hypothesis 1 (H1). *Perceived dissatisfaction with physical market influences switching cost toward e-grocery shopping.*

Hypothesis 2 (H2). *Perceived dissatisfaction with physical market influences switching intention toward e-grocery shopping.*

2.3. Alternative Attractiveness of E-Grocery as a Pull Factor

Alternative attractiveness is a positive perception that describes a prospective thing in the new destination, which attracts customers to switch. According to the push–pull–mooring perspective, naturally and unconsciously, when a customer's evaluation results show interest in a new alternative, the switching intention has been raised [16]. Customers switch when the alternative product (brand) or service offers more advantages and benefits than the previous product (brand) or service provider. In other words, the alternative attractiveness becomes a factor that drives switching intention when the provided services are more satisfactory [31,32]. From the perspective of e-services, service quality of information systems will lead to more vital satisfaction that urges the customer to switch to a new service [33]. Lin, Jin, Zhao, Yu, and Su [23] indicated that the ease of use of online learning applications and perceived usefulness are aspects of the pull factors that encourage switching intention to use online learning media. Otherwise, the attractiveness of alternatives contributes to the switching shopping behavior from shopping in physical markets to e-grocery mobile application services [8,26,34,35]. The hypotheses proposed in this study are as follows.

Hypothesis 3 (H3). *The alternative attractiveness influences switching cost toward e-grocery shopping.*

Hypothesis 4 (H4). *The alternative attractiveness influences switching intention toward e-grocery shopping.*

2.3.1. Perceived Ease of Use and Usefulness

The technology acceptance model predicts whether a new information system can be accepted by potential users [36]. The technology acceptance model mentioned several indicators of the quality of information systems, namely perceived ease of use and usefulness and other supporting external factors. Especially in food delivery applications, perceived ease of use criteria is the ease of learning, controlling, understanding, and being skilled in using the mobile application to order, transact, and pay digitally [35]. Perceived ease of use of an information system indirectly increases the readiness of users to adapt to new technology [36]. For example, during a pandemic, when the e-grocery mobile application is easily accessible, has straightforward navigation, and stands easy to operate, it will encourage consumers to switch to e-grocery services quickly [37]. In addition to perceived ease of use, a mobile application should also provide optimal benefits for users. Several criteria of perceived usefulness include accelerating work completion, improving performance, increasing productivity, increasing work effectiveness, and simplifying work [24,34]. In addition, some customers feel practically supported when using grocery and food delivery services [38,39], as they should not go to the physical market and encounter traffic and crowdedness. The influence of perceived ease of use and usefulness was examined by testing the following hypotheses.

Hypothesis 5 (H5). *Perceived ease of use influences e-grocery shopping attractiveness.*

Hypothesis 6 (H6). *Perceived usefulness influences e-grocery shopping attractiveness.*

2.3.2. Perceived Value

In addition, the attractiveness of e-grocery mobile shopping is not only about the quality of the information system; an e-grocery shopping service should offer a better perceived value than shopping in the physical market. Perceived value represents a trade-off between the quality (benefits) received and the sacrifices (financial, time, and effort) that consumers spend to consume goods and services [40,41]. Specifically, Refs. [32,42] stated that e-service quality is the essential factor impacting high perceived value for online shopping. In the context of retail shopping, the perceived value reflects the product performance and consumer appreciation of the reliability of the service, then compared with the price that must be paid [32].

Meanwhile, other studies stated that product quality, perceived price fairness, and healthy consumption contribute to the perceived value and repurchase intention for shopping organic products [43]. Likewise, Ref. [9] mentioned that perceived price fairness potently encourages perceived value and repurchase intention for e-grocery shopping. Based on previous research, perceived value is an essential factor impacting purchasing decisions on whether to stay (loyal) or prefer other service alternatives (switching). So, the hypothesis proposed in this study is as follows.

Hypothesis 7 (H7). *Perceived value influences e-grocery shopping attractiveness.*

2.4. Switching Cost toward E-Grocery Shopping as a Mooring Factors

The simplicity of the push–pull perspective turned out to be insufficient to explain the complexity of the factors that cause switching behavior. The concept of contemporary migration explains that evaluating push and pull factors cannot confirm the reasons for switching behavior [44]. Instead, the mooring factor analyzed the possibility of intervention as a trigger to accelerate or inhibit the impulse to switch. One of the mooring factors widely discussed in previous studies is switching costs. Switching cost is an anchoring factor in switching intention. The perceived sacrifice, both financial and non-financial, is often a consideration for someone to accept new behavior. The switching costs include time, effort, sacrifice, the consequences of uncertainty, the amount of coverage for risks, and the ability to adapt to new behavior [45]. When the evaluation results show relatively high switching costs, customers tend to stay loyal to existing ones.

On the contrary, if a new product (brand) and service offer many benefits, the customer can deal with the consequences of switching. Then, the customer's tendency will be quickly switched to a new one [31]. This study summarizes this theoretical and previous research review with the following hypothesis.

Hypothesis 8 (H8). *Switching cost influences switching intention toward e-grocery shopping.*

2.4.1. Health Consciousness

Health consciousness is the awareness of and concern about self-healthiness, family healthiness, and people's healthiness [46]. Health consciousness assesses an individual's readiness to make various health-related decisions. Health consciousness affects a person's preferences and buying behavior in food products [47,48]. For example, health-conscious individuals consume organic food to improve their quality of life [49–51]. Thus, health-conscious people will be more motivated to turn to credible alternatives. In addition, when consumers are health-oriented, they are more likely to care about product quality and tend to avoid the risk associated with potential health issues [9,14,52]. Based on their knowledge and health consciousness, one is willing to make behavioral changes, including changing grocery shopping habits from physical markets to online grocery shopping [13,48]. During the COVID-19 pandemic, health consciousness is considered one of the factors that minimize switching costs [14]. In addition, people tend to pay more attention to food hygiene and safety, the cleanliness of shopping locations, and service facilities that can

minimize the virus' risk [10]. The influence of health consciousness was examined by testing the following hypothesis.

Hypothesis 9 (H9). *Health consciousness influences switching cost toward e-grocery shopping.*

2.4.2. Personal Innovativeness

Personal innovativeness is accepting new ideas in developing information systems technology [53]. Individual beliefs and attitudes toward technologies are critical in predicting behavioral intention [54]. In addition, personal voluntariness and experience also have a role in the intention to adopt technology [55]. Likewise, innovative personal traits and situational encouragement often trigger the transition of someone with technology constraints to become a technology adopter [48,56]. The personal efficacy of technology improves users' innovation in their expertness in IT-related activities [48]. The magnitude of the acceptance ability will encourage the willingness to try new things or the latest digital applications [57]. For example, a study of digital payment stated that personal innovativeness determines the intention to switch to electronic payment services at physical stores [12,19].

In applying the unified theory of acceptance and use of technology (UTAUT) concept, personal innovativeness is a potential factor influencing behavioral intention [58]. During the COVID-19 pandemic, social distancing had become a situational impetus for one to adopt online shopping services. The urge is becoming stronger because personal innovation toward high technology strengthens people's trust in online shopping services [59]. However, limited studies still explain that personal innovativeness can minimize switching costs. Therefore, the higher the personal innovativeness of technological novelty, the smaller the perceived sacrifice to make changes (switching cost). Based on theoretical studies and previous research, the proposed hypothesis is as follows.

Hypothesis 10 (H10). *Personal innovativeness influences switching cost toward e-grocery shopping.*

2.4.3. The Role of Mooring Factor as a Moderator

Based on a push–pull–mooring perspective, the mooring factor does not directly affect switching intention. However, the variables included in the mooring factor often take on the role of moderators that facilitate switching behavior. For example, a study at the beginning of the pandemic stated that health consciousness was essential in determining the location and media used to shop for groceries [13]. Another study stated that health consciousness significantly encourages the emergence of purchase intentions for organic products [48]. However, this study has not researched the possible role of health consciousness as a moderating variable. Furthermore, research on traceable agricultural products has placed health consciousness as a dimension of the mooring factor that moderates the causality of push–pull factors on switching intention [14]. Based on a review of previous research, this study proposes a hypothesis about the moderating effect of health consciousness on the causality of switching costs on switching intention towards e-grocery shopping.

Handarkho and Harjoseputro [12] have investigated the role of personal innovation as a mooring factor in driving the intensity of the use of electronic payment services in a physical store, which has a significant effect. However, this study has not tested the moderating effect of personal innovativeness on the intention of using electronic payment services. However, other studies on payment systems have seen the potential for personal innovation as part of the mooring factor that simultaneously moderates the causality of the driving factors for the intention to switch [19]. Therefore, based on previous research, this study proposes a hypothesis to test personal innovation's ability to moderate the push–pull factors on switching intentions to use e-grocery shopping services.

Another factor suspected of being a mooring factor is switching costs. Various previous studies have investigated the role of switching cost in determining switching intention [19,31,48]. Moreover, consumers will consider switching behavior's consequences, constraints, and

risks. Furthermore, this study will explore how moderate switching costs affect the causality of push–pull factors on the switching intention. According to the previous research review, the proposed hypotheses are as follows.

Hypothesis 11 (H11). *Switching costs moderate the causal relationship of perceived dissatisfaction with physical markets to switching intention toward e-grocery shopping.*

Hypothesis 12 (H12). *Switching costs moderate the causal relationship of alternative attractiveness to switching intention toward e-grocery shopping.*

Hypothesis 13 (H13). *Health consciousness moderates the causal relationship of switching cost to switching intention toward e-grocery shopping.*

Hypothesis 14 (H14). *Personal innovativeness moderates the causal relationship of switching cost to switching intention toward e-grocery shopping.*

3. Methodology

3.1. Sampling and Data Collection

This quantitative research used the survey method and the non-probability sampling approach in which each individual has an unequal opportunity to be a selected respondent (sample). The sample selection process uses the purposive sampling technique, a combination of convenience and judgmental sampling based on considerations of ease of collecting sampling. Furthermore, the researcher has set specific criteria for recruiting respondents [60]. This study distributed questionnaires online through social media to obtain the respondents who matched the criteria. The researcher set sample criteria in the screening question section of the questionnaire that the respondents are residents of Jakarta, Indonesia, who were aware of the existence of e-grocery shopping services through mobile applications, such as Tanihub, Sayurbox, Cari Sayur, or Happyfresh. The sample size for SEM analysis is a minimum of 200 samples, or 5–10 times the number of indicators [61,62]. The number of instruments (items) used in this study was 39. Through the distribution of online questionnaires, 265 Jakarta residents filled out the questionnaire. However, the result of the final sample was 252 respondents for empirical analysis. So, it can be concluded that the number of samples meets the sample size criteria.

According to the data collection, the sample's socio-demographic characteristics comprised 193 (76.6 percent) women and 59 (23.4 percent) men. Regarding the age group, most of the respondents in the sample are aged 25–30 years and between 31–40 years, and most respondents are married. In addition, most of the respondents' education level is undergraduate, and they work as employees with an average monthly income of between 400 and USD 700. The socio-demographic characteristics of respondents are relevant to the Ken Research of 4 April 2022, which stated the demand for online grocery shopping mainly comes from working professionals and married couples because they have less time to visit stores to buy groceries physically. Additionally, most are housewives or wives who care for the family's food needs. About 49.7 percent of the total population in Indonesia are women, so it makes sense that most e-grocery customers are women. Furthermore, the customers who make about 70 percent of grocery orders are 25–37 years old [63]. All the information regarding the socio-demographic characteristics of the respondents is presented in Table 1.

Table 1. Socio-demographic characteristics of respondents.

Socio-Demographic Items	Frequency	Percentage
	n = 252	
Gender		
Male	59	23.4
Female	193	76.6

Table 1. *Cont.*

Socio-Demographic Items	Frequency	Percentage
	n = 252	
Marital Status		
Single	87	34.5
Married	164	65.1
Divorced/Widowed	1	0.4
Age		
25–30 years old	181	71.8
30–39 years old	56	22.2
40–49 years old	11	4.4
50 years old and over	4	1.6
Education		
High school degree	20	8.0
Under-graduate	194	77.0
Post-graduate	38	15.0
Occupation		
Self-employed	69	27.4
Employee	126	50.0
Housewife	57	22.6
Monthly Income		
Under USD 400	27	10.7
Between USD 400–700	128	50.8
Over USD 700	97	38.5

3.2. Research Instrument

The questionnaire was organized into two sections. The first section included six items to classify the characteristic of the socio-demographic characteristics of the respondents, such as gender, marital status, age, education level, occupation, and average monthly income. The second section measures consumer switching behavior, including 39 items on the construct, which were modified and adapted from a previous study.

For example, perceived dissatisfaction with the physical market as a push factor has eight items adapted from [10,24,31]; alternative attractiveness as a pull factor has four items adapted from [8]; perceived ease of use has four items adapted from [24,34]; perceived usefulness has four items adapted from [24,34]; perceived value has four items adapted from [9,10,33]; switching costs as a mooring factor has four items adapted from [19]; health consciousness has five items adapted from [47]; personal innovativeness has four items adapted from [19]; and switching intentions has three items adapted from [19]. The research questionnaire is attached in Appendix A.

The questionnaire proposed several items that describe the measurement of variables and asked respondents to provide an assessment based on a Likert scale, which describes the degree of agreement. It starts from "Strongly Disagree" and ends with "Strongly Agree", which are worth 1 to 5 points. Furthermore, the respondents' assessment will be analyzed to measure the ability of the independent variable to explain the dependent variable. Previously, this study conducted a pilot study to test the validity and reliability of the instrument on 30 respondents. All the proposed hypotheses in the conceptual model are depicted in Figure 1.

3.3. Analytical Method

This study used covariance-based structural equation modeling (CB-SEM) as the analytical method capable of simultaneously estimating several separate but interconnected regressions [62]. This study conducted several tests and analyses using the statistical package for the social science (SPSS) and the analysis of moment structure (AMOS) software. There is a three-step approach to conducting the data analysis. First, the validity and

reliability construct was assessed by conducting confirmatory factor analysis (CFA). Second, the goodness-of-fit testing ensures that the structural model meets the criteria of absolute indices. Third, the proposed hypotheses were conducted by structural equation modeling (SEM) to examine the structural model and moderating effects.

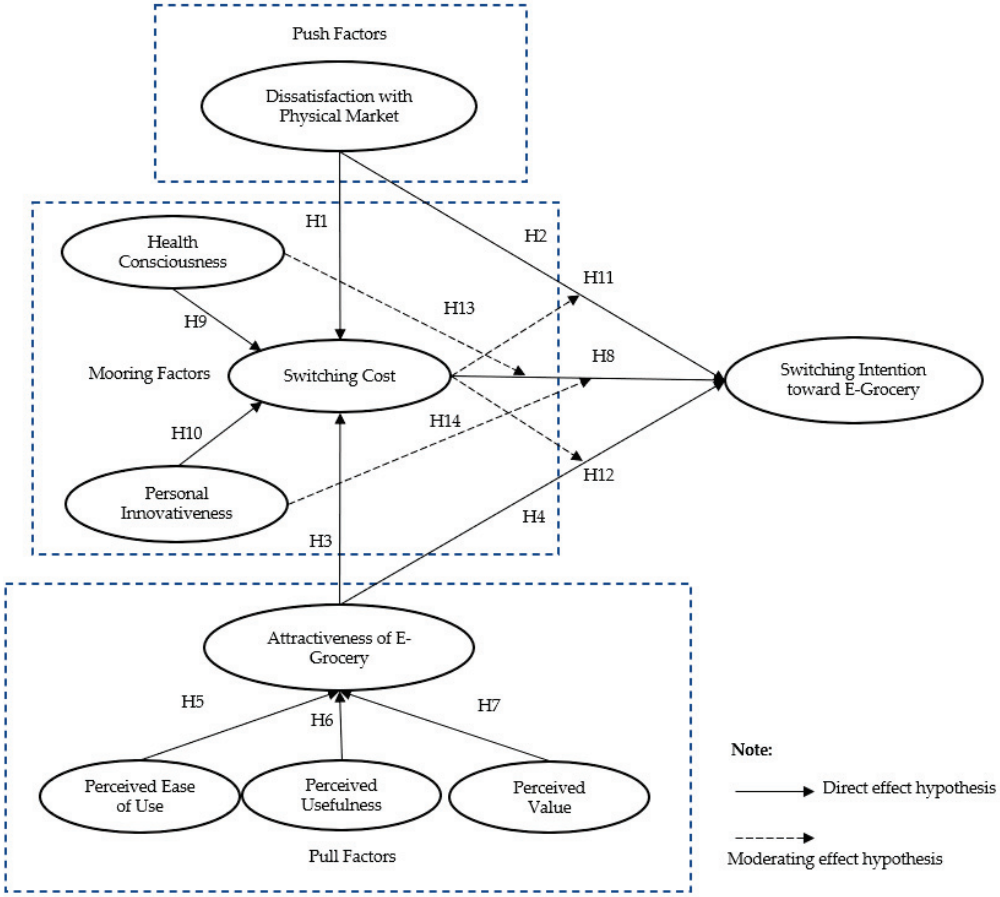

Figure 1. The Conceptual Framework.

4. Data Analysis and Result

In this study, confirmatory factor analysis (CFA) examined the measurement model fit to test the validity of the convergent and discriminant latent factors. The results of the CFA declared that all items were valid with a loading factor value above 0.5 and reliable with a Cronbach's alpha value above 0.6. As its next step, this research should ensure that the structural model has goodness of fit by considering the value of the absolute indices component based on certain criteria. Several absolute index components, namely chi-square ($\chi 2$) with a probability cut-off value of >0.05; root mean square error of approximation (RMSEA) with a cut-off value of <0.08; goodness of fit index (GFI) with a cut-off value of 0.90; adjusted goodness of fit (AGFI) with a limit value of 0.90; CMIN/DF with a limit value < 2.0; the Tucker–Lewis index (TLI) with a cut-off value > 0.95, and a comparative fit index (CFI) with a cut-off value of >0.95. This study eliminated the items with a high standard error in the modification indices to ensure the structural model achieves goodness of fit. At the same time, five items were eliminated: one item on perceived dissatisfaction, one item on perceived usefulness, one item on switching cost, and two items on personal innovativeness. By eliminating items on modification indices, the structural model achieved a good fit in which the value of the chi-square was 505.826 with the probability value being 0.174; RMSEA was 0.016; GFI was 0.901; AGFI was 0.876; CMIN/DF was 1.060; TLI was 0.996; CFI was 0.997. The result of the CFA after eliminating the items is reported in Table 2.

Table 2. Confirmatory factor analysis.

Variables	Items	Loading Factor	Cronbach's Alpha
Perceived dissatisfaction with physical market	DSAT1	0.952	0.936
	DSAT2	0.937	
	DSAT3	0.939	
	DSAT4	0.833	
	DSAT5	0.885	
	DSAT6	0.887	
	DSAT8	0.818	
Alternative attractiveness	ATT1	0.925	0.939
	ATT2	0.891	
	ATT3	0.926	
	ATT4	0.935	
Perceived ease of use	EAS1	0.948	0.962
	EAS2	0.957	
	EAS3	0.943	
	EAS4	0.948	
Perceived usefulness	USE1	0.933	0.955
	USE2	0.941	
	USE3	0.942	
Perceived value	VAL1	0.903	0.918
	VAL2	0.874	
	VAL3	0.904	
	VAL4	0.904	
Switching cost toward e-grocery shopping	SWC1	0.903	0.929
	SWC2	0.898	
	SWC3	0.912	
Health consciousness	HEA1	0.805	0.812
	HEA2	0.826	
	HEA3	0.798	
	HEA4	0.767	
Personal innovativeness	INO2	0.908	0.911
	INO3	0.916	
Switching intention toward e-grocery shopping	SWI1	0.896	0.901
	SWI2	0.915	
	SWI3	0.932	

Furthermore, this study conducted hypothesis testing based on the regression estimation results. The causality relationship among variables is declared significant if the probability value is below 0.05 and the C.R. value above 1.96. As a result, there are two hypotheses proposed that were rejected. As a result, H1, which proposed that the causal relationship of perceived dissatisfaction with the physical market to switching costs toward e-grocery shopping, has a probability value of 0.263 (above 0.05) and a C.R. value of 1.120 (below 1.96), so it can be concluded that H1 is rejected. Then, H2, which proposed the causal relationship of perceived dissatisfaction with the physical market to switching intention toward e-grocery shopping, has a probability value of 0.069 (above 0.05) and a C.R. value of 1.817 (below 1.96), so it can be concluded that H2 is rejected. However, other hypotheses that were proposed are supported. The result of the structural model is depicted in Figure 2.

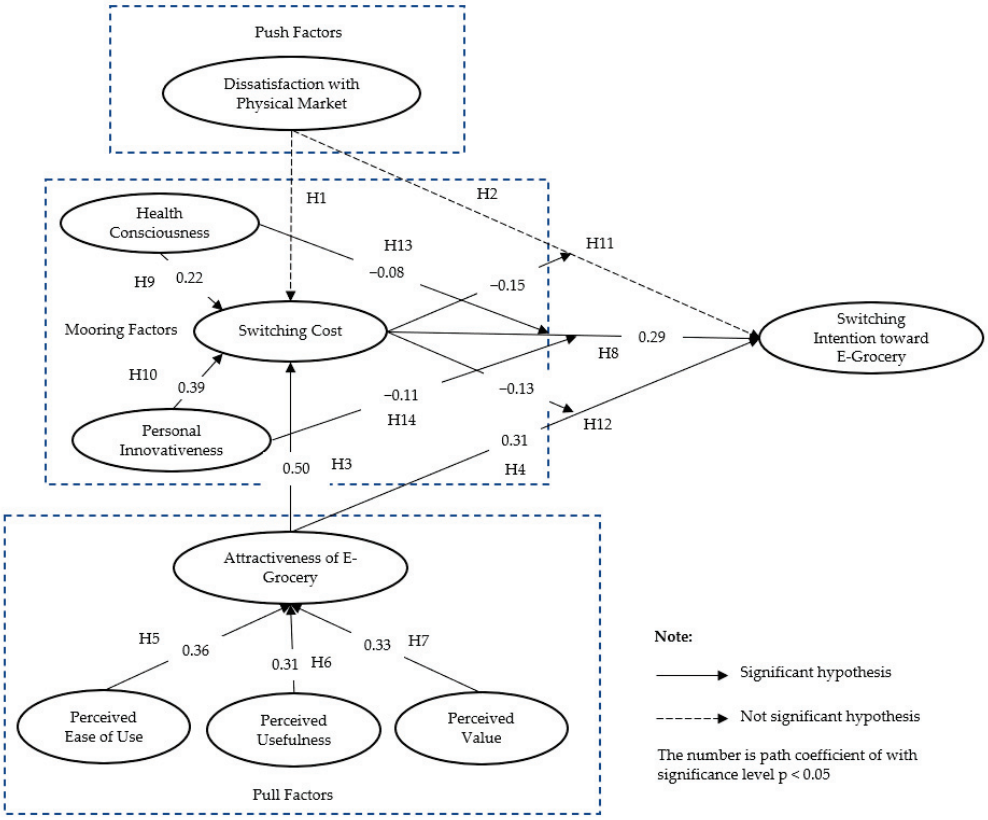

Figure 2. The Result of Structural Model.

The result of the proposed hypotheses and regression estimation are reported in Table 3.

Table 3. Estimation regression of structural model analysis.

Hypotheses				Estimate	S.E.	C.R.	*p*	Result
H1.	DSAT	→	SWC	0.087	0.077	1.120	0.263	Not supported
H2.	DSAT	→	SWI	0.127	0.070	1.817	0.069	Not supported
H3.	ATT	→	SWC	0.504	0.111	4.550	***	Supported
H4.	ATT	→	SWI	0.314	0.129	2.435	0.015	Supported
H5.	EAS	→	ATT	0.358	0.123	2.919	0.004	Supported
H6.	USE	→	ATT	0.314	0.110	2.855	0.004	Supported
H7.	VAL	→	ATT	0.332	0.062	5.382	***	Supported
H8.	SWC	→	SWI	0.294	0.123	2.388	0.017	Supported
H9.	HEA	→	SWC	0.220	0.104	2.116	0.034	Supported
H10.	INO	→	SWC	0.394	0.095	4.152	***	Supported

Notes: DSAT = dissatisfaction, ATT = alternative attractiveness, EAS = perceived ease of use, USE = perceived usefulness, VAL = perceived value, SWC = switching cost, HEA = health consciousness, INO = personal innovativeness, and SWI = switching intention. Significance level $p < 0.05$ and *** for significance level $p < 0.001$.

In addition to the hypothesis testing of the direct effect, this study also conducted hypothesis testing for moderating effect. To examine the hypothesis proposed regarding the moderating effect, previously, we had to calculate the multiplication of the z-score of the moderator variable with the z-score of the independent variable that affected the dependent variable. Then, the moderation model was calculated on the AMOS software to obtain the regression estimation results. As a result, the proposed hypotheses of the moderation model are supported. The result of the hypotheses of the moderation effect is shown in Table 4.

Table 4. Estimation regression of moderation structure.

Hypothesis of Moderating Effect				Estimate	S.E.	C.R.	*p*	Result
H11.	SWC × DSAT	→	SWI	−0.151	0.034	−4.407	***	Reversely Supported
H12.	SWC × ATT	→	SWI	−0.129	0.036	−3.604	***	Reversely Supported
H13.	HEA × SWC	→	SWI	−0.076	0.030	−2.576	0.010	Reversely Supported
H14.	INO × SWC	→	SWI	−0.112	0.040	−2.780	0.005	Reversely Supported

Notes: DSAT = perceived dissatisfaction, ATT = alternative attractiveness, HEA = health consciousness, INO = personal innovativeness, SWC = switching cost, and SWI = switching intention. Significance level $p < 0.05$ and *** for significance level $p < 0.001$.

5. Discussion and Conclusions

This study developed and examined the factors contributing to the intention to switch to e-grocery shopping through a push–pull–mooring framework. Through the PPM framework, the discussion does not only focus on the low attractiveness of the origin point and the high attractiveness of the destination point (alternative), the more crucial mooring factor is also considered to trigger switching acceleration. Research findings suggest dissatisfaction with the physical market does not motivate switching to e-grocery shopping services. People complain about the inconvenience of traditional markets, but it does not make them want to switch to e-grocery services [19]. Even during the COVID-19 pandemic, there is a high risk of shopping in physical markets, but it does not encourage customers to switch to using e-grocery services.

Thus, the findings reject H1 and H2, which state that perceived dissatisfaction with the physical market does not affect switching costs and intentions toward e-grocery shopping. The pandemic is pushing customers to shop from alternative places and media [64]. However, this does not mean that customers will quickly accept the consequences of switching (switching cost) from the old habit of shopping for groceries in physical markets to e-grocery services [45]. Especially in Indonesia, e-grocery services seem to be an alternative shopping service that supports meeting customer needs in certain situations. However, this does not necessarily eliminate consumer interest in conventional shopping, which provides personal transactions between sellers and buyers. The emergence of a shift in shopping behavior through e-grocery is more due to customer volunteerism, particularly for people with high health consciousness and personal innovativeness, so they tend to overlook the switching cost to e-grocery services [12,14,19].

In addition, the result stated that the attractiveness of e-grocery shopping as the pull factor has a binding effect on the switching cost and intention to switch to e-grocery shopping. The finding stated that the attractiveness of e-grocery has the most substantial effect on switching costs compared to other factors, such as health consciousness and personal innovativeness, with an estimated coefficient value of 0.504. Likewise, the finding mentioned that e-grocery attractiveness as a pull factor significantly affects increasing the intention to use e-grocery services. The more attractive the impression of the attractiveness of e-grocery shopping, the easier for customers to accept the switching cost (consequences) and switch to e-grocery services. Among several factors that support the attractiveness of e-grocery services, perceived ease of use is the most decisive factor contributing to the attractiveness of e-grocery services, with a coefficient estimated value of 0.358. It means that e-grocery shopping service providers must focus on increasing the quality of e-grocery applications and ensure that the application is user-friendly. Likewise, e-grocery applications need to optimize customer benefits by developing service features tailored to customer tastes and needs [38]. Furthermore, several factors to improve the perceived value of e-grocery shopping are product quality, availability, delivery service, and perceived price fairness [9,10]. Even others that cannot be measured financially, such as the company's reputation, brand image, or company credibility, also play a role as contributors to high perceived value [31,41].

Regarding the role of the mooring factor, the finding mentioned that switching costs contributed to the switching intention toward e-grocery shopping. Switching costs consist

of monetary or non-monetary costs incurred due to switching. Switching cost has a role that is sensitive to switching intention. Every switching behavior will have its consequences. Nevertheless, the magnitude of the consequences depends on how a person responds to a change. In the case of e-grocery shopping, some of the monetary switching costs incurred could be product prices and shipping costs. At the same time, non-monetary switching costs could be the time to adapt to learn the use of electronic ordering systems and the risk of uncertainty in delivery times [45]. However, for people with high personal innovativeness, these non-monetary transfer costs can be easily overcome [55]. Likewise, people with a high level of health consciousness tend to have personal triggers that encourage them to ignore switching costs, so they immediately switch to e-grocery services [64].

Switching shopping behavior often impacts customers during the adaptation process [8]. Switching towards e-grocery shopping requires consumers to understand how to use e-grocery mobile applications, how the shopping procedures work, and various possible uncertainties that cannot be predicted in advance and arise as part of the consequences of e-transactions [10,12,19]. Health consciousness and personal innovativeness significantly affect switching costs toward e-grocery shopping. Interestingly, the finding showed that personal innovativeness plays a vital role in minimizing switching costs compared to health consciousness, with an estimated coefficient value of 0.394. Individuals with high curiosity and innovativeness towards technological novelty make it easier to adapt to using e-grocery shopping services [12,19]. However, this study has not yet tested the personal innovativeness encouraging switching intentions. In addition to personal innovativeness, the finding showed that health consciousness also contributed to the acceptance of switching costs. The pandemic provided extraordinary knowledge and experience about the importance of health [13]. At that time, health consciousness became a motivation for engaging with the switching costs and minimizing the switching costs that arise [13,14,48], then encouraging customers to switch to e-grocery services.

The mooring factor moderates and can speed up and inhibit switching intentions. The regression of the moderation structure estimation shows that switching costs' contribution to the causality of perceived dissatisfaction with the physical market and switching intention is greater than the attractiveness of e-grocery services, with an estimated coefficient of −0.151. Perceived dissatisfaction with physical market services is a reason for one to reduce the value of switching costs, thereby accelerating the intention to switch to e-grocery. Other studies found that switching costs are sensitive in determining the intention to use e-learning and digital payment [19,31]. Therefore, the magnitude of the switching costs has a relative value; perceived dissatisfaction with the physical market will be a strong impetus for switching to e-grocery. The motivation will reduce the cost of switching and overlook the obstacles due to moving. Likewise, the moderating role of switching costs on the causality of the attractiveness of e-grocery services on switching intentions indicates that the higher the perceived attractiveness of e-grocery shopping the lower the risks and possible consequences of switching. The interest in the convenience and benefits of electronic services and an improved value of e-grocery shopping causes one to disregard the consequences of the risks that may arise from online shopping [31,49]. Thus, customers tend to switch to e-grocery shopping services immediately.

This study has positioned health consciousness and personal innovativeness as important moderating variables influencing the causality of switching costs on switching intention. This research has proven that personal innovativeness is a crucial trigger in the causality of switching costs to the switching intention toward e-grocery shopping. The estimated regression value of personal innovativeness as a moderator is −0.076, better than health consciousness. Personal innovativeness in adopting technology contributes to minimizing the obstacles of operating an e-grocery application. In addition, it will encourage the adaptation process to be more straightforward in switching to e-grocery shopping.

Furthermore, during the pandemic, health consciousness has become a reason to accept the switching costs. People ignore various barriers to using e-grocery services based

on their knowledge and health consciousness. As a result, customers quickly adapted to various information systems applications to meet their needs continuously.

6. Managerial Implication, Limitation, and Future Research Direction

The application of the push–pull–mooring framework shows that the attractiveness of e-grocery as a pull factor plays a vital role in the intention to switch to e-grocery shopping. All e-grocery attractiveness factors, such as perceived ease of use, usability, and shopping value, have a significant effect. Research findings contribute to building modern grocery retail businesses' competitiveness and customer attractiveness through developing e-grocery services to maintain business continuity and long-term customer loyalty. The attractiveness of e-grocery shopping will not only arise due to situational encouragement from the COVID-19 pandemic, but customers will still be interested in using e-grocery shopping services in the post-pandemic period. For this reason, the results provide recommendations to e-grocery shopping providers to improve the system's quality to make it more accessible and provide straightforward navigation. In addition, the interface of the e-grocery application should be more attractive and emphasize improving the shopping experience, which indicates an increase in the perceived value of e-grocery shopping. In addition, developing new features is also one of the recommendations to optimize the specific benefits of e-grocery shopping compared to shopping in the physical market. The Indonesia Online Grocery Market Outlook to 2026 report from Ken Research stated that e-grocery service providers need to prepare a strategy to respond to the growth of the e-grocery market in Indonesia, population growth, and high internet penetration for online shopping [65].

Based on the socio-demographic characteristics of the respondents, most of the e-grocery shopping enthusiasts are millennial consumers with tech-savvy characteristics. They tend to have highly innovative personalities and quickly adapt to new technologies. In addition, e-grocery services also need to highlight the potential for customer health awareness to pay more attention to product freshness, food safety standards, and hygiene as a market attraction and unique selling points of e-grocery services. Likewise, the timeliness of delivery services and the flexibility of delivery schedules are the main attractions of e-grocery services for urban communities compared to the value of shopping in the physical market.

Despite the various findings and managerial implications presented, this study still has limitations in certain aspects. First, the findings represent consumer spending behavior in Indonesia, so there is still potential for different findings if further research applies the conceptual model in other countries or even in different research fields. However, other studies can utilize the result as a reference for analyzing e-grocery shopping behavior on the characteristics of society and culture that are almost similar to Indonesia, such as countries in Southeast Asia where the e-grocery retail industry is an emerging market. Second, this study is limited to examining certain factors that influence switching intentions towards e-grocery shopping in Indonesia during the pandemic, as the period of consumer surveys present in a conceptual research model. For this reason, further research could include other variables driving the intention to switch to e-grocery shopping. Third, this study has not tested the role of respondents' socio-demographic characteristics in shopping behavior and preferences for e-grocery services. Thus, further research can comprehensively analyze and formulate groceries retail businesses' marketing strategies.

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Appendix A

Table A1. Research Questionnaire.

Variables and Items	References
Push Factors—Perceived Dissatisfaction (DSAT) DSAT1. I feel unhappy making purchases in the physical market. DSAT2. The crowd of physical markets makes me uncomfortable. DSAT3. I am worried about the cleanliness of the physical market during the COVID-19 pandemic. DSAT4. Shopping at the physical market wastes my time. DSAT5. I cannot flexibly arrange my schedule to shop in the physical market. DSAT6. I can arrive at the physical market without effort (R). DSAT7. The environment of the physical market is appropriate to my situation during COVID-19 pandemic. DSAT8. Overall, I feel dissatisfied shopping in the physical market.	[10,24,31]
Pull Factors—Alternative Attractiveness (ATT) ATT1. E-grocery shopping has better offers than physical market. ATT2. The service performance on e-grocery shopping is more interesting than physical market. ATT3. The e-grocery shopping application is effective to meet my needs. ATT4. Overall, the e-grocery shopping application is more exciting than physical market.	[8]
Perceived Usefulness (USE) USE1. Using e-grocery shopping application helps me accomplish thing so quickly. USE2. Using e-grocery shopping application increases my productivity. USE3. Using e-grocery shopping application enhances my effectiveness. USE4. Overall, using e-grocery shopping application give me a benefit.	[24,34]
Perceived Ease of Use (EAS) EAS1. Learning to use the e-grocery shopping application is easy for me. EAS2. There is a clear and understandable navigation at the e-grocery shopping application. EAS3. It is easy for me to become skillful at using the e-grocery shopping application. EAS4. Overall, the e-grocery shopping application is easy to use.	[24,34]
Perceived Value (VAL) VAL1. Compared to physical market, the product's price at the e-grocery shopping application is acceptable. VAL2. Compared to physical market, the product's price at the e-grocery shopping application is very economical. VAL3. Compared to physical market, the product at e-the grocery shopping application has a good value. VAL4. The e-grocery shopping application has a good level of service performance for the money I spend.	[9,10,33]
Mooring Factors—Switching cost (SWC) SWC1. It would take a lot of time changing to e-grocery shopping. SWC2. It would take a lot of effort changing to e-grocery shopping. SWC3. It would take a lot of learning costs to switch to e-grocery shopping. SWC4. In general, it would be a hassle changing to e-grocery shopping.	[19]

Table A1. *Cont.*

Variables and Items	References
Health Consciousness (HEA) HEA1. I am very conscious about my health and the health of others for whom I shop. HEA2. I assume accountability for the state of my health and others in the household for whom I shop. HEA3. I am very involved with my health and the health of others for whom I shop. HEA4. I am very concerned about the number of artificial preservatives in food. HEA5. The safety of food nowadays concerns me a lot.	[47]
Personal Innovativeness INO1. If I heard about a new information technology, I would look for ways to experiment with it. INO2. Among my peers, I am usually the first to try out new information technologies. INO3. For me, experimenting with new technologies is challenging. INO4. I like to experiment with new information technologies.	[19]
Switching intention (SWI) SWI1: I plan to use e-grocery shopping in the future. SWI2: I will reduce my physical grocery shopping to e-grocery shopping. SWI3: E-grocery shopping is likely to become the primary shopping method of mine in the future.	[19]

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Metric and Spectral Insight into Bee-Pollen-to-Bee-Bread Transformation Process

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Abstract: Due to numerous bioactive constituents, both bee pollen (BP) and bee bread (BB) represent valuable food supplements. The transformation of BP into BB is a complex biochemical in-hive process that enables the preservation of the pollen's nutritional value. The aim of this study was to determine the depth of the honeycomb cells in which bees store pollen and to provide a spectral insight into the chemical changes that occur during the BP-to-BB transformation process. This study was carried out on three experimental colonies of *Apis mellifera* carnica, from which fresh BP was collected using pollen traps, while BB samples were manually extracted from the cells two weeks after BP sampling. The samples were analyzed using infrared (FTIR-ATR) spectroscopy, and the depth of the cells was measured using a caliper. The results showed that the average depth of the cells was 11.0 mm, and that the bees stored BB up to an average of 7.85 mm, thus covering between 2/3 and 3/4 (71.4%) of the cell. The FTIR-ATR analysis revealed unique spectral profiles of both BP and BB, indicating compositional changes primarily reflected in a higher water content and an altered composition of the carbohydrate fraction (and, to a lesser extent, the lipid fraction) in BB compared to BP.

Keywords: bee pollen; bee bread; bee-pollen-to-bee-bread transformation process; honeycomb cell depth; FTIR-ATR spectral profiles

1. Introduction

Due to numerous bioactive constituents, both bee pollen and bee bread represent a rich source of nutrients and could be beneficial food supplements. Moreover, nowadays, they stand out as an emblematic example of underutilized sources of bioactive compounds [1]. Of all bee products, bee bread is the least researched and utilized, although it has been proven to exhibit health-promoting properties, such as antimicrobial, antioxidant, antiradical, and anti-inflammatory activities [2–12].

The production of bee pollen, and consequently bee bread, is a complex biological process that represents and starts with a unique mode of synergy of plants and honey bees (*Apis mellifera* L.). When performing their pollination services for numerous plant species, honey bees collect pollen from the anthers of the plants on their hairs, mix it with a small amount of their salivary gland secretions and nectar, place it into specialized organs (pollen basket) on their hind legs, and carry it to the hive where the bee pollen is extruded into the honeycomb cells, where it is further processed (subjected to fermentation) for conservation purpose. Such bee-stored pollen serves as the main source of proteins, lipids, minerals, and vitamins in the honey bees' nutrition [13]. Prior to in-hive storage, the pollen grains collected by the bees are agglutinated in the pollen basket by moistening with bee

salivary secretions and nectar, which results in the formation of a pellet made of pollen grains, whose size ranges from 1.4 to 4.0 mm [14,15]. This pellet form of the field-foraged pollen placed in the pollen baskets is known as bee pollen or pollen load.

The chemical composition of pollen varies with the plant species, the environment during pollen development, and the age of plant when the pollen developed, as well the nutrient status of the plant [13], which makes bee pollen equally variable in composition [14,16–18]. Also, this large variability in the chemical composition of pollen results in an equally large variability in its nutritional value for the honey bees [13]. The chemical compositions of bee pollen have drawn intensive worldwide research attention, especially in the last two decades. As overviewed by Thakur and Nanda [14], based on a systematic review of 100 studies, bee pollen contains on average 54.22% (18.50–84.25%) carbohydrates, 21.30% (4.50–40.70%) proteins, 5.31% (0.41–13.50%) lipids, and 8.75% (0.15–31.26%) fiber, while other bee pollen constituents are represented in smaller, but still considerable, amounts, such as phenolic compounds, vitamins, minerals, volatile compounds, and enzymes [16,18–22]. It has been generally stated that the moisture content in bee pollen varies from 1.5 to 13% [1], although fresh bee pollen contains on average 17.5% moisture, and often more than 20% moisture [14,16].

Bee pollen is a well-balanced food for the honey bee colony, however, its composition makes it susceptible to rapid degradation under the in-hive conditions (35 °C). Therefore, honey bees have developed a mechanism to stop the in-hive deterioration of bee pollen and preserve its nutritional value by converting it into so-called bee bread. The transformation of bee pollen into bee bread represents a natural biochemical in-hive process that takes place directly in the honeycomb cells. Namely, the worker bees cover the bee pollen stored in the cells with a thin layer of honey and add salivary gland secretions containing various enzymes [3,23,24].

Altogether, this triggers a microbial transformation of BP to BB, which is carried out by three distinctive groups of microbes. First, aerobic bacteria, such as *Pseudomonas* spp., predigest the bee pollen and consume oxygen, thus creating anaerobic conditions. Lactic acid bacteria (LAB), primarily *Streptococcus* spp. and *Lactobacillus* spp., takeover and ferment the carbohydrates into lactic acid, increasing the acidity and creating favorable conditions for the growth of microscopic fungi. Finally, *Saccharomyces* spp. metabolize the remaining carbohydrates [25]. Although the exact mechanism of the biotransformation of BP to BB is not yet fully understood, LAB are mainly involved in the fermentation and stabilization of BB, while *Pseudomonas* spp. and *Saccharomyces* spp. might play a central role in the degradation of pollen walls and membranes [26]. After 15 days of transformation, the microbial diversity in the BB is greatly reduced compared to that of the pollen, and the pH of BB is around 4, which allows the conservation of BB by slowing the growth of spoilage microorganisms [3,5,25].

The lower pH value of bee bread, caused by the lactic acid fermentation, in addition to the presence of various digestive enzymes (such as invertase, aminopeptidase, phosphatase, β-glucosidase, amylase, phosphatase, glucose-oxidase, and others) [3,5,27] contributes to the higher nutrient bioavailability of bee bread compared to bee pollen [28,29], as well as better beneficial/protective effects in terms of antimicrobial activity [2,4,6,9,10,30]. Compared to bee pollen, the chemical composition of bee bread has been explored to a lesser extent, therefore, this bee product can still be considered as insufficiently investigated. Given that the chemical composition of bee bread is the result of the fermentation of bee pollen, its composition differs compared to that of bee pollen, which is primarily manifested in a lower proportion of carbohydrates and a higher proportion of water, proteins, and ash [1].

As elaborated above, honeycomb represents a natural ripening media in which bee pollen is converted into more stable and more beneficial/bioavailable bee bread. Based on old, but still valid, literature data, Bader et al. [31] stated that *A. mellifera* honeycomb is typically constructed from a series of hexagonal cells with edge lengths ranging from ca. 2.25 to 2.75 mm, an edge thicknesses of ca. 0.75 mm, and average depths ranging from ca.

10 to 11 mm. The mode of bee pollen storage in the honeycomb cells is generally known; however, this is based on a visual approximation. It has been mostly stated that honey bees store bee pollen in up to 3/4 of the cell [7,32], or that the bee pollen stored in the cells occupies about 2/3 of the cell [33]. However, to the best of our knowledge, there are no exact metric data on the depth of the honeycomb cells in which honey bees store their collected pollen loads (data on the bee bread storage depth) in the available scientific literature. In addition, the background mechanisms of the chemical conversion of bee pollen into bee bread based on the simultaneous investigation of both substances have not yet been investigated sufficiently. Therefore, the aim of this study was to determine the depth of the honeycomb cells in which honey bees store pollen during the bee-pollen-to-bee-bread transformation process and to provide a spectral insight into the chemical changes in the pollen composition from the initial raw material (bee pollen) to the final product (bee bread).

2. Materials and Methods

2.1. Experimental Design

This study was carried out on three experimental colonies of Carniolan honey bees (*Apis mellifera carnica*, Pollmann, 1879) placed in Langstroth-Rooth hives (H1, H2, and H3) and situated at the experimental apiary of the University of Zagreb Faculty of Agriculture. The experimental colonies were uniformed by strength according to the method described by Delaplane et al. [34] prior to the experiment, which was conducted during the April–May period of the production season in 2021. Front-mounted pollen traps were placed at the entrance of the experimental hives to ensure the collection of bee pollen samples. In addition, frames with honeycombs containing empty worker cells were placed in each experimental colony (in a honey super at lateral positions) to enable monitoring and storage of the pollen load in the cells, as well as further sampling and analysis of both the honeycomb and bee bread.

2.2. Sampling of Bee Pollen and Bee Bread

The bee pollen samples (BP; n = 3; 1 pooled sample/experimental colony) were collected using front-mounted pollen traps placed at the entrance of the experimental hives. A frame with stored bee pollen was pooled out from each experimental honey bee colony two weeks after bee pollen sampling, and individual bee bread samples were manually extracted directly from the honeycomb cells (BB; n = 105; 35 samples/experimental colony) using a small spatula. The samples of BP were stored in small glass containers (25 mL) and the BB samples were stored in Eppendorf tubes (1 mL) at −18 °C until analysis.

2.3. Determination of the Cell Depth of Bee Bread Storage and Complementary Cell Measurements

The frames with honeycombs that were isolated from each experimental colony and used for BB sampling were also used for obtaining the metric data on the pollen storage, i.e., for the determination of the depth of the honeycomb cell in which the honey bees store bee bread. The honeycombs were cut with a scalpel to obtain a fine cross-section, which enabled precise measurements. The total depth of the honeycomb cells (n = 30/colony) and the depth of the cells in which the bee bread was stored (n = 100/colony) were measured in accordance with Svečnjak et al. [35] methodology, whereas the method of measuring the longest possible length along A–B (deepest point in the cell) was chosen, as presented in Figure 1. In addition to measuring targeted cells filled with BB, the total depth of the cells was also measured as an auxiliary measure for determining the average depth of *A. m. carnica* bee bread storage in relation to the total cell depth. Additional complementary measurements of the honeycomb cells, i.e., measurement of the smallest side length along *C–D* and the angle of the hexagonal cell (n = 30/colony), were also performed to obtain additional data on the geometrical properties of *A. m. carnica* honeycomb cells in which BP and BB are stored.

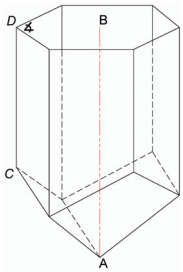

Figure 1. A three-dimensional view of the honeycomb cell representing conducted cell depth measurement along the A–B length and complementary measurements of the smallest side length (*C*–*D*) and the angle (∡) of the hexagonal cell.

The measurements of the depth and side length of the honeycomb cells were carried out using a caliper (Traceable Digital Caliper, Fisherbrand^{TM}, UK, measuring range: 0–150 mm, resolution: 0.01 mm), while the angle of the hexagonal honeycomb cells was measured using a precise digital protractor (Leman, Saint-Clair-de-la-Tour, France, measuring range: 0°–360°, resolution: 0.05°).

2.4. Statistical Analysis

In order to assess the differences in the cell depth between the three experimental colonies, as well as the distribution of bee bread according to the depth of its storage in the honeycomb cells, data were analyzed by means of descriptive statistics, classical one-way analysis of variance (ANOVA), and Kruskal–Wallis one-way ANOVA. The mentioned data analyses were performed using the statistical software package Statistica-StatSoft v.7. [36].

2.5. FTIR-ATR Spectroscopy and Spectral Data Analysis

The collected BP and BB samples were analyzed using Fourier transform infrared spectroscopy (FTIR) coupled with an attenuated total reflectance (ATR) accessory. For this purpose, a Cary 660 FTIR spectrometer (Agilent Technologies, Palo Alto, CA, USA) coupled with a Golden Gate single-reflection diamond ATR accessory (Specac) was used. Prior to the spectral analysis, the BP samples were pulverized with a porcelain mortar into homogenates, while the BB samples were analyzed as obtained. To obtain spectra, approximately 3 mg of sample was pressed onto a diamond ATR plate using a self-leveling sapphire anvil in order to ensure a thin uniform layer of each sample. The absorption infrared (IR) spectra of the BP and BB samples were recorded in a mid-infrared region (4000–400 cm^{-1}). Spectra were acquired at a nominal resolution of 4 cm^{-1} and at room temperature (24 ± 2 °C). Two replicate spectra (32 scans/spectrum) of each BP and BB sample were recorded using different aliquots. The spectra were recorded and pre-processed using the Resolutions Pro version 5.3.0 software package [37], while further spectral data analysis was carried out using Origin version 8.1 [38]. Qualitative analysis and the identification of analyte signals observed in the BP and BB spectra were performed using spectral atlases and the available scientific literature. In order to elucidate overlapping spectral effects related to water signals, a complementary analysis was performed on the BP and BB samples that were lyophilized (as described below) and reanalyzed with the same FTIR-ATR procedure. Also, for the same purpose, water loss was determined gravimetrically.

2.6. Freeze-Drying (Lyophilisation) of BP and BB Samples

Freeze-drying of the BP and BB samples was carried out at −50 °C (under 1 mbar pressure) over 24 h by using an Alpha 1-4 LSCplus laboratory freeze-dryer (Christ, Osterode am Harz, Germany). In addition, water loss was determined gravimetrically. For this purpose, 2 g of BP and BB (pooled) samples from H1, H2, and H3 were weighed before lyophilization and reweighed after this treatment by using a precise analytical balance MS 204 Mettler Toledo (Columbus, OH, USA).

3. Results and Discussion

3.1. Determination of the Cell Depth of Bee Bread Storage

In order to estimate the depth of the bee bread storage in relation to the total depth of the honeycomb cells, the latter was also determined. As presented in Table 1, the average total depth of the honeycomb cells determined in experimental colony H1 was 10.99 mm, 11.01 mm in H2, and 11.01 mm colony H3, which reflects a great similarity of average values and confirms the well-known uniform architecture of honeycomb cells. The determined maximum values of the cell depth in the three experimental honey bee colonies also revealed high resemblance, at 12.05 mm, 11.98 mm. and 12.36 mm, respectively, while the most noticeable differences between the colonies (although not statistically significant, as noted below) were observed for the minimum cell depth values (9.71 mm determined in the H1 colony, 8.97 mm in the H2 colony, and 9.37 mm in H3 colony).

Table 1. Descriptive statistics for the depth of *A. m. carnica* honeycomb cells (n = 30 cells/colony).

Depth of Honeycomb Cell (mm)	Experimental Colony			
	H1	H2	H3	Total
Average	10.99	11.01	11.01	11.00
Minimum	9.71	8.97	9.37	9.35
Maximum	12.05	11.98	12.36	12.13
Standard deviation	0.57	0.81	0.79	0.72

As presented in Figure 2, the results of the one-way ANOVA showed no statistically significant differences between the colonies with regard to the measured depth of the honeycomb cells (p = 0.990524).

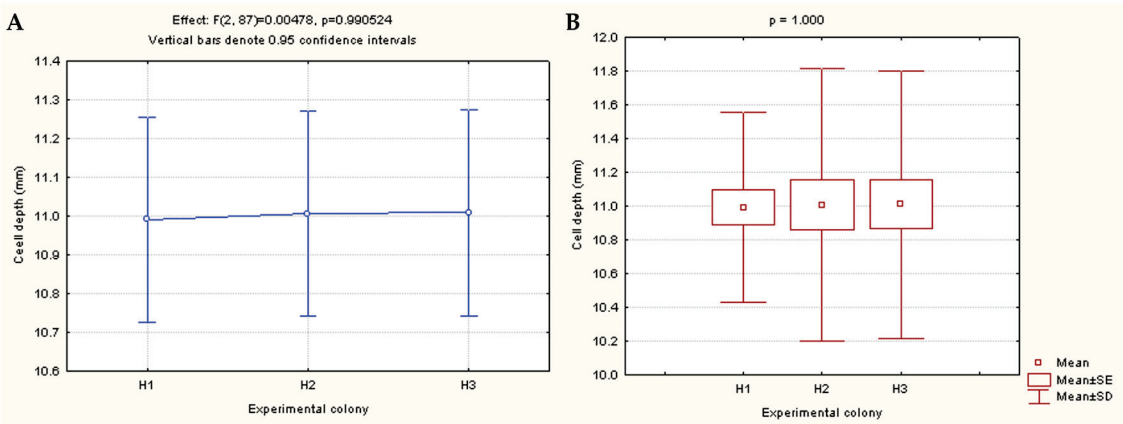

Figure 2. Effects of one-way ANOVA showing differences in the depth of *A. m. carnica* honeycomb cells between three experimental colonies (H1, H2, and H3) (**A**); Differences presented via effects/box and whisker plot of Kruskal–Wallis one-way ANOVA (**B**).

The overall results showed that the average depth (mean ± SD) of *A. m. carnica* honeycomb cells was 11.00 ± 0.72 mm. This is in compliance with the old literature data reporting 11.00 mm as an average cell depth of *A. mellifera* worker cells [39], as well as the recent data on the cell depth (ranging from 9.23 to 13.06 mm, depending on the comb age, on average 11.11 mm) reported for honeycomb constructed by *A. m. carnica* [40]. The obtained results are also similar to those reported for the average depth of the standard brood cells of European dark bees (*Apis mellifera mellifera*), i.e., 11.03 ± 0.64 [41]. Compared to the available scientific literature reporting on the cell dimensions of other bee species, moderate differences were observed. As reported by Yang et al. [42], the average depth of the worker cells determined for Chinese bees (*Apis cerana cerana*) was 9.595 mm ± 0.066 mm and was 12.088 mm ± 0.040 mm for Italian bees (*Apis mellifera*

ligustica). The data on the cell depth reported for Africanized honey bees (*Apis mellifera scutelata*) investigated in two agro-ecological systems in Western Ethiopia revealed that the cell depth in the highland and mid-altitude region ranged from 9.6 mm to 11.4 mm, respectively [43].

As shown in Table 2, the average depth of the honeycomb in which the honey bees stored bee bread ranged from 7.38 mm in the H1 colony to 8.02 mm in H3 and 8.14 mm in experimental colony H2. The minimum depth of the bee bread storage was 5.19 mm in colony H1, 5.25 mm in colony H2, and 5.20 mm in colony H3, while the maximum depth of the comb cells in the H1 colony was 10.26 mm, 10.71 mm in H2, and 9.72 mm in the H3 colony.

Table 2. Descriptive statistics for the depth of honeycomb cells in which honey bees store bee bread (n = 100 cells/colony).

Depth of the Cell in Which Bees Store Bee Bread (mm)	Experimental Colony			
	H1	H2	H3	Total
Average	7.38	8.14	8.02	7.85
Minimum	5.19	5.25	5.20	5.21
Maximum	10.26	10.71	9.72	10.23
Standard deviation	1.19	1.09	1.00	1.09

The results of the one-way ANOVA showed statistically significant differences between the colonies with regard to the bee bread storage depth (p = 0.00002) (Figure 3).

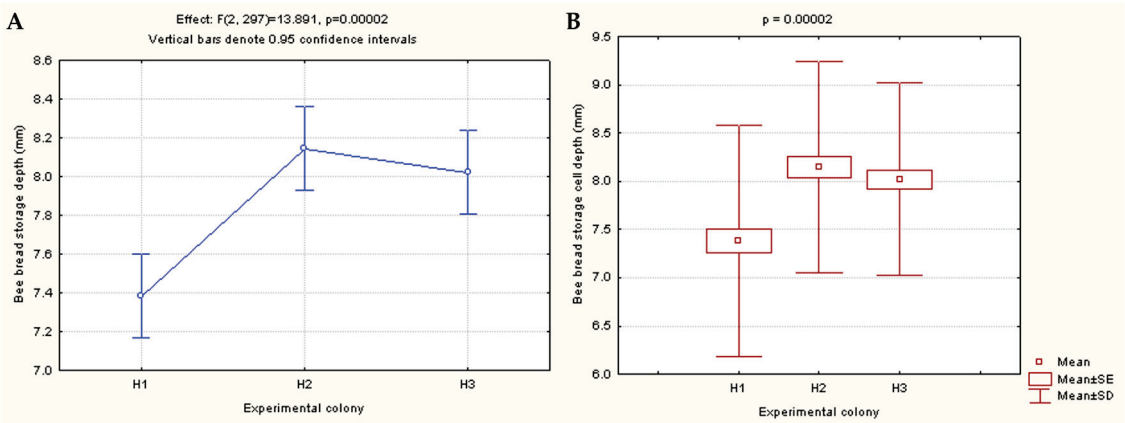

Figure 3. Effects of one-way ANOVA showing differences in the cell depth of bee bread storage between three experimental colonies (H1, H2, and H3) (**A**); Differences presented via effects/box and whisker plot of Kruskal–Wallis one-way ANOVA (**B**).

Differences in the mode of bee bread storage were also observed. A distribution of bee bread according to the depth of its storage in the honeycomb cells of the three experimental colonies (H1, H2, and H3) is presented in Figure 4.

The results have revealed that most of the bee bread was stored between 6.5 and 9.5 mm of the cell, with an average of 7.85 mm. Part of the results related to the lower values of bee bread storage (<6.5 mm) observed in all three of the experimental colonies can be explained by the simultaneous consumption of bee bread by the honey bees during the experiment, as they tend to consume freshly stored pollen as well [44].

To the best of our knowledge, there are no exact metric data about the depth of bee bread storage in the available scientific literature. This may be explained by the fact that the measurements of the depth and/or estimations of the internal volume of the cell represent a demanding task due to the unique hexagonal cell geometry. The mode of bee pollen storage in the honeycomb cells is generally known, and it has been mostly stated that honey

bees store bee pollen in up to 3/4 of the cell [7,32], or that the bee pollen stored in the cells occupies about 2/3 of the cell [33]. Thus, the information about the cell depth in which bee pollen/bee bread is stored in the honeycomb cells has been simplified/generalized based on a visual approximation, which implies that bee bread occupies between 66.6% (2/3) and 75.0% (3/4) of the cell.

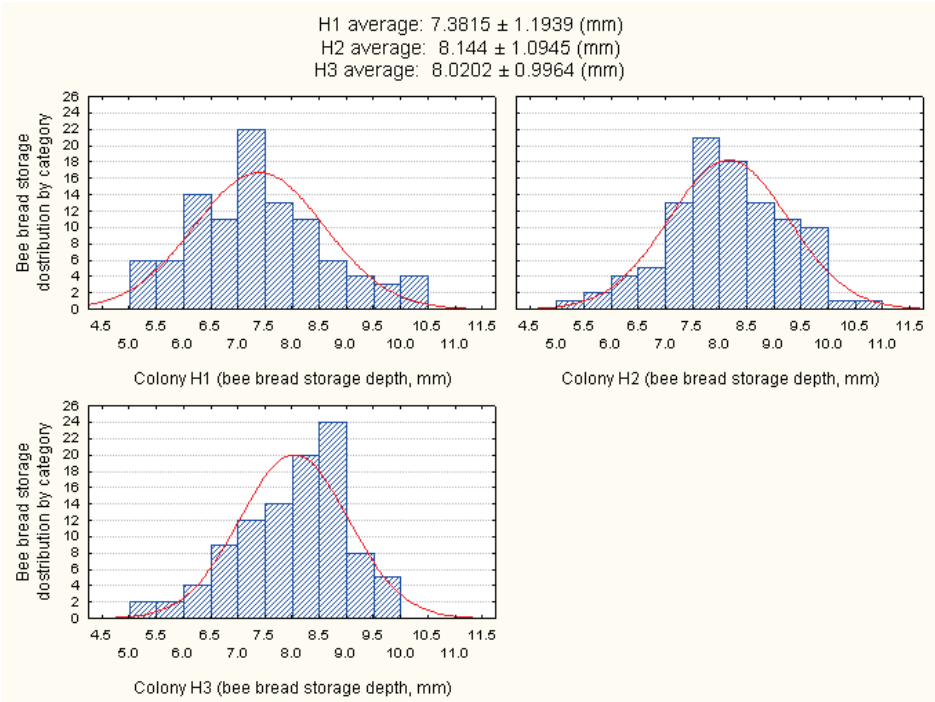

Figure 4. Categorized histogram showing a distribution of bee bread according to the depth of its storage in the honeycomb cells of three experimental colonies (H1, H2, and H3).

The overall metric data obtained in this study have revealed that the average depth of the honeycomb cells constructed by the *A. m. carnica* workers was 11 mm, and that the bees stored bee bread up to an average of 7.85 mm of cell depth (Figure 5), thus covering between 2/3 and 3/4 (71.4%) of the honeycomb cell.

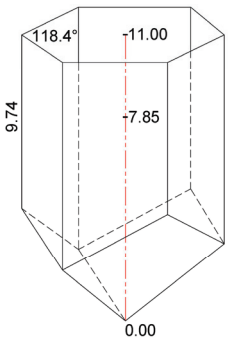

Figure 5. A three-dimensional view of the honeycomb cell representing the obtained results on the total cell depth (11.00 mm) and the depth of bee bread storage (7.85 mm) in *A. m. carnica* honeycomb, along with results on complementary measurements (average values of the smallest side length and the angle of the hexagonal cell).

To be more specific, in terms of the usual representation of bee bread storage in the form of arithmetic fractions in relation to the total cell depth, the closest value implied by the results of this study would be 17/24 of the cell depth. To the best of our knowledge, this finding represents the first report, i.e., the first metric data, on the cell depth in which

A. m. carnica honey bees store bee bread. These data may be employed to investigate the hive-level distribution and storage of bee bread and to estimate the annual production and economic value of bee bread production in general.

Figure 5 also shows the results of the complementary measurements of the smallest side length and the angle of the hexagonal cells obtained for the analyzed honeycombs (average values based on n = 30 cells/experimental colony H1, H2, and H3). The results have revealed that the smallest side length of the analyzed honeycomb cells ranged from 9.12 to 10.63 mm, with an average of 9.74 mm, while the angle of the hexagonal cells ranged from 117.8° to 119.2°, with an average of 118.4° (Figure 1). The results have revealed a great similarity of the smallest side length to the angle of the hexagonal cells, both within and between the colonies, thus reflecting consistency and uniformity in *A. m. carnica* honeycomb construction. These complementary metric data represent an additional insight into the geometrical properties of *A. m. carnica* honeycomb cells where the BP-to-BB transformation pathway occurs and may also be used for a further investigation into BP/BB storage in the honeycomb cells, as well as other cell-related studies. The descriptive statistics for the smallest side length and the angle of the hexagonal cells for colonies H1, H2, and H3 are presented in Tables 3 and 4, respectively.

Table 3. Descriptive statistics for the smallest side length of honeycomb cells in which honey bees store bee bread (n = 30 cells/colony).

Side Length of the Honeycomb Cell (mm)	Experimental Colony			
	H1	**H2**	**H3**	**Total**
Average	9.73	9.63	9.87	9.74
Minimum	9.12	9.12	9.11	9.12
Maximum	10.47	10.66	10.76	10.63
Standard deviation	0.39	0.35	0.48	0.41

Table 4. Descriptive statistics for the angle of hexagonal honeycomb cells in which honey bees store bee bread (n = 30 cells/colony).

Angle (∡) of Hexagonal Honeycomb Cell (°)	Experimental Colony			
	H1	**H2**	**H3**	**Total**
Average	118.5	118.4	118.4	118.4
Minimum	117.8	117.8	117.7	117.8
Maximum	119.1	119.2	119.4	119.2
Standard deviation	0.37	0.39	0.41	0.39

3.2. Spectral Analysis of Bee Pollen and Bee Bread

FTIR-ATR analysis has been employed for BP or BB analysis in few recent studies. The first FTIR-ATR study of bee pollen was conducted by Anjos et al. [45], who reported on the usefulness of this analytical tool for studying the overall chemical composition of bee pollen. Further investigations on bee pollen composition using FTIR-ATR spectroscopy were conducted by several authors [16,17,46,47], among which Prđun et al. [16] and Castiglioni et al. [17] presented the most comprehensive spectral analysis of unifloral and/or multifloral bee pollen, as well as their physicochemical characterization. The only study dealing with FTIR analysis of bee bread was reported by Dranca et al. [48]. However, the assignment of vibrational modes presented in this study is actually based on the spectrum of bee pollen from another (previous) study of the same authors, and not on the spectrum of bee bread investigated in a respective study (i.e., spectrum of crude BP was presented and tentatively interpreted instead of BB spectrum, and the authors justified this by the 'spectra resemblance' of BP and BB). Such a presentation of the results of the spectral analysis of BB (based on FTIR analysis of another substance/BP, without presenting the BB spectrum itself) is misleading and raises the question of its eligibility. Also, it should

be noted that only the integral spectral profiles of the BP and BB samples show a general resemblance, but the spectral differences between BP and BB are noticeable (as well as expected, considering the background chemical alterations of the BP-to-BB transformation pathway), which is presented and elaborated in our study.

Figure 6 represents raw the FTIR-ATR spectra of multifloral bee pollen (n = 3; 1 pooled sample/colony) collected from the three experimental colonies (H1, H2, and H3) and the raw FTIR-ATR spectra of the bee bread samples (n = 35/colony) collected from individual honeycomb cells of the same experimental colonies. As presented in Figure 6A, the bee pollen collected from the different colonies showed a great similarity of spectral features, i.e., no noticeable differences in their chemical composition. This was expected, considering that the experimental colonies were situated in the same location during the same period (the honey bees will have collected available bee pollen of the same botanical origin, and, in addition, the samples were homogenized prior to the FTIR-ATR analysis). The general spectral profiles of the analyzed bee pollen correspond to those reported in previous studies of bee pollen using FTIR-ATR spectroscopy [16,17,45–47].

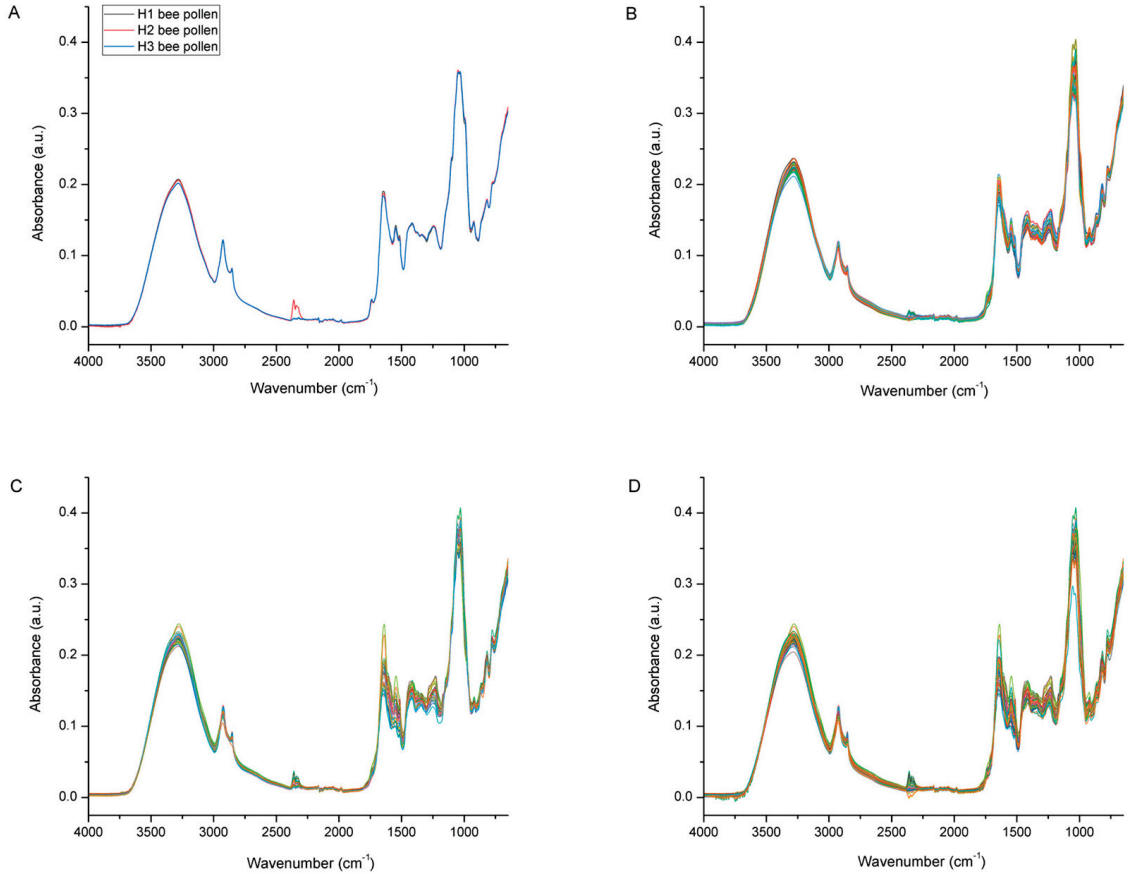

Figure 6. FTIR-ATR spectra of multifloral bee pollen (n = 1/colony) collected from experimental colonies H1, H2, and H3 (**A**); FTIR-ATR spectra of bee bread samples (n = 35/colony) collected from individual honeycomb cells of experimental colonies H1 (**B**), H2 (**C**), and H3 (**D**); different colors on (**B**–**D**) denote spectra of bee bread samples collected from individual honeycomb cells.

Figure 6B–D shows the FTIR-ATR spectra of the bee bread samples (n = 35/colony) collected from individual honeycomb cells from the experimental colonies H1, H2, and H3, respectively. Obvious spectral variations were observed throughout the entire spectral region of the bee bread samples collected from each colony, which indicates variability in the chemical composition of the individual bee bread samples. Those variations were most pronounced in the spectral region between 3600 and 3000 cm^{-1} (indicating alterations in the water and carbohydrate content), but were even more prominent in the

fingerprint region between 1700 and 750 cm^{-1} (indicating variations related to the major BB constituents—sugars, proteins, and lipids). A detailed assignment of the individual bands observed in these regions is provided below in Figures 7 and 8. The mentioned variations are the result of a specific way of storing the pollen load in the honeycomb cells, which causes inhomogeneity in the composition of the bee bread samples in individual honeycomb cells (pollen of various plant species is placed in the cells); however, part of such variations may also be explained by the different stage of fermentation of the bee bread in the individual cells [5].

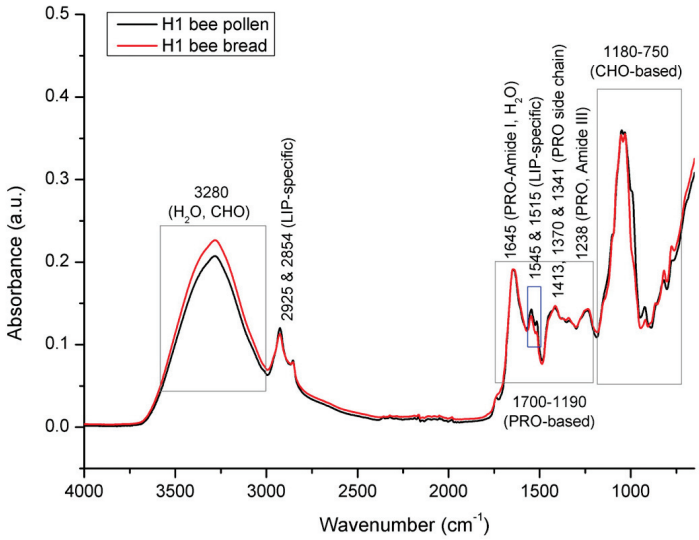

Figure 7. Average FTIR-ATR spectrum of bee pollen vs. bee bread from experimental colony H1, representing comparative spectral features with the assignation of major underlying molecular vibrations (whole spectral region from 4000 to 600 cm^{-1}). CHO = carbohydrates; PRO = proteins; LIP = lipids.

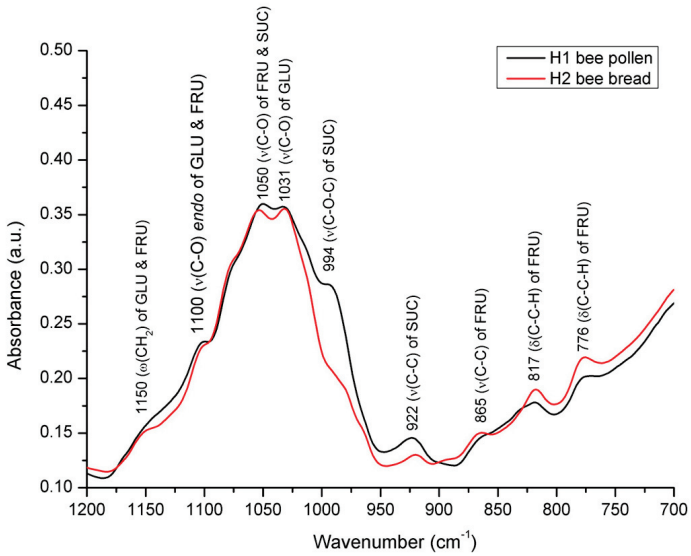

Figure 8. Average FTIR-ATR spectrum of bee pollen vs. bee bread from experimental colony H1 representing comparative spectral features with the assignation of major underlying molecular vibrations (carbohydrate-specific spectral region from 1200 to 700 cm^{-1}). ν = *in-plane* stretching vibration; δ = *in-plane* bending vibration (deformation); ω = *out-of-plane* bending vibration (wagging); GLU = glucose; FRU = fructose; SUC = sucrose.

The chemical characterization of both bee pollen and bee bread is provided further in Figures 7 and 8 via a comparative overview of their spectral profiles, elucidating the chemical alterations that occur during the bee-pollen-to-bee-bread transformation pathway.

Figure 7 represents comparative spectral features of bee pollen (average spectra of pooled multifloral bee pollen sample/colony) and bee bread (average spectra based on n = 35 bee bread samples/colony) collected from experimental colony H1. Both bee pollen (BP) and bee bread (BB) represent a complex organic mixture of various constituents, including all major biological macromolecules (proteins, carbohydrates, and lipids). Consequently, their FTIR-ATR spectra exhibit a broad variety of absorption bands, as well as numerous overlapping spectral effects, arising from diverse molecular vibrations of these constituents. As summarized by Giampieri et al. [1], the composition of both BP and BB vary significantly. BP is composed of 1.5–13.8% water, 18.5–82.0% of carbohydrates, 2.5–62.0% of proteins, 0.41–24.40% of lipids, 0.15–30.0% of dietary fibers, and 0.5–6.5% of ash; while BB comprises 5.91–30.12% water, 13.02–72.23% of carbohydrates, 17.11–30.34% of proteins, 1.95–11.95% of lipids, and 1.93–3.42% of ash. Generally, there are a lot of data on the composition of bee pollen and bee bread individually in the available scientific literature, however, there is only one record on the simultaneous comparative analyses of both of these substances from the same hives [28]. However, in their study, Mayda et al. [28] concluded that the total protein, total fatty acids, and moisture content of the BB samples were lower than those of the BP samples from the same hive. This is not entirely in compliance with the results obtained in our study, as well as those from other reports investigating the total composition of BP and BB, as overviewed by Giampieri et al. [1]. To be more specific, our results (as presented in Figure 7), as well as those of other reports, indicate a higher content of moisture in BB compared to BP, while no noticeable differences in the proportion of proteins were found between BP and BB (which is expected, given that the major purpose of in-hive BP-to-BB conversion is the preservation of proteins and considering that BP is the main source of proteins for honey bees). The contradiction on the moisture content reported by Mayda et al. [28] can be explained by the rather vague and unfounded interpretation of the results on the moisture content obtained in the respective study, given that BP and BB were found to have similar moisture levels, i.e., the moisture content of BP was between 17.3% and 23%, while in BB it was between 17.7% and 22.3%. These data do not support the general conclusion that BB contains a lower moisture content, considering the presented range values, as well as the almost-equal average values (19.4% for BP and 19.06% for BB). In addition, the respective study was carried out on a small number of BP and BB samples (five BP and five BB pooled samples), which further calls into question the conclusion on the lower moisture content found in BB. It should also be emphasized that the organoleptic profile of BB vs. BP, as well as the fact that BP is moistened with a layer of honey during the BP-to-BB transformation process, implies a higher moisture content in BB compared to BP. The allegation on the proportion of lipids/fatty acids is in compliance with previous studies and our results.

As presented in Figure 7, the results of the spectral analysis have revealed that the most prominent spectral differences between BP and BB are manifested in the spectral range from 3600 to 3000 cm^{-1}, and in a particular segment of the fingerprint region (1700–750 cm^{-1}). The intensity of a broad and strong absorption band with an absorption maximum at 3280 cm^{-1} occurring in the spectral range from 3600 to 3000 cm^{-1} that is primarily assigned to O–H stretching vibrations of water and partially to carbohydrates [16,49–51], is higher in BB compared to that observed in BP, which primarily reflects a higher proportion of water in BB, and, partly, changes in the sugar fraction profile. It should be noted that an absorption band assigned to the N–H stretching vibrations of proteins (Amide A band) also typically arises in the same (3600–3000 cm^{-1}) spectral region [51,52], but it is overlapped by the more intense vibrations of O–H groups of water and carbohydrates [16], which makes this region non-specific for the monitoring of proteins in the analyzed samples.

Two IR analyte signals observed in the spectral region from 3000 to 2920 cm^{-1}, the medium intensity signal arising at 2925 cm^{-1}, and the weaker absorption band observed at

2854 cm^{-1} correspond to the stretching vibrations of the aliphatic C–H groups and/or CH_2 groups, and can generally be related to the molecular vibrations of numerous bee pollen constituents, such as carbohydrates, cellulose, lipids, fatty acids, and other long-chain structures [16,17,45–47]. However, it can be concluded that the signals observed at 2925 cm^{-1} and 2854 cm^{-1} are primarily associated with the asymmetric and symmetric stretching vibrations of the CH_2 groups of lipids (aliphatic chains), considering that triglycerides are the most abundant component of the lipid fraction in BP (followed by diglyceride and free fatty acids) [53], and they typically absorb IR radiation strongly in this region [35,51,54,55]. These signals were found to be stronger in BP compared to those in BB, which indicates a higher amount of lipids in BP compared to that of BB. This was confirmed by a stronger intensity of absorption bands arising at 1544 cm^{-1} and 1515 cm^{-1} that are also related to lipids, as explained below. It should be mentioned the C–H stretching vibrations of BP carbohydrates are also represented with two signals at positions similar to 2925 and 2854 cm^{-1} [16,45], but are overlapped by the mentioned molecular vibrations of lipids, as they exhibit more intensive signals compared to C–H stretching of carbohydrates in this spectral region.

As emphasized in Figure 7, the integral spectral profiles of BP and BB are very similar in most of the spectral regions between 1700 and 1190 cm^{-1}, which is characterized by predominant protein-related absorption bands. This region is populated by a series of indicative absorption bands that are highly specific for the molecular vibrations of proteins (although they overlap fewer intensive signals of other BP/BB constituents exhibiting signals in this region, such as those of sugars, as elaborated by Prđun et al. [16]).

A medium-intensity absorption band observed at 1645 cm^{-1} is typical for protein structures (β-sheet) and can be assigned to the Amide I band, which primarily comprises stretching vibrations of the C=O (70–85%) and C–N groups (10–20%) [51,52]. As elaborated in detail by Prđun et al. [16], this band position is also characteristic for the molecular vibrations of water (H–O–H deformation vibration) and lipids (COO– and C=C stretching vibration). Expectedly, the overlapping effects of the aforementioned vibrations were reflected in this region. In order to elucidate these overlaps and exclude the water signal, an additional spectral analysis was performed on lyophilized samples, together with the water loss evaluation, as elaborated in detail below.

Other protein-related signals attributed to the protein side chain COO– stretching vibrations can be observed at 1413, 1370, and 1341 cm^{-1}, while the absorption band arising at 1238 cm^{-1} occurs due to the Amide III band, which comprises 30% of N–H bending, 30% of C–N stretching, 10% of C–O stretching, and 10% of O=C–N bending vibrations [51]. The high similarity of the BP and BB spectral pattern, with regard to the aforementioned protein-related signals occurring in the spectral region from 1700 to 1190 cm^{-1} (with slightly higher intensities of corresponding analyte signals in BB), indicates a compositional similarity/stability in terms of the proportion of proteins in the analyzed BP and BB samples and confirms the successful conservation of bee pollen by transformation into bee bread. An exception in terms of the observed differences in this spectral envelope is represented by a higher absorbance intensity of two neighboring signals at 1544 cm^{-1} and 1515 cm^{-1} associated with C=C stretching vibrations of the aromatic structures of lipids in the BP sample. As reported by Conte et al. [53], in addition to the predominant triglycerides, diglycerides, and fatty acids, the lipid fraction of BP also contains a high content of phospholipids, tocopherols, and phytosterols. These compounds represent more complex constituents of the BP lipid fraction and are characterized by aromatic ring structures, which is reflected in the spectrum in terms of the mentioned signals. Along with the aforementioned absorptions at 2925 and 2854 cm^{-1}, specific for aliphatic chains of lipids that proved to be higher in BP, the intensity of the adjacent bands arising at 1544 and 1515 cm^{-1} also reflects a higher proportion of lipids in BP compared to that found in BB. This is in accordance with data from the available scientific literature, according to which the proportion of lipids in BP ranges from 0.41 to 24% [1,14,18], and in BB from 1.9 to 11.6% [1,3]. The higher content of lipids in BP compared to that found in BB can

be explained by a particular mechanism of action of microorganisms during the BP-to-BB transformation process. Generally, several groups of microorganisms are involved in the conversion of BP to BB, mainly *Pseudomonas*, LAB, and microscopic fungi. They are all known to produce lipases and hydrolyze lipids [56,57]. Although LAB are considered to be weakly lipolytic compared to *Pseudomonas* and microscopic fungi, their lipolytic activity is also well-documented [58]. Therefore, all three groups of microorganisms may play an important role in the lipid degradation of BP observed in our study.

It should be noted here that the Amide II band, which comprises N–H bending and C–N stretching vibrations, and typically absorbs between 1510 and 1580 cm^{-1}, is overlapped by the former lipid-based C=C stretching that arises at 1544 and 1515 cm^{-1}, as elaborated by Prđun et al. [16]. These C=C stretching vibrations (both or individual) are often (mis)assigned primarily as the Amide II band of proteins; however, it has to be emphasized that the position, shape, and intensity of the adjacent bands at 1544 and 1515 cm^{-1} observed in the BP/BB spectrum do not correspond to the Amide II band characteristics. Indeed, Amide II typically absorbs between 1510 and 1580 cm^{-1} (mostly around 1550–1560 cm^{-1}) [51], but it appears as a single medium-broad and conspicuous band, not in the form or as a part of narrow adjacent bands (such as those observed in the BP/BB spectra).

Along with the above-mentioned spectral features reflecting differences in the water content, the most prominent differences between the BP and BB spectra were observed in the fingerprint region from 1180 to 750 cm^{-1} (Figure 8).

As accentuated in Figure 8, the FTIR-ATR spectra of BP and BB differ in terms of both alterations in the position and the intensity of the absorption bands. Namely, it was observed that the intensity of the absorption bands at 994 cm^{-1} and 922 cm^{-1}, the sucrose-characteristic signals assigned to C–O–C stretching vibrations and C–C stretching vibrations, respectively [50,59,60], are significantly lower in BB compared to that observed in BP. This indicates a breakage of both C–O–C and C–C glycosidic bonds of sucrose during the fermentation of BP (decomposition of sucrose), which causes conformational changes in the sugar fraction in BB, as further explained and presented in Figure 8. Moreover, a significant decrease in the sucrose signal at 994 cm^{-1} (to the level of being barely noticeable) in BB confirms the predominance of monosaccharides in BB compared to the predominant sucrose in BP, as it is known that there is little absorption at this position (near 1000 cm^{-1}) in the monosaccharides [49].

As elaborated by Bakour et al. [6], sucrose appears in a low proportion in bee bread due to the fact that, during fermentation, sucrose is used by bacteria and yeasts as an energy source. However, in order to utilize sucrose, LAB and yeasts must first convert it to fermentable monosaccharides (glucose and fructose) by invertases (sucrase and saccharase). The mentioned spectral observations reflecting low sucrose content in BB are further supported by data from the available scientific literature, according to which the proportion of sucrose in BP ranges from 5.87 to 22.04% [16], while in BB it is found almost in trace amounts [6], i.e., 0.845−1.49% [1].

Furthermore, a comparative spectral analysis of BP vs. BB has revealed that considerable amounts of glucose are present in both BP and BB, but a slightly higher proportion was found in BP, which is reflected in the spectra of the analyzed samples. Namely, the absorption band at 922 cm^{-1}, characteristic for C–C stretching vibrations of glucose, is more intense in the spectrum of bee pollen, while these differences are less pronounced at the position of the second band, characteristic for glucose, at 1031 cm^{-1}. The aforementioned observations can also be associated with previously published data on the proportion of glucose, which in bee pollen averages at 12.4% [16] and at 5.7% in bee bread [6].

Noticeable spectral differences between BP and BB were also observed in terms of higher absorbance intensities of bands observed in BB at 865, 817, and 776 cm^{-1}. These absorption bands are attributed to the molecular vibrations of fructose. The first signal appears due to the C–C stretching vibrations, while the other two correspond to the C–C–H deformation vibrations [49,61]. A higher proportion of fructose in BB compared to BP is

supported by the literature data emphasizing fructose as the most abundant sugar in BB (up to 19.73%), followed by 8.82−12.40 of glucose, and 0.845−1.49% of sucrose [1].

The overall spectral variations in this sugar-based spectral envelope (1200–750 cm^{-1}) indicate a lower content of sucrose (and to a lesser extent glucose) and a higher proportion of fructose in BB compared to that found in BP, which is primarily a consequence of the hydrolysis of sucrose to glucose and fructose by invertases produced by honey bees and various groups of microorganisms. Glucose and fructose are, thus, the main fermentable sugars in bee pollen, and, usually, glucose is fermented much faster than fructose, which is mainly related to the preferential use of glucose by microorganisms [62].

Polysaccharides and oligosaccharides are considered minor BP constituents, and, as such, they contribute little to the overall spectral features associated with the BP carbohydrate fraction. The oligosaccharides in BP (such as isomaltose, raffinose, trehalose, and erlose) are represented in a low proportion (<1.5%, with an exception of maltose, which ranges from 0.16 to 6.03%), while cellulose (as the main component of the layers of pollen grains) is the most abundant BP polysaccharide, comprising on average 3–4% of BP [1,14].

The same trend of chemical changes (differences in the proportion of water and the changed profile of the sugar fraction, and to a lesser extent the lipid fraction) were also observed with comparative spectral analysis of BP vs. BB from experimental colonies H2 (Figure 9A) and H3 (Figure 9B).

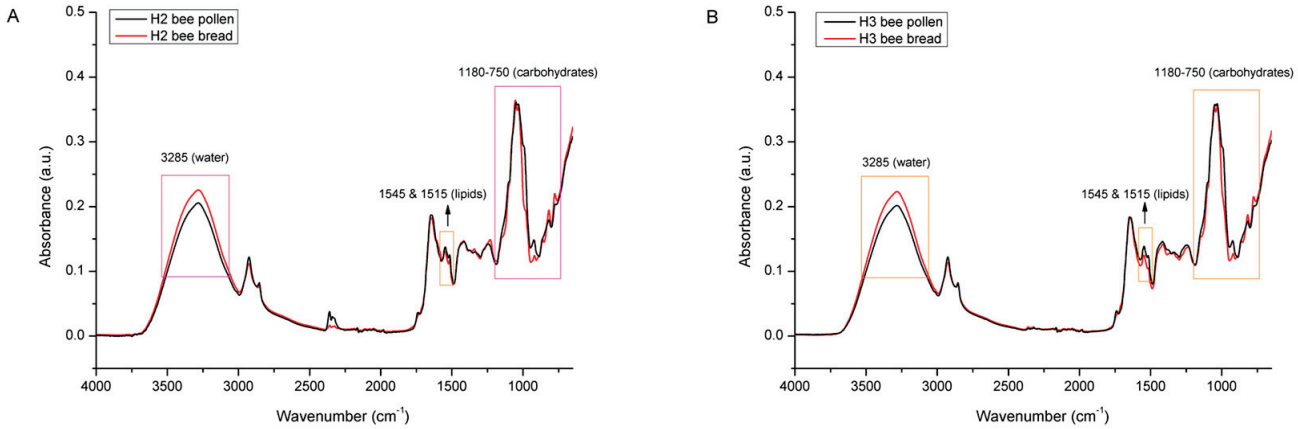

Figure 9. Average FTIR-ATR spectrum of bee pollen vs. bee bread from experimental colony H2 (**A**) and H3 (**B**), representing comparative spectral features with the assignation of major underlying molecular vibrations in the whole spectral region (4000–600 cm^{-1}).

In order to elucidate the spectral effects related to overlapping water signals, the investigated BP and BB samples were lyophilized and reanalyzed with FTIR-ATR spectroscopy. Figure 10 shows the comparative spectral features of crude vs. lyophilized BP from colony H1. As freeze-drying (lyophilization) causes dehydration of the treated samples, it has affected the water signals in the BP spectrum, thus enabling the confirmation of the water contribution to particular absorption bands. The major spectral effect observed in the lyophilized BP compared to the crude BP was reflected in the decrease in water signals at 1645 cm^{-1} and 3280 cm^{-1} and a simultaneous increase in the intensity of the absorption bands related to the sugar fraction in the spectral region between 1200 and 700 cm^{-1} (primarily due to the changed concentration of monosaccharaides in BP, i.e., glucose and fructose). The higher concentration of monosaccharides in the lyophilized BP sample is also reflected in the spectral region between 1500 and 1200 cm^{-1}, in terms of a minor intensity increase in signals observed at 1410 cm^{-1} and 1342 cm^{-1}, corresponding to the C–O–H deformation of glucose and fructose, respectively [50,61].

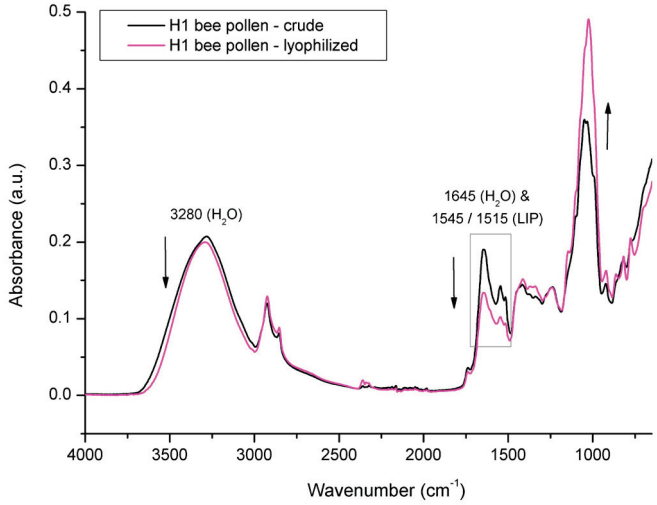

Figure 10. Average FTIR-ATR spectrum of crude bee pollen vs. lyophilized bee pollen from experimental colony H1, representing comparative spectral features.

The same mode of freeze-drying action was carried out on lyophilized vs. crude BB (Figure 11); however, the decrease in intensity of both water signals in BB was less pronounced, which indicates less intensive water loss in BB compared to that of BP during the same lyophilization treatment. These spectral observations were in compliance with the results on water loss obtained gravimetrically for the BP and BB samples. Namely, the water loss determined for BP from experimental colony H1 was 14.6% and was 10.5% for BB. These results indicate a higher proportion of residual water in the lyophilized BB compared to that of the lyophilized BP; however, this still needs to be elucidated, but it can be assumed this is a consequence of differently hydrated forms of constituents in BP and BB. It was also observed that the water loss in the BP and BB samples was followed by a decrease in the signal intensity at 1645 cm^{-1}, which was more pronounced compared to the decrease observed at 3280 cm^{-1}. This can be explained by the contribution of O–H stretching vibrations of both water and carbohydrates to the absorption band at 3280 cm^{-1}, which somewhat neutralizes the intensity decrease in this band. Similar spectral effects in relation to water- vs. sugar-associated vibrations have been observed by other authors [49,50,61].

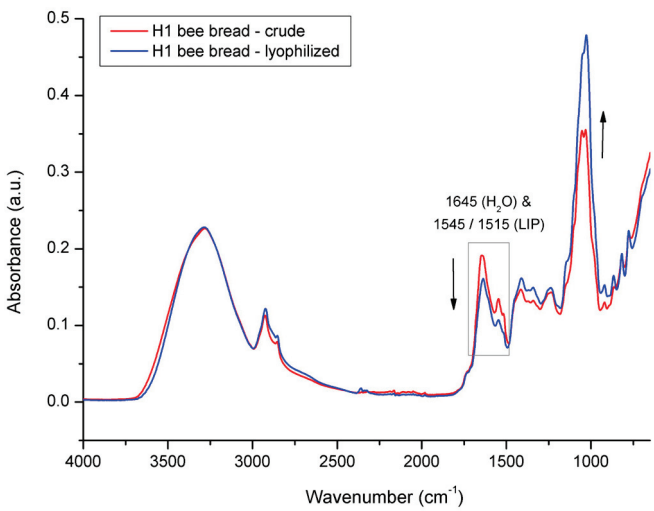

Figure 11. Average FTIR-ATR spectrum of crude bee bread vs. lyophilized bee bread from experimental colony H1, representing comparative spectral features.

The spectral analysis of crude vs. lyophilized BP has also revealed changes in the lipid fraction. Moreover, it was observed that lyophilization also causes the degradation of a particular group of lipids, i.e., lipids with aromatic structures represented by absorption bands occurring at 1544 cm^{-1} and 1515 cm^{-1} whose intensities were found to be decreased in both BP and BB. Similar effects of lyophilization and/or other drying methods on the lipid fraction of BP were observed by other authors [53,63–65]. For example, Conte et al. [53] reported that tocopherol shows a significant decrease after freeze-drying treatment, i.e., α -tocopherol, δ-tocopherol, and γ-tocopherol showed a reduction of 60%, 75%, and 90%, respectively.

The degradation of lipids caused by lyophilization was also reported for other types of organic specimens, such as plants (e.g., tarragon), lipomers and various liposomal formulations, algae, and vegetable oils [66–70]. Along with the water decrease, the weaker intensity of signal at 1645 cm^{-1} in the lyophilized BP/BB samples is probably partially related to a lipid decrease as well, given that the COO– and C=C stretching vibration of lipids are overlapped by H–O–H deformation vibration of water in this spectral region. It can be assumed that lyophilization also affects other less represented lipids that are a part of pollen grains from which BP is comprised, such as glycophospholipids, sphingolipids, sterols, and oxylipids, as well as lipopolysaccharides [71]; however, these minor BP constituents should be further investigated, as they are rarely mentioned in the literature covering BP/BB.

All of the above-described spectral effects (a decrease in water and lipid content, as well as an increase in sugar fraction due to changes in the concentration of individual constituents) were also observed in the lyophilized BP and BB samples from experimental colonies H2 and H3, as presented in Figure 12. Also, the determined water loss for those samples was similar to the results obtained for the samples from H1, i.e., the water loss determined in BP from colony H2 was 14.67% and 9.38% for BB, while the BP from the H3 colony exhibited 14.78% water loss and 10.89% in BB.

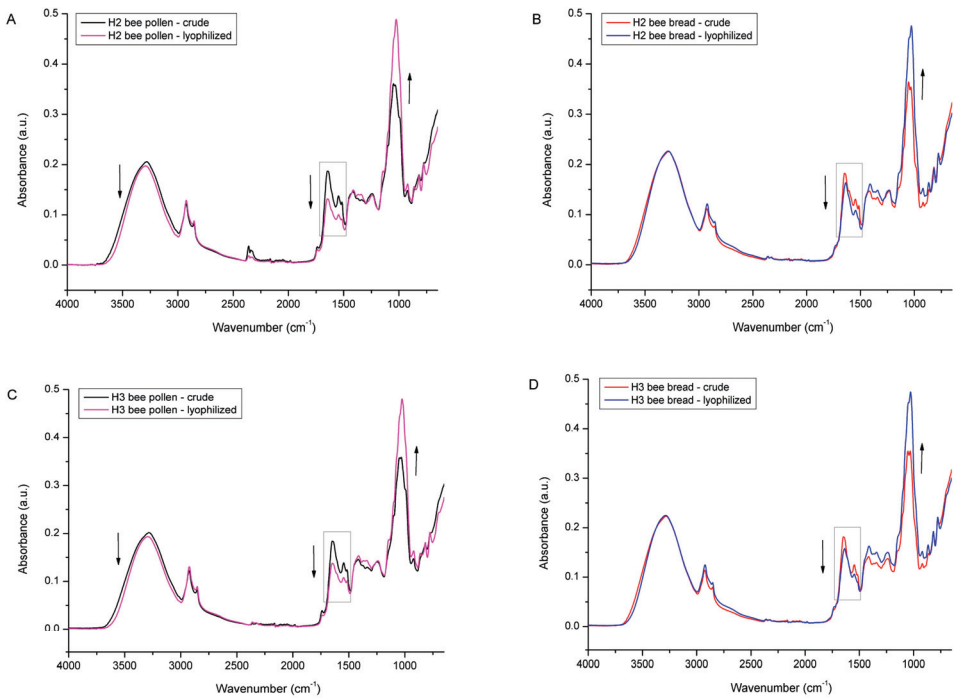

Figure 12. Average FTIR-ATR spectrum of crude bee pollen vs. lyophilized bee pollen (**A**) and crude bee bread vs. lyophilized bee bread (**B**) from experimental colony H2; crude bee pollen vs. lyophilized bee pollen (**C**) and crude bee bread vs. lyophilized bee bread (**D**) from experimental colony H3.

The overall results of the spectral analysis conducted on the BP/BB samples collected from three honey bee colonies confirm the same mode of chemical alterations during the

transformation process of bee pollen into bee bread. These changes are primarily the result of lactic acid fermentation, but it can be assumed that the presence of particular enzymes in bee bread also contributes to sugar-related modifications. Also, the presented results confirm the effectiveness of the bee pollen preservation process, given that the basic chemical composition of BP remains preserved but enriched in the BB form by numerous beneficial elements (the presence of lactic acid, a lower pH, better nutrient bioavailability, and protective/antimicrobial properties).

4. Conclusions

In this study, we have focused our research on the investigation of the in-hive environment (honeycomb) and chemical changes that occur during the transformation of bee pollen into bee bread by monitoring the metric and spectral aspects of this process on three experimental colonies of Carniolan honey bee (*A. m. carnica*). The results have shown that the average depth of the honeycomb (worker) cells was 11.00 mm, and that the bees stored bee pollen up to an average of 7.85 mm of cell depth, thus covering between $^{2}/_{3}$ and $^{3}/_{4}$ (71.4%) of the honeycomb cell—to be more specific and mathematically accurate, $^{17}/_{24}$ of the honeycomb cell. This finding represents the first report, i.e., the first metric data, on the cell depth at which *A.m. carnica* honey bees store their bee bread. The results of the complementary cell measurements have revealed that the smallest side length of the analyzed honeycomb cells ranged from 9.12 to 10.63 mm, with an average of 9.74 mm, while the angle of the hexagonal cell ranged from 117.8° to 119.2°, with an average of 118.4°. These metric data may be employed to investigate the hive-level distribution and storage of bee bread and to estimate the annual production and economic value of bee bread production in general.

We have also provided a detailed assignation of the molecular vibrations observed in bee pollen and bee bread (crude and lyophilized) and elucidated the additional aspects of bee-pollen-to-bee-bread conversion based on a comparative spectral overview of both substances collected simultaneously from three experimental *A. m. carnica* colonies. The FTIR-ATR analysis has revealed a unique spectral pattern of both the bee pollen and the bee bread samples, indicating compositional changes primarily reflected in a higher water content and an altered composition of the sugar fraction (a lower content of sucrose and a higher proportion of fructose in the bee bread compared to the bee pollen), and, to a lesser extent, the lipid fraction (a lower lipid content in the bee bread compared to the bee pollen). Further investigation should be focused on additional microbiological assaying aiming to determine the detailed background mechanisms of the bee-pollen-to-bee-bread transformation pathway.

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The Behavioral Intention to Adopt Circular Economy-Based Digital Technology for Agricultural Waste Valorization

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Abstract: Thailand generates considerable amounts of agricultural food waste. This research focuses on the manufacturing and retail agricultural food system in the northeastern region of Thailand. Our study aimed to investigate the user segments and factors that influence users' behavioral intentions to utilize mobile technology for agricultural waste valorization. This study is based on the Unified Theory of the Adoption and Utilization of Technology (UTAUT2). In order to classify these segments, we performed a cluster analysis using demographic variables: gender, age, and income. In addition, the researchers employed a method known as multigroup structural equation modeling to determine and contrast the users' behavioral intentions. The results showed two types of users: (1) older users with various income ranges, and (2) younger users with a low-income range. Explicitly, age and income were the significant variables for the demographic segmentation, but gender was not. The results also revealed that social influence, price value, and trust highly affected the behavioral intentions of older and various-income users, but did not influence younger and low-income users. However, privacy strongly affected the behavioral intentions in the younger segment, but not those in the older one. Lastly, habit or regularity influenced the behavioral intentions of users in both segments. This study highlights implications for how developers and practitioners might adapt their platform strategies using a circular agricultural platform and user behaviors.

Keywords: agricultural waste; circular economy; digital platform; user intention

1. Introduction

Food waste is produced in large quantities in industrial production, agricultural processing, domestic consumption, and retail. It is one of the world's most significant problems in both wealthy and developing nations. Every year, over one billion tons of food is lost or thrown away, accounting for one third of all the food produced for human use, resulting in significant social, economic, and environmental problems [1]. In terms of the total municipal solid waste yearly (MSW) produced in ASEAN, Thailand has the second highest amount of MSW (26.77 million tonnes/year), while the first is from Indonesia, with 64 million tonnes/year, and in third place is Vietnam, with 22 million tonnes/year [2]. The food industry generates a large amount of by-products, which causes substantial economic, managerial, and environmental issues, in addition to a significant loss of precious resources. The fruit processing sector falls under the category of food processing. International law addresses the disposal of fruit industry by-products (peels, seeds, and oilseed meals) as a difficulty. Finding new prospective application areas for these wastes to further utilize them for the creation of high-value goods has therefore received increased attention. Currently, the fruit processing industry discards its by-products (peel and seed) because they have no economic use. Because of the scarcity of landfills and the high cost of transportation, the disposal of these wastes incurs extra costs for the fruit processing industry. Due to their

high chemical oxygen demand (COD) and biological oxygen demand (BOD), as well as their rapid rate of disintegration, which provides an ideal environment for the reproduction of insects, they should be disposed of carefully.

Both manufacturers and retailers are likely to throw away unconsumed processed and fresh foods. This amount of waste from agricultural production, including the manufacturing and retail industries, is classified by a proportion of 50%, which is made up of raw and cooked peel and seed. According to the United Nations Food and Agriculture Organization, the breakdown of logistical and infrastructural systems causes some countries to waste 55 percent of their agricultural output [3]. Whether pickled, preserved, or dried, these processed products cause problems with waste disposal and affect pollution in terms of smells and community cleanliness, which cannot be dealt with efficiently [4,5]. Based on previous research [6–9], the development of agri-waste management platforms could still be novel, leaving a research gap in the development of digital platforms as innovative tools for agricultural waste management in Thailand.

Moreover, the circular economy is used to solve food waste, by converting this waste into high-value-added products [10]. Hence, developing agri-waste digital platforms to use as an intermediary for the purchase of scraps from fruit/vegetable processing can help to reduce the agricultural waste issues in northeastern Thailand. This northeast region contains 46% of the agricultural holdings in Thailand and 47% of its farm area, with an average holding size of 3.2 hectares. Wastes, in this case, may come from fruits such as mangoes, oranges, pomelos, coconuts, limes, corns, and sugarcanes, and vegetables such as tomatoes, lettuces, kales, and cabbages. Farmers or sellers play a significant role in the platform by bringing the waste to be sold using this platform. Still, most of the previous studies on digital platforms as an innovative tool for managing food waste have focused on technology and innovation to develop digital platforms, leaving a second research gap in exploring behavioral intentions in a deeper dimension with regard to digital platforms [11–13]. Previous research related to circular-economy-based digital technology has included process-based information systems (PBIS), which help with digital tracking, modeling, and sensing for recycling, reuse, and remanufacturing [14,15].

Therefore, developing a digital platform can help solve inefficient agri-waste management by collecting and managing waste data and providing possible business partners that could use agricultural waste as a high-value-added product in the future. The swimlane diagram of this digital platform is demonstrated in Figure 1. This digital platform helps to gather the network of vegetable and fruit retailers in fresh markets and processed food manufacturers that have food wastes such as peels, seeds, and flesh. It allows businesses that need materials transformed from these wastes (such as paper, bioplastic, vegan leather, plywood, and straws, among others) to order their value-added materials/products from this platform. The biomaterial pilot plant acts in the middle and is responsible for transforming these agricultural wastes into value-added materials/products. This platform also helps to manage the monetary transaction from the beginning, including collecting money from the business customers, distributing money to waste sellers, managing logistics, and the final stage, which is to send the materials/products to the business customers.

However, the idea of a circular economy is still relatively novel in Thailand, particularly among food merchants and farmers. It is necessary to have a profound understanding of the individuals that would use this technology. Based on previous research, digital platform developers can better comprehend user behaviors when categorizing these users into specific segments and analyzing the factors affecting their use intention [9,16]. However, only a small number of studies have focused on the factors influencing these behavioral intentions and the segmentation of digital platform users for a circular economy. In addition, this study contributes to the current body of the literature by analyzing the moderating effect of demographic segments on a number of factors that influence behavioral intentions. On the basis of their gender, age, and annual income, the users were divided into two distinct demographic subgroups. The research framework was based on the Unified Theory of the Adoption and Utilization of Technology (UTAUT2), which posits the determinants of

technology adoption, including performance expectancy, effort expectancy, social influence, facilitating condition, hedonic motivation, price value, and habit [17]. The UTAUT2 was justifiable in this context because evidence revealed that the UTAUT2 has been employed in research on food and agricultural technology to predict users' behavioral intentions [18–20]. An additional academic contribution is that the UTAUT2 can be expanded with more variables, such as trust and privacy [21], to enrich the research framework and provide novelty for technology adoption concerning circular-economy-based digital technology.

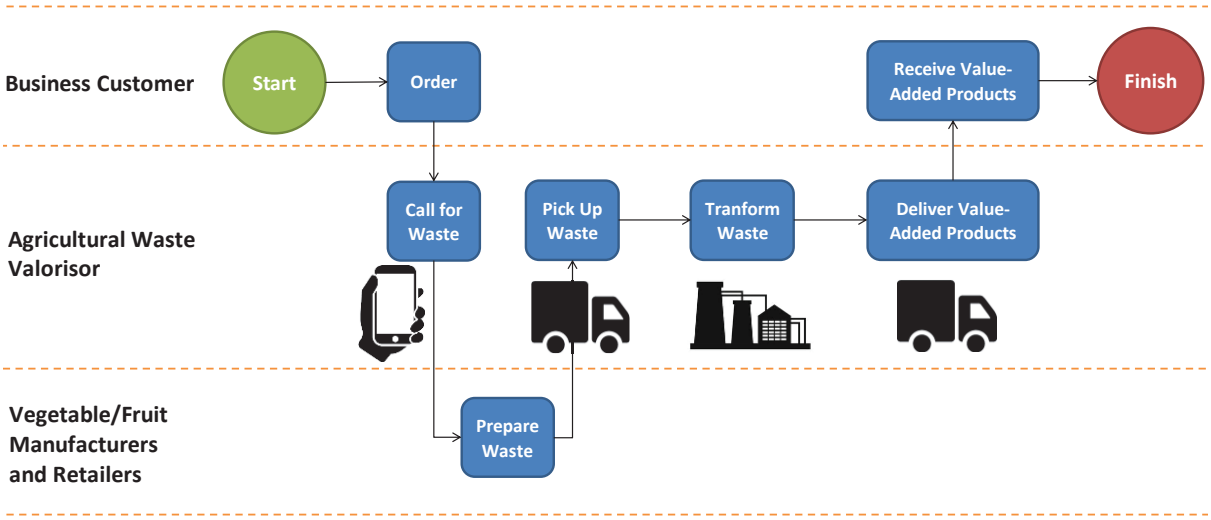

Figure 1. Swimlane diagram of digital waste management platform. Source: Figure created by authors 2023.

With this novel platform, this study contributes to bridging the gap of factors that influence users' behavioral intentions toward a digital waste management platform. Explicitly, this study aimed to deeply understand the digital adoption behaviors of users who are vegetable and fruit retailers and processed food retailers. First, we classified the users using the multivariate demographic segmentation approach. Then, we employed the multigroup structural equation modeling approach to explore the factors influencing their behavioral intentions towards adopting digital technology based on the UTAUT2 model.

2. Literature Review and Hypothesis Development

The structural equation model (SEM) has been utilized in many circular economy studies to show the link between customer/user perceptions, attitudes, and behavioral intentions [22–26]. These papers have discussed firm structures, mechanisms, and performances. However, a digital circular model has rarely been discussed. In the present study, a review of the relevant literature was carried out to pinpoint the relevant factors, models, and determinants. In order to achieve the objectives of this investigation, the UTAUT2 model was utilized using the SEM framework.

2.1. The Unified Theory of Acceptance and Use of Technology 2: UTAUT2

Recent research has utilized the UTAUT2 to explain users' behavioral intentions towards adopting digital platforms in the food and agricultural industry [18–20]. The UTAUT2 is extended from the Unified Theory of Acceptance and Use of Technology (UTAUT), which is based on sociology and psychology and is one of the most recent theories of how people accept new technologies. It is a development of prior technology acceptance models, which have been widely used in studies on how people embrace new information technologies. The UTAUT is based on eight models of technology acceptance [17] that have been used in a number of similar studies on consumer technology uptake [27–30]. Referring to a previous study, the UTAUT has been used often in the social sciences [31].

The UTAUT is a theory that can be applied broadly and contains model components that are accurate and reliable. These model elements are used for projecting and explaining user acceptance behaviors [32,33]. It has been demonstrated that the theory is capable of explaining a significant amount of variability in a wide range of technological adoption and usage behaviors [17,34,35]. The UTAUT explains that technology acceptance can be determined by performance expectancy, effort expectancy, social influence, and facilitating conditions, while demographic variables such as gender, age, and income moderate this relationship [17].

The UTAUT2 added three more determinants of technology acceptance to the original UTAUT model, including hedonic motivation, price value, and habit [36]. The UTAUT2 was utilized in this research because it comprises acceptance and use models (adoption) of cutting-edge information technology that have been tested and verified in previous research. As a result, in the quest for an acceptable model that embraces practically all the components driving users' behavioral intentions towards a fruits and vegetables waste management platform, the UTAUT2 was the most acceptable theoretical foundation to supply the conceptual model utilized in this research. The main constructs in the UTAUT2 are: performance expectancy (PE), effort expectancy (EE), social influence (SI), facilitating condition (FC), hedonic motivation (HM), price value (PV), and habit (HB), plus two extended variables: trust (TR) and privacy (PR), which were proposed as direct determinants of the behavior intentions of users. In addition, gender, age, and income were assumed to influence this usage intention and behavior.

Due to the high amount of garbage generated by fruit and vegetable waste from sellers and farmers, a prototype of the platform concept was created to serve companies for purchasing their fruit and vegetable waste. The platform would collect information from the merchants and farmers in each area who desired to sell their garbage. The platform would then convert this vegetable and fruit waste into usable items or transform them into biological products from plant waste, such as paper and organic leather. However, there have been few studies in Thailand on platforms that act as an intermediary for acquiring leftover vegetables and fruits, as well as the transformation process of these leftovers into high-value products. Consequently, the researchers aimed to investigate the elements that impact personal preferences for utilizing this platform and acting as an intermediary in the trade of vegetable and fruit waste from merchants and farmers.

2.2. Performance Expectancy (PE)

The possibility that this new system and application would assist users in meeting their requirements and goals in a more practical and efficient manner is referred to as the performance expectancy [17]. In conformity with previous studies, an important relationship between performance expectancy and behavioral intention was revealed [37]. If customers feel that a new system would save them more time and effort than the existing systems, they are more likely to be satisfied and plan to utilize the new system [17,38–40]. Regarding food-related performance expectations, the inherent mobility and adaptability of mobile food-ordering applications have facilitated more convenient interactions between clients and restaurants. For instance, when using a mobile food-ordering app, a customer may visit any restaurant at any time, have a broad choice of food selections, obtain sufficient information, and make orders without traveling. Given issues such as traffic or wasting time looking for parking, mobile food-ordering applications are extremely significant. Therefore, if a customer experiences a high degree of utilitarian value in using such creative applications, they are more likely to be content and delighted with their experience. This is because of the increased likelihood that they will use these apps again. According to the research of Yeo et al. (2017), customers' propensities to utilize online food-ordering systems are significantly influenced by the usability of the system, which is a factor that is analogous to the performance expectancy [41].

Hypothesis H1. *Performance expectancy will positively influence users' intentions to use the fruit and vegetable waste management platform.*

2.3. Effort Expectancy (EE)

Effort expectancy evaluates the degree of usability associated with the usage of information technology. Venkatesh et al. (2003) defined effort expectancy as the degree of simplicity involved in using an information system [17]. It indicates the extent of user expectations that the usage of such platforms would not need physical and mental exertion. Existing research has shown that effort anticipation favorably modifies behavioral intentions [34,42,43]. Performance expectancy also has a role in mediating this effect [35]. This implies that people will have high expectations for the outcomes that are expected of them and be more open to using technology if they believe it is simple to use. However, the level of effort that may be anticipated is proportional to the extent to which users sell their waste products via the platform. This is because the ease with which customers may obtain essential information by using a trading platform in the shortest amount of time possible has a high probability of influencing the amount of time these customers spend using the platform. Because of this, clients who learn how easy it is to use the platform for trading may not be reluctant to use it.

With this proposition that relates to effort expectancy, its considerable influence on consumer desires to adopt mobile food-ordering applications has been experimentally shown [44]. The amount of time and effort required from customers may also reflect how simple or difficult it is to use these programs for ordering food via mobile devices. For this reason, it can be said that consumers will be content with their experience of utilizing these applications as long as they judge the effort and complexity to be low. According to the findings of Amin et al. (2014), there is a significant correlation between the simplicity of using a mobile app, the amount of effort needed, and the level of customer satisfaction [45].

Hypothesis H2. *Effort expectancy will positively influence users' intentions to use the fruit and vegetable waste management platform.*

2.4. Social Influence (SI)

Social influence is a marketing term that refers to the ability to influence the thoughts of people in a social network online. The greater a person's influence, the more enticing they are to companies and other individuals attempting to promote or sell an idea or product. A second definition of social influence was provided by Turner and Oakes (1986) [46], who referred to it as "the processes by which individuals directly or indirectly affect the attitudes, feelings, and behaviors of others". Information about other people is a prerequisite for exerting social influence, and direct contact with these individuals is not always necessary for this to take place [47]. In the past, a person's social influence was restricted to the individuals in their immediate social circle; however, the internet and other social media platforms have significantly increased the scope of a person's social impact [48]. It is the conviction held by a person that other people should take advantage of their available technological resources [17]. In the early stages of a person's interaction with new technologies, social influence is particularly significant, because the information received from the people around them contributes to the usefulness of a specific technology [21]. These experiences give a more realistic foundation for an individual's continued use of technology, despite the fact that its use reduces over time and becomes outmoded as technology advances.

Researchers have stated that consumers' food waste habits are complicated as a result of the interplay between numerous home activities, and that influencing these behaviors is crucial [49,50]. The social impact theory might be one way that people learn from one another, resulting in attitude and behavior modification [51]. Households may be able to lessen their effects on the natural environment if they are able to harness this for pro-environmental behavior changes.

Hypothesis H3. *Social Influence will positively influence users' intentions to use the fruit and vegetable waste management platform.*

2.5. Facilitating Condition (FC)

The phrase "the extent to which an individual feels that an organizational and technical infrastructure exists to support the operation of the system" is what is meant when one refers to "facilitating conditions". In e-commerce, the term "facilitating condition" refers to resources such as a computer, tablet, mobile phone, internet access, and the ability to make payments online, as well as the expertise needed to install and use essential software [17]. Earlier studies on the desirability of platforms have shown that users' perceptions of their convenience (i.e., having the tools and help necessary to use technology) have a direct influence on their behavioral intentions to use the technology [52]. Consumers are motivated to use mobile shopping technologies [53], online banking [54], online airline ticketing [55], and also mobile payment services when they have the technology and infrastructure support they need [56]. This shows that facilitating conditions influence the behavioral intentions of users in a positive manner. Additionally, consumers with adequate financial resources are more at ease and satisfied when utilizing technology. Users that are more proficient with a platform and those that have a higher technical expertise are also likely to continue using it.

Hypothesis H4. *Facilitating conditions will positively influence users' intentions to use the fruit and vegetable waste management platform.*

2.6. Hedonic Motivation (HM)

The level of enjoyment one derives from using cutting-edge technology is known as hedonic motivation, and it has been acknowledged as being crucial for the adoption and application of technology [17]. This idea has been defined as perceived enjoyment in various theories or models of technological acceptance [36]. If technology is delightful and entertaining to use, its users can derive enjoyment from it [28]. According to Leong et al.'s [57] study on mobile entertainment, consumers are eager to use mobile entertainment if it will bring them happiness and joy. Based on previous research, customers will adopt new technology when they believe that using it would make them more comfortable, happy, and amused. People will be more inclined to use a platform if they think utilizing it will be pleasurable [40]. As a result, hedonic motivation is defined as the moment when individuals want to use a platform consistently, and their continued behavior is based on knowledge or experience [17]. Moreover, it has been established that hedonic motivation is a crucial component of the behavioral intention to adopt mobile internet in a consumer setting [36]. Diverse genres of mobile applications, such as games, can provide users with enjoyment and diversion. If a customer believes that using mobile applications is fun, he or she will be more inclined to utilize them. In recent years, people have become more reliant on food delivery as a result of the present pace of life and the possibility of finding additional eateries provided by this food delivery [58].

Hypothesis H5. *Hedonic motivation will positively influence users' intentions to use the fruit and vegetable waste management platform.*

2.7. Price Value (PV)

Compared to organizational settings, the use of technology in the context of the customer may incur additional financial costs. Consequently, customers can cognitively weigh the advantages of adopting new technologies against the costs associated with their use. Customers will be more eager to adopt these new technologies if their price-to-value ratio is more favorable. This, in turn, requires that customers perceive using this technology as more useful and valuable than the monetary expenditure that is spent as a result of using the technology [36]. Based on the findings of earlier studies, the economic value of a product is a crucial component in the formulation of behavioral intentions when deciding on customer acceptance and the usage of technological products [40]. When utilizing a program, users will continue to weigh its associated costs. If the advantages outweigh

these costs, the user will continue to use the program over time. This is consistent with the findings of Hew et al. [59], who said that price value influences behavioral intentions [59]. Among the elements responsible for processing food delivery apps, demand, price changes, discount offers, the availability of pricing comparisons, and the simplicity of selection are the most prominent [60,61]. Because of the burden that it places on their finances, large families normally make fewer purchases of home-delivered meals than families of a smaller size do; large families are more likely to take advantage of various discounts and deals [62]. Similarly, Koiri et al. (2019) suggested that restaurants should provide customer incentives such as discounts or cash-back offers as a way of fostering a good attitude and take into account that people do not want to pay online [63]. Pricing value has a positive impact on the willingness to use technology when it is thought that the advantages of using this technology surpass its monetary expenditures [36].

Hypothesis H6. *Price value will positively influence users' intentions to use the fruit and vegetable waste management platform.*

2.8. Habit (H)

Habit refers to the belief that behavior is automatic in an individual [64]. Previous studies have discovered that habit has both direct and indirect effects on behavioral intentions [36]. Food habits are established over time and grocery shopping could quickly become an established part of one's weekly schedule [65]. Most food waste studies incorporate consumers' purchasing habits, which may be a key driver in identifying their food waste behaviors [66–68]. According to Stefan et al. [69], shopping behaviors that lead to overbuying or the purchase of unexpected products significantly affect how individuals dispose of their food. Most people's shopping regimen includes buying more than they need [70]. Buying in excess and getting carried away with exceptional promotions such as buy-one-get-one-free or mixing multiple goods can lead to food waste [71,72]. Furthermore, multiple studies have demonstrated that people who prepare shopping lists and buy just what they need waste less food [73,74].

Hypothesis H7. *Habit will positively influence users' intentions to use the fruit and vegetable waste management platform.*

2.9. Trust (TR)

Zhou et al. (2010) defined trust as "the degree of ease associated with the use of the system" [35]. Trust is an enabler in distributed systems. It enables internet commerce and safe agent-based apps. Despite the need to standardize trust and its related concepts, many researchers have employed a very precise meaning of trust as being connected to authentication or the capacity to pay for purchases. Prior studies have shown that trust does not have much of an effect on a person's intentions toward their actions [37]. Trust is a crucial consumer factor in other food situations. However, one recent study investigated the reasons that trust functions as an obstacle to platform adoption, which revealed that quality and interface concerns are important challenges that customers may experience while using meal delivery services [75]. Thereby, barriers to utilizing meal delivery apps might be related to the technological characteristics of an app, as well as the actual experience in terms of the quality of the food and the service that is provided. Applications specializing in food delivery, in particular, are examples of technology-based services that enable users to order food for consumption physically. These apps may present users with challenges numerous times, both before and after the transaction is completed. This is consistent with prior studies that have shown that mobile app services with online-to-offline settings, such as food delivery applications, app functionality, and offline usage, are critical [76].

Hypothesis H8. *Trust will positively influence users' intentions to use the fruit and vegetable waste management platform.*

2.10. Privacy (PR)

The successful adoption and adaptation of technology relies heavily on the protection of personal information. This is the extent to which an individual's right to control the information collected on them by third parties is protected [77]. Previous research has clarified that a user's inclination to utilize an application is largely determined by their level of trust [78]. Previous studies have discovered that privacy has a significant impact on behavioral intentions [79]. In this day and age of the internet, the protection of private information is of the utmost importance, as it poses a risk to the integrity of online financial transactions, as well as the preservation of personally identifiable information [80]. When it comes to the usage of mobile apps for a variety of tasks, such as online shopping or online food delivery [81], particularly financial operations [82], users place a high value on the protection of their private information as a crucial consideration. If the safety of the transaction can be guaranteed, users of apps for online food delivery will have a greater propensity to utilize such services [77,82].

Hypothesis H9. *Privacy will positively influence users' intentions to use the fruit and vegetable waste management platform.*

2.11. Behavioral Intention (BI)

The term "behavioral intention" is used to describe the degree to which a person has made up their mind about whether they will participate in a certain future behavior [83]. Perceived usefulness and trust may play important roles in establishing the behavioral intent to adopt mobile commerce [84]. Researchers have proposed that behavioral intentions to utilize online platforms for home fights is highly affected by both performance and effort expectations. Furthermore, social influence has a significant impact on behavioral intentions towards embracing mobile use [85]. Previous research has found that several independent factors can impact these behavioral intentions. As a result, the dependent variables chosen would be determined by the theory employed and the study situation. Behavioral intentions, as defined by Ajzen (2015), are what show how much effort people are willing to put into accomplishing a job [86]. In contrast, Malhotra and McCort (2001) said that marketing scholars still place a premium on learning more about consumers' future plans [87]. Despite this, a customer's purpose continues to stand out as a distinctive feature that plays an extra substantial influence on consumer behaviors. To better predict a customer's actual behavior on the path leading up to a specific action, it may be useful to first obtain some insight into that customer's reasons [88].

A person's conceptual framework and level of readiness to act, in relation to food waste, are both internal and contextual factors. Behavioral intention is a significant predictor of actual behavior [86]. As a result, the hypothesis accounts for the positive impact of meaning on food waste management actions [89]. In Shenzhen, China, 491 construction workers were surveyed regarding their thoughts and behaviors about construction waste. Waste reduction behavior is affected by individuals' intentions to do so, as shown by recent research [90]. Customers' food waste habits can be better understood, and evidence of the positive effect of behavioral intentions on actual waste reduction can be provided [91].

2.12. Moderation Effects of Demographic Variables

The UTAUT2 was selected as the main theory in this research. Hence, demographic variables such as age, gender, and income would moderate the relationship among the main UTAUT2 variables. This section reviews the roles of age, gender, and income, which have an impact on the use of technology.

Inglehart (2015) first presented the Generational Cohort Theory as a method for segmenting a population by generation [92]. Consequently, generational cohorts tend to share similar beliefs, values, and attitudes because they share the same early adulthood experiences and social, political, and economic events (ages 17–24). These experiences

and occurrences affect their core beliefs in areas such as tolerance, money, jobs, and sexual conduct [93].

As was mentioned earlier, the participants in this study came from four different generations: baby boomers, who were born between 1946 and 1965; Gen X, who were born between 1966 and 1980; Gen Y, who were born between 1981 and 1995; and Gen Z, who were born between 1996–2013 [94,95].

Presently, most of the population comprises older individuals, who are classed as baby boomers. During the formation year in terms of social, political, and economic issues, baby boomers are generally prosperous. Because of these experiences, the baby boomer is ideal. They are positive, self-confident, and communicate well. They value education and are avid product users [96]. The baby boomer generation is frequently described as the least tech-savvy of the generations when studying information technology and media [97]. Although their rate of mobile data and technology use continues to rise [98,99], they continue to lag behind younger generations. Baby boomers tend to have high intentions towards purchase upcycled foods compared to Gen X. Due to lifestyle differences, baby boomers seem to support upcycled food [100].

Unlike younger generations, Gen X is not surrounded by and preoccupied with technology; therefore, they are considered "digital natives". They must invest a great deal of time and energy into acquiring digital abilities [101]. Members of Gen X are seen as being gloomy, cynical, socially insecure, and lacking in established conventions, which is in stark contrast to the optimistic attitude of the baby boomer generation [102]. A previous study found that Gen X have the lowest intentions towards purchasing upcycled foods, due to a decrease in the perceived quality of these upcycled foods [100].

The expansion of the economy occurred along with the maturation of members from Generation Y. The rapid development of new technologies (such as the introduction of the internet and other forms of social media), globalization, and popular culture impact people's way of life [103]. In contrast to its predecessor, Generation X, the generation known as Generation Y is seen as being upbeat and self-assured. They respond by taking the necessary steps to fix a problem when it occurs. Because of their superior strength and speed, members of Generation Y are capable of performing many tasks at once [104,105]. In terms of social connections, interests, friendships, and civic activities, technology plays an integral role in their lives [106]. Because its members are digital natives whose lives revolved around technological advancement, Gen Y is commonly referred to as "the Internet Generation". According to previous research, members of Gen Y consider buying organic foods because of concerns about their health, and their trust in organic food impacts their purchasing intentiosn. However, higher prices reduce Gen Y's organic product purchasing intentions [100].

Gen Z is a generation that has a significant impact on the nation's economy and society. Even though Thailand has entered an aging culture, Generation Z advise the elderly in their product purchases. The Hakuhodo Institute of Life and Living ASEAN: HILL ASEAN, a major advertising agency from Japan, conducted a study of such consumer behaviors in six ASEAN countries and found that members of Gen Z, most of whom have Gen X parents, are people born in the social media and internet era. They receive a lot of information from the internet. They objectively consider the words and actions of previous generations. From a broad perspective, they want to solve the social problems that may arise from previous generations by giving equal importance to themselves, their families, and those around them, being ready to work together to solve these problems, even if there are differences between them. As a result, previous research has shown that Gen Z's dietary preferences can be influenced by a good impression of diet and food [100].

Gender has been found to impact behavioral intentions towards using technology. Gender is a social framework that differentiates between the limitations and possibilities based on sex categories, and this differentiation has ramifications on various levels [107]. Gender is built in several different ways, including through differences in women's and men's access to protective factors (such as resources) and differences in their exposure to

risk factors (such as stresses). Men and women are satisfied with different things. For instance, a recent study found that gender moderates the relationship between performance expectancy, facilitating conditions, social influence, and behavioral intentions towards accepting e-training technology [108].

Additionally, income may play a moderating role in the technology acceptance model [109]. This study examined customer intentions towards adopting an e-ticket airfare platform. This study found that the perceived usefulness of the older group with middle-to-high incomes was lower than that of the younger group with low incomes. Unsurprisingly, younger respondents reported a greater perception of perceived ease of use than older respondents. The younger respondents were more sensitive to price than their older counterparts. Young people had a greater perception of hedonic motivation than older individuals. Lastly, younger respondents had greater behavioral intentions towards purchasing airfares through e-commerce than older respondents.

Therefore, we hypothesize that, together, demographic variables (age, gender, and income) have a moderating effect on this UTAUT2 model. This moderating effect is presented using a multivariate demographic cluster analysis, signifying the academic novelty in this study. We also decided to omit the use behavior construct from this model because this platform is a concept prototype, so no actual use can be investigated. Additionally, the constructs of trust and privacy were added to the model, indicating an additional theoretical contribution to this study.

Taking into account the literature studies and theories, Figure 2 also depicts the conceptual model of this investigation.

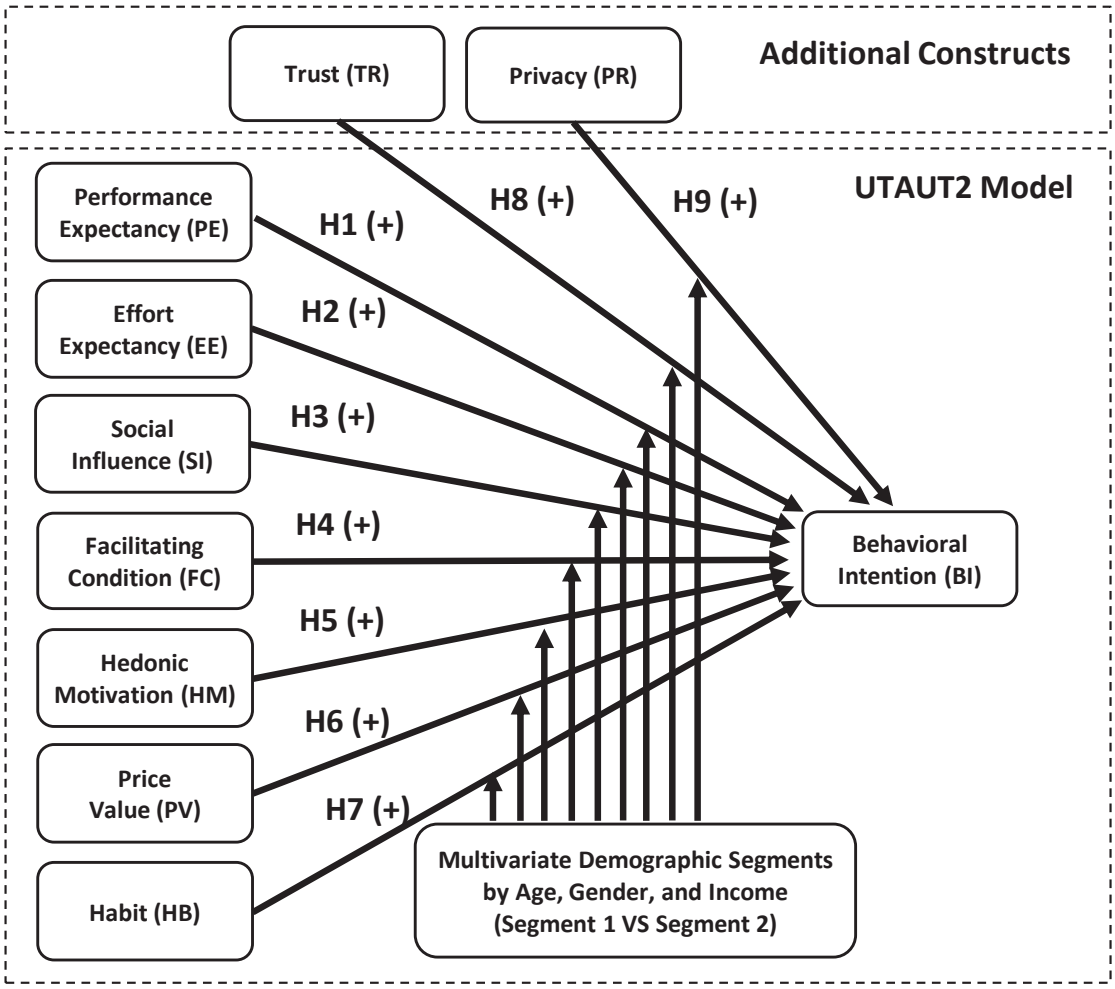

Figure 2. Research framework. Source: Figure adapted by authors (2023).

3. Methodology

The method in this study mainly employed a quantitative analysis centered around the UTAUT2 theory. This section involves the sampling, data collection, and data analysis.

3.1. Sampling and Data Collection

For the sample size in a data analysis, it is suggested that no particular criterion be adhered to when selecting a specific sample size for a confirmatory factor analysis (CFA), the first stage of structural equation modeling (SEM) [110]. Tabachnick and Fidell (2007) [111] speculated that CFAs depend on sample size and might be less stable when examined using a small sample. If a structural model contains fewer than seven constructs, a minimum sample size of 300 is advised [110]. On the contrary, Kline (2016) suggested 200 observations as the standard sample size for an SEM investigation [112]. As a result, the researchers intended to collect data using a structured questionnaire obtained through intercept surveys with 350 respondents.

This study utilized a combination of quota and purposive sampling techniques. Obtaining data from a group that is representative of the whole is the purpose of this sampling technique [113]. The research takes into account the proportions of the quota responders drawn from the whole population of farmers and sellers in the northeast of Thailand (350 respondents: 200 farmers and 150 sellers). It was decided to employ the quota sampling approach in order to select an equal number of fruit and vegetable farmers and sellers from the provinces with sizable agricultural areas and fresh markets, including Nakhon Ratchasima (n = 70), Khon Kaen (n = 70), Ubon Ratchathani (n = 70), Sri Saket (n = 70), and Roi-et (n = 70) [114]. This purposive sampling method was employed because we focused only on the respondents who were vegetable or fruit sellers and farmers from the selected markets and farms in those provinces.

An intercept survey was used as the method for data collection because it was the most effective for gathering perception data from the respondents located in the designated areas. This method enabled respondents to complete the questionnaire in a single setting. Consequently, the quality of their feedback was enhanced by reducing distractions [115]. The respondents, who were farmers and merchants, were purposively asked to respond to this questionnaire. Furthermore, in order to avoid ambiguity that might contribute to response bias, the researchers only allowed the respondents to reply to the questionnaire once. First, the surveyor began by asking the respondents whether they were farmers (or retailers) who were potential users of this digital platform to ascertain the survey. The questionnaires used were confidential and provided the respondents with anonymity. Before responding to the questions, the respondents were informed of the research objectives. All the respondents had to be at least 20 years old, able to comprehend Thai, and willing to answer the questions. They were asked about their age, Thai reading ability, and participation intentions. This questionnaire could take about 5–10 min to complete. If they felt uncomfortable responding to the questionnaire, the respondents were free to decline at any time. This survey was conducted following the approval of the Khon Kaen University Ethics Committee for Human Research (HE643227).

Despite this, we were able to utilize data from only 326 respondents (200 farmers and 126 sellers) from the previously determined locations in northeastern Thailand. Out of 100 percent of the questionnaires distributed, the usable rate was only 93.14 percent. This was because some respondents did not complete all the questions, while some took the questionnaires but never returned them. The data curation and utilization were governed by human research ethics considerations to ensure the confidentiality of the respondents' information. Before responding to the questionnaires, the respondents were instructed about using this digital platform. The process flow of this platform was also described according to Figure 1.

The questionnaire was divided into two main parts (see Appendix A): demographic profiles and user perceptions. In the demographic part, there were three questions that asked about age (the Gen Z ages were between 20–27, Gen Y ages were between 28–41,

Gen X ages were between 42–56, and baby boomer ages were between 57–76 [94,95]), gender (male and female), and income (less than BHT 15,000, BHT 15,000–20,000, BHT 25,001–30,000, and more than BHT 30,000). For the perception part, the questions were adapted from Venkatesh et al. [36] and Alam et al. [21]. The questionnaire referenced the determining elements and models. To quantify the constructs, this study made use of a five-point Likert scale, with 1 representing strong disagreement and 5 representing strong agreement.

3.2. Data Analysis

In this study, we first addressed the issue of common method variance (CMV) before analyzing the data using the statistical tools. CMV occurs when variables within the same model are studied using the same method or same source, leading to systematic error variations and biasing the evaluated relationship. In order to investigate CMV, this study used Harman's single-factor test, originally developed by Podsakoff et al. (2011) [116]. This allowed the researchers to collect both dependent and independent variables from the respondents. The results showed that the total variance was 39.325%, which was less than the 50% criterion [116].

To categorize the respondents by age, gender, and income, the researcher employed a multivariate cluster analysis. To begin, we used a hierarchical cluster analysis to build the clusters by increasing the levels of similarity and dissimilarity among the groups [117]. Secondly, the hierarchical cluster result was validated using a centroid cluster analysis. Lastly, the squared Euclidean distance was employed to minimize the average squared distance between the values that were observed, and the value was estimated [118]. By observing the dendrogram, the Elbow method was used to determine a suitable number of clusters. As a follow-up, a series of chi-square tests were run to confirm any significant variations identified among the clusters in terms of the segmentation by demographics. Next, we conducted a *t*-test to compare the mean perception scores of Segment 1 and Segment 2 and to check whether there were any differences between the clusters [119,120]. To ascertain the normality of the data set, we used the Kolmogorov–Smirnov, Shapiro–Wilk, Skewness, and Kurtosis tests to ensure that the data were normally distributed. Both the Kolmogorov–Smirnov and Shapiro–Wilk tests yielded statistically significant results (p-values < 0.001). Furthermore, the perception scores for the Skewness and Kurtosis values fell within the acceptable range of 1.00 to 1.00. Therefore, the normality conditions were met by this data set.

The structural equation modeling (SEM) approach was used to analyze this study's data, utilizing the statistic program IBM SPSS Amos 26. Among the statistical techniques in SEM are confirmatory factor analysis (CFA), path analysis, causal modeling using latent variables, analysis of variance, and multiple linear regression [121]. This method was utilized to explore user behavioral intentions in food and agricultural research [9,16,18,19,122] In practice, two steps of SEM were used to evaluate the model estimate [123]. First, the outer CFA model was assessed to establish the validity and dependability of the relationship between each indicator and its variable. The goodness of fit (GOF), discriminant validity, and convergent validity were all examined at this stage. The second stage consistsed of a GOF study of the inner structural model to determine the overall structural validity. The final phase of this technique involved the use of a multigroup moderation analysis to evaluate the moderating impact of the multivariate demographic segmentation on the structural relationship revealed by the UTAUT2 hypothesis. Using a measurement invariance (MI) analysis with the demographic segment as a moderating factor, the sample was divided into two groups in this stage.

4. Results of the Study

4.1. Multivariate Demographic Segmentation

According to the cluster analysis results from Table 1, we divided the users into Segment 1 (n = 122) and Segment 2 (n = 204). The chi-square test demonstrated that gender was

an insignificant variable for the demographic segmentation (p-value = 0.163 > 0.01). Most respondents in Segment 1 were people from Generation X and baby boomers. Furthermore, most people in this group had low incomes and were fruit and vegetable retailers, but the higher-income earners were manufacturing officials. However, in Segment 2, Gen Z and Gen Y members made up the bulk of the participants, who clearly earned less than BHT 15,000. This result concluded that the users were classified into two different groups: (1) older people with various income ranges, and (2) young people with low incomes, where gender was ineffective in classifying these segments. As for Segment 1, the respondents' monthly incomes were less than BHT 15,000.

Table 1. Descriptive statistics for the demographic profiles.

Demographic Profile	Measure	Segment 1		Segment 2		Total		Chi-Square Test
		n	%	*n*	%	*n*	%	
Segment size		122		204		326		
Gender	Male	55	16.9	76	23.3	131	40.2	0.163
	Female	67	20.6	128	39.3	195	59.8	
Age	Baby Boomer	31	9.5	0	0	31	9.5	***
	Gen X	83	25.5	0	0	83	25.5	
	Gen Y	5	1.5	76	23.3	81	24.8	
	Gen Z	3	0.9	128	39.3	131	40.2	
Income (Baht)	Less than 15,000	54	16.6	126	38.7	180	55.2	***
	15,001–20,000	23	7.1	57	17.5	80	24.5	
	20,001–25,000	12	3.7	20	6.1	32	9.8	
	25,001–30,000	15	4.6	1	0.3	16	4.9	
	More than 30,000	18	5.5	0	0	18	5.5	

Source: data adapted from authors (2023). Note: *** denotes significant at <0.01; 1 dollar is roughly 37.90 Bath (Retrieved from: wise.com, visit date 13 October 2022).

Next, the perception scores of Segment 1 (older people with various income ranges) and Segment 2 (young people with low incomes) were compared. Table 2 shows that, compared to Segment 1, the users in Segment 2 had higher mean scores across the board with regard to performance expectancy, effort expectancy, social influence, habit, and behavioral intentions. In contrast, the Segment 1 respondents averaged a greater pricing value and a higher level of privacy than the Segment 2 respondents. However, regarding facilitating conditions and hedonic motivation, comparing the mean scores of Segments 1 and 2 was inconclusive.

After applying t-tests across the two groups, there was a statistically significant difference between the groups' mean scores, given p-values of <0.05, <0.01, and <0.001. Table 2 demonstrates that Segment 2 tended to have a greater perception that the platform may increase productivity (PE3) than Segment 1. Segment 2 also expected the platform to be easier to learn than Segment 1 (EE1). Moreover, the perceptions of social influence regarding referrals (SI1), influencers (SI2), and respected people (SI3) in Segment 2 seemed to be better off than those in Segment 1. The perception of habits, such as addiction (HB2) and routine (HB3), in Segment 2 tended to be higher than those in Segment 1. Segment 2 also expected to have the necessary knowledge to utilize the platform more than Segment 1 (FC2). In contrast, the t-test results show that Segment 1 expected to have more support resources to help them utilize the platform (FC1) and required more privacy (PR4) than Segment 2.

There are two primary steps in conducting a statistical test with SEM: the measurement model (CFA) and the structural model [123].

Table 2. Independent sample *t*-test result.

Psychographic Profile	Measure	Segment 1		Segment 2		Mean Diff	t	*t*-Test
		Mean	SD	Mean	SD			
Performance Expectancy	PE1	3.76	0.834	3.93	0.915	−0.164	−1.620	0.334
	PE2	3.61	0.886	3.87	0.886	−0.253	−2.494	0.078
	PE3	3.60	1.081	3.94	0.886	−0.343	−3.110	***
Effort Expectancy	EE1	3.65	1.012	3.79	0.888	−0.142	−1.323	**
	EE2	3.73	0.927	3.85	0.894	−0.119	−1.142	0.053
	EE3	3.83	0.924	3.92	0.987	−0.089	−0.805	0.483
	EE4	3.75	0.875	3.92	0.961	−0.163	−1.527	0.702
Social Influence	SI1	3.57	1.052	3.76	0.779	−0.186	−1.825	***
	SI2	3.33	1.071	3.72	0.852	−0.388	−3.604	***
	SI3	3.34	0.994	3.77	0.849	−0.425	−4.104	**
	SI4	3.49	0.956	3.72	0.864	−0.224	−2.175	0.057
Facilitating Condition	FC1	3.86	0.930	3.80	0.803	0.062	0.632	**
	FC2	3.57	0.953	3.82	0.811	−0.250	−2.517	***
	FC3	3.88	0.809	3.91	0.960	−0.030	−0.287	0.418
	FC4	3.94	0.865	3.88	0.924	−0.060	0.584	0.512
Hedonic Motivation	HM1	3.79	0.964	3.73	0.877	0.056	0.543	0.101
	HM2	3.35	0.961	3.68	0.890	−0.324	−3.087	0.240
	HM3	3.36	0.954	3.66	0.881	−0.301	−2.894	0.167
	HM4	3.84	0.894	3.80	0.952	0.032	0.302	0.659
Price Value	PV1	4.05	0.952	3.85	0.983	0.201	1.808	0.999
	PV2	3.95	0.935	3.80	0.938	0.152	1.416	0.628
	PV3	4.01	0.895	3.83	0.980	0.180	1.655	0.718
	PV4	3.91	0.927	3.82	0.992	0.086	0.779	0.267
Habit	HB1	3.59	0.985	3.65	0.877	−0.062	−0.587	0.097
	HB2	3.27	1.240	3.58	0.887	−0.313	−2.646	***
	HB3	3.38	1.063	3.69	0.910	−0.309	−2.787	*
Trust	TR1	4.06	0.893	3.87	0.938	0.185	1.752	0.518
	TR2	3.71	0.904	3.81	0.939	−0.101	−0.949	0.810
	TR3	3.86	0.930	3.83	0.927	0.027	0.257	0.649
	TR4	3.97	0.881	3.87	0.919	0.100	0.961	0.418
Privacy	PR1	3.93	0.946	3.89	0.948	0.039	0.359	0.825
	PR2	3.89	0.925	3.81	1.026	0.085	0.747	0.233
	PR3	3.98	0.909	3.83	1.013	0.150	1.346	0.519
	PR4	3.96	0.827	3.83	1.067	0.131	1.159	**
Behavioral Intention	BI1	3.79	0.845	3.84	0.946	−0.051	−0.493	0.905
	BI2	3.51	0.893	3.74	0.955	−0.232	−2.174	0.899
	BI3	3.64	0.863	3.78	0.960	−0.140	−1.323	0.902
	BI4	3.74	0.851	3.79	0.908	−0.056	−0.556	0.954

Source: data adapted from authors (2023). Note: *** denotes significant at <0.001, ** at <0.01, and * at <0.05.

4.2. Confirmatory Factor Analysis (CFA)

A CFA was utilized in order to conduct tests on the measurement model. Within the scope of this investigation, the model was evaluated with regard to its internal consistency, convergent validity, and discriminant validity. The CFA was carried out by coupling all the constructs to their respective covariances. Before testing could begin, every construct had to have its own set of manifest variables. The goodness of fit (GOF) of the entire connection might be developed based on the covariances among the errors that occurred within the same constructs. This analysis can be elaborated as follows.

4.2.1. The Goodness of Fit (GOF)

In Table 3, we see the GOF measurements and thresholds. All the metrics met or exceeded the established standards; hence, the outcomes were acceptable. The values for the comparative fit index (CFI; 0.913), incremental fit index (IFI; 0.0914), TLI Tucker–Lewis index (TLI; 0.900), and root mean square error of approximation (RMSEA; 0.071) all exceeded their predetermined thresholds for goodness of fit. In terms of the GOF condition, the stated thresholds were a CMIN/df less than 3.00, CFI larger than 0.900, IFI greater than 0.900, TLI greater than 0.900, and RMSEA less than 0.100.

Table 3. The goodness of fit of measurement model.

Fit Indices	Value	Threshold	Assessment
p-value	≤0.001		Acceptable for complex model
CMIN/*df*	2.655	<3.00	Pass
CFI	0.913	>0.900	Pass
IFI	0.914	>0.900	Pass
TLI	0.900	>0.900	Pass
RMSEA.	0.071	<0.100	Pass

Source: data adapted from authors (2023). Note: CMIN/*df* = Chi-square/degree of freedom, CFI = comparative fit index, IFI = incremental fit index, TLI = Tucker–Lewis index, and RMSEA = root mean square error approximation.

4.2.2. Convergent Validity

A comparison of the model's outcomes with the predetermined thresholds for the fit index was used to analyze the convergent validity. Cronbach's alphas, average variance extracted (AVE), and composite reliability (CR) were utilized to analyze the measures' degrees of consistency against the recommended thresholds for an AVE and CR of 0.05 and 0.70, respectively. Accordingly, the thresholds for the convergent validity measurements and the derived indicators are listed as follows.

Table 4 shows that, when the calculated measures were compared to the thresholds, the values for the performance expectancy, effort expectancy, social influence, facilitating condition, hedonic motivation, price value, habit, trust, privacy, and behavioral intention all passed the convergent validity criteria. In terms of the constructs, each and every indicator reached a level of statistical significance of <0.001, and all the AVEs were greater than the thresholds (AVE > 0.50). On the other hand, the Cronbach's alphas and CR values were all higher than 0.7, which indicated that all the indicators included in this measurement model met the criteria for the convergent validity.

Table 4. Convergent validity.

Construct	Indicator	Loading	*p*-Value	Cronbach's Alphas (Threshold = 0.70)	AVE (Threshold = 0.50)	CR (Threshold = 0.70)
Performance Expectancy	PE2	0.764	***	0.862	0.685	0.867
	PE3	0.878	***			
	PE4	0.873	***			
Effort Expectancy	EE1	0.77	***	0.907	0.711	0.907
	EE2	0.825	***			
	EE3	0.902	***			
	EE4	0.869	***			
Social Influence	SI1	0.734	***	0.902	0.681	0.895
	SI2	0.842	***			
	SI3	0.878	***			
	SI4	0.839	***			

Table 4. *Cont.*

Construct	Indicator	Loading	*p*-Value	Cronbach's Alphas (Threshold = 0.70)	AVE (Threshold = 0.50)	CR (Threshold = 0.70)
Facilitating Condition	FC1	0.813	***	0.894	0.695	0.901
	FC2	0.768	***			
	FC3	0.863	***			
	FC4	0.885	***			
Hedonic Motivation	HM1	0.715	***	0.868	0.633	0.873
	HM2	0.869	***			
	HM3	0.828	***			
	HM4	0.764	***			
Price Value	PV1	0.877	***	0.933	0.782	0.935
	PV2	0.914	***			
	PV3	0.905	***			
	PV4	0.839	***			
Habit	HB1	0.822	***	0.897	0.749	0.899
	HB2	0.876	***			
	HB3	0.896	***			
Trust	TR1	0.892	***	0.94	0.799	0.941
	TR2	0.837	***			
	TR3	0.921	***			
	TR4	0.922	***			
Privacy	PR1	0.845	***	0.943	0.807	0.943
	PR2	0.932	***			
	PR3	0.922	***			
	PR4	0.891	***			
Behavioral Intention	BI1	0.893	***	0.94	0.801	0.942
	BI2	0.855	***			
	BI3	0.918	***			
	BI4	0.913	***			

Source: data adapted from authors (2023). Note: AVE = average variance extracted, CR = composite validity, *** significant <0.001.

4.2.3. Discriminant Validity

The discriminant validity of a test or measurement is defined as the degree to which it varies from another test or measurement with the same underlying idea. To evaluate this component, the Fornell and Larcker criteria were utilized to compare the square root AVEs (located on the diagonal) and the correlations of the various matrices. Table 5 shows that the square root of each bolded AVE was bigger than the off-diagonal correlation coefficients. This implies that all of the variable compositions may theoretically measure the unique constructs, and the outcome of this was satisfactory. Furthermore, each AVE's square root was greater than the off-diagonal correlation coefficients.

Table 5. Discriminant validity.

	Fornell and Larcker Criterion									
	BI	**PR**	**TR**	**HB**	**PV**	**HM**	**FC**	**SI**	**EE**	**PE**
BI	0.895									
PR	0.685	0.898								
TR	0.644	0.818	0.894							
HB	0.67	0.359	0.487	0.865						
PV	0.667	0.789	0.804	0.389	0.884					
HM	0.733	0.605	0.633	0.66	0.658	0.796				
FC	0.683	0.675	0.706	0.451	0.746	0.654	0.833			
SI	0.718	0.443	0.481	0.718	0.476	0.712	0.535	0.825		
EE	0.638	0.661	0.697	0.45	0.722	0.613	0.713	0.574	0.843	
PE	0.649	0.438	0.513	0.666	0.478	0.617	0.607	0.696	0.633	0.828
	HTMT Ratio Approach									
	BI	**PR**	**TR**	**HB**	**PV**	**HM**	**FC**	**SI**	**EE**	**PE**
BI	-	-	-	-	-	-	-	-	-	-
PR	0.685	-	-	-	-	-	-	-	-	-
TR	0.644	0.819	-	-	-	-	-	-	-	-
HB	0.617	0.359	0.487	-	-	-	-	-	-	-
PV	0.667	0.789	0.804	0.390	-	-	-	-	-	-
HM	0.734	0.606	0.634	0.661	0.659	-	-	-	-	-
FC	0.683	0.675	0.707	0.451	0.746	0.739	-	-	-	-
SI	0.708	0.437	0.474	0.707	0.469	0.702	0.528	-	-	-
EE	0.638	0.662	0.698	0.451	0.722	0.613	0.713	0.566	-	-
PE	0.650	0.438	0.513	0.667	0.478	0.618	0.607	0.687	0.634	-

Source: data adapted from authors (2023). Note: BI = Behavioral Intention, PR = Privacy, TR = Trust, HB = Habit, PV = Price Value, HM = Hedonic Motivation, FC = Facilitating Condition, SI = Social Influence, EE = Effort Expectancy, and PE = Performance Expectancy.

In addition, Henseler et al. (2015) used the heterotrait–monotrait (HTMT) ratio technique to examine discriminant validity [124]. This was performed because the Fornell and Larcker (1981) criterion was criticized for its lack of reliability in addressing the distinctiveness between latent variables [124]. Specifically, this problem was addressed by Henseler et al. (2015). HTMT values greater than 0.90 suggest the presence of discriminant validity between the associated latent variables. According to Table 5, each value on the HTMT is lower than 0.90, indicating that it satisfies the criteria for the discriminant validity.

4.3. Structural Model

We come to demonstrate the SEM analysis after achieving the prerequisite for the reliability and validity. According to Table 6, as Hu and Bentler (2009) suggested, the goodness of fit criteria mostly supported this structural model [125]. According to Table 7, the structural model's test results supported H3, H4, and H7 to H9 at a significant level of 0.05 or less. This showed that the correlations between the constructs were statistically significant. The analysis was based on the following concepts: performance expectancy (PE), effort expectancy (EE), social influence (SI), facilitating condition (FC), hedonic motivation (HM), price value (PV), habit (H), trust (TR), privacy (PR), and behavioral intention (BI).

Table 6. The goodness of fit of structural model.

Fit Indices	Value	Threshold	Assessment
p-value	≤0.001		Acceptable for complex model
CMIN/df	2.470	<3.00	Pass
CFI	0.925	>0.900	Pass
IFI	0.926	>0.900	Pass
TLI	0.915	>0.900	Pass
RMSE	0.067	<0.100	Pass

Source: data adapted from authors (2023). Note: CMIN/*df* = Chi-square/degree of freedom, CFI = comparative fit index, IFI = incremental fit index, TLI = Tucker–Lewis index, RMSEA = root mean square error approximation.

Table 7. Hypothesis test results from.

Hypothesis	Endogenous Variable	Exogenous Variable	Standardized Estimate	*p*-Value	Result
H1	Performance Expectancy	Behavioral Intention	0.054	0.403	Rejected
H2	Effort Expectancy	Behavioral Intention	−0.012	0.857	Rejected
H3	Social Influence	Behavioral Intention	0.222	***	Supported
H4	Facilitating Condition	Behavioral Intention	0.143	0.030 **	Supported
H5	Hedonic Motivation	Behavioral Intention	0.085	0.227	Rejected
H6	Price Value	Behavioral Intention	0.119	0.126	Rejected
H7	Habit	Behavioral Intention	0.259	***	Supported
H8	Trust	Behavioral Intention	0.158	0.046 **	Supported
H9	Privacy	Behavioral Intention	0.365	***	Supported

Source: data adapted from authors (2023). Note: *** denotes significant at ≤0.001 and ** at ≤0.05.

The results rejected H1, which hypothesized that performance expectancy would positively influence the users' intentions to use the fruit and vegetable waste management platform. This result demonstrated an explicitly contradictory result with a standardized loading of 0.054 (p-value = 0.403).

H2 was rejected, which meant that effort expectancy had no effect on the users' intentions to use the fruit and vegetable waste management platform. With a standardized loading of −0.012 (p-value = 0.857), this result showed a conflicting outcome.

H3 was supported, which recommended that social influence would positively influence the users' intentions to use the fruit and vegetable waste management platform, with a standardized loading of 0.222 (p-value < 0.001). This study demonstrated that the inclination to use the platform was affected by social factors such as close friends, family, friends, and notable persons.

H4 was supported, which recommended that, with a standardized loading of 0.143 (p-value = 0.030 < 0.05), facilitating conditions would positively influence users' intentions to use the fruit and vegetable waste management platform. This result was consistent with the hypothesis that users' perceptions of convenience have a direct influence on their behavioral intentions to use technology. This indicates that consumers are motivated to use mobile shopping technologies when they have the necessary support from both the infrastructure and the technical side.

Moreover, the outcomes rejected H5, which stated that hedonic motivation does not influence the users' intentions to use the fruit and vegetable waste management platform, with a standardized loading of 0.085 (p-value = 0.227).

The outcomes also rejected H6, which asserted that price value would positively influence the users' intentions to use the fruit and vegetable waste management platform. With a standardization factor of 0.119 (p-value = 0.126), this result was contradictory.

H7 was supported, indicating that habit would positively influence the users' intentions to use the fruit and vegetable waste management platform, with a standardized loading of 0.259 (p-value < 0.001). This study's findings recommended that the routine activities of users had an effect on their intentions to use the platform.

H8 was supported, which hypothesized that trust would positively influence the users' intentions to use the fruit and vegetable waste management platform, given a standardized loading of 0.158 (p-value = 0.046 < 0.05). The results of this survey showed that the users of the platform were quite conscious of the trust that is provided by the platform.

H9 was supported, which recommended that privacy would positively influence the users' intentions to use the fruit and vegetable waste management platform, with a standardized loading of 0.365 (p-value < 0.001). This study demonstrated that the platform users had a high level of awareness regarding the safety of their personal data.

4.4. Multigroup Moderation Analysis

Measurement invariance (MI) is a method that utilizes indicators to determine a latent characteristic across all the respondents in Segments 1 and 2 [121]. The MI technique has three parts: configural invariance, metric invariance, and scalar invariance. The distinction between full and partial MI is based on the findings from the following investigation. When only the conditions for configural invariance and metric invariance are met, partial invariance can be considered to exist. Despite this, full measurement invariance is established after both partial MI and scalar invariance are taken into account [121].

According to Table 8, all the CFI, IFI, and TLI values for configural invariance, metric invariance, and scalar invariance were high enough (>0.0900) to be considered an accepted fit [126]. The findings demonstrated that the specified criteria were met by the remaining fit indices. The configuration invariance, metric invariance, and scalar invariance were acceptable. Thus, the full MI was constructed.

Table 8. Measurement invariance.

Fit Indices	Configural Invariance	Metric Invariance	Scalar Invariance	Threshold
p-value	≤0.001	≤0.001	≤0.001	
CFI	0.923	0.917	0.906	>0.900
IFI	0.924	0.918	0.907	>0.900
TLI	0.912	0.917	0.906	>0.900
RMSEA	0.049	0.051	0.053	<0.10
	Acceptable	Acceptable	Acceptable	

Source: data adapted from authors (2023). Note: CFI = comparative fit index, IFI = incremental fit index, TLI = Tucker–Lewis index, RMSEA = root mean square error approximation.

Table 9 displays the GOF measures and thresholds for the multigroup structural model. All the results were acceptable because they were above the minimum requirements that were specified. The comparative fit index (CFI; 0.923), incremental fit index (IFI; 0.924), Tucker–Lewis index (TLI; 0.912), and root mean square error of approximation (RMSEA; 0.049) passed the thresholds.

Table 9. The goodness of fit of the multigroup structural model.

Fit Indices	Value	Threshold	Assessment
p-value	≤0.001		Acceptable for complex model
CMIN/*df*	1.785	<3.00	Pass
CFI	0.923	>0.900	Pass
IFI	0.924	>0.900	Pass
TLI	0.912	>0.900	Pass
RMSE	0.049	<0.100	Pass

Source: data adapted from authors (2023). Note: CMIN/*df* = Chi-square/degree of freedom, CFI = comparative fit index, IFI = incremental fit index, TLI = Tucker–Lewis index, RMSEA = root mean square error approximation.

After the MGA was run, the hypothesis test results for Segments 1 (I) and Segment 2 (II) could be analyzed separately. According to Table 10 and Figure 3, H1 (I) and (II), H2 (I) and (II), H3 (II), H4 (I) and (II), H5 (I) and (II), H6 (II), H8 (II), and H9 (I) were not statistically significant, due to the *p*-values of <0.05, <0.01, or <0.001. This insignificant relationship implies that, when separating the data into two segments, performance expectation, effort expectance, facilitating condition, and hedonic motivation did not influence the behavioral intentions to use the platform. This result occurred in both segments. However, H3 (I), H6 (I), H7 (I) and (II), H8 (I), and H9 (II) were accepted because their *p*-values were less than the given level of significance. Additionally, the critical ratio difference revealed a significant path difference only for H7 (critical ratio = $|-2.011| > |1.96|$), indicating that the loadings of Segments 1 and 2 were statistically different. These results are discussed in more detail in the next section.

Table 10. Test result of loading differences.

Hypothesis	Relationship	Segment 1			Segment 2			Critical Ratio Difference	Threshold
		Std. Est.	*p*-Value	Result	Std. Est.	*p*-Value	Result		
H1	PE → BI	0.153	0.288	Rejected	0.016	0.852	Rejected	−0.939	|1.96|
H2	EE → BI	−0.075	0.464	Rejected	0.066	0.474	Rejected	1.024	|1.96|
H3	SI → BI	0.251	0.042 *	Supported	0.159	0.052	Rejected	−0.34	|1.96|
H4	FC → BI	0.145	0.139	Rejected	0.141	0.134	Rejected	0.172	|1.96|
H5	HM → BI	0.041	0.681	Rejected	0.128	0.213	Rejected	0.347	|1.96|
H6	PV → BI	0.401	0.005 **	Supported	0.022	0.827	Rejected	−2.011 *	|1.96|
H7	HB → BI	0.299	0.020 *	Supported	0.182	0.029 *	Supported	−0.348	|1.96|
H8	TR → BI	0.304	0.032 *	Supported	0.059	0.575	Rejected	1.224	|1.96|
H9	PR → BI	0.246	0.063	Rejected	0.394	***	Supported	1.528	|1.96|

Source: data adapted from authors (2023). Note: *** denotes significant at ≤0.001, ** at ≤0.01, and * at ≤0.05. BI = Behavioral Intention, PR = Privacy, TR = Trust, HB = Habit, PV = Price Value, HM = Hedonic Motivation, FC = Facilitating Condition, SI = Social Influence, EE = Effort Expectancy, and PE = Performance Expectancy.

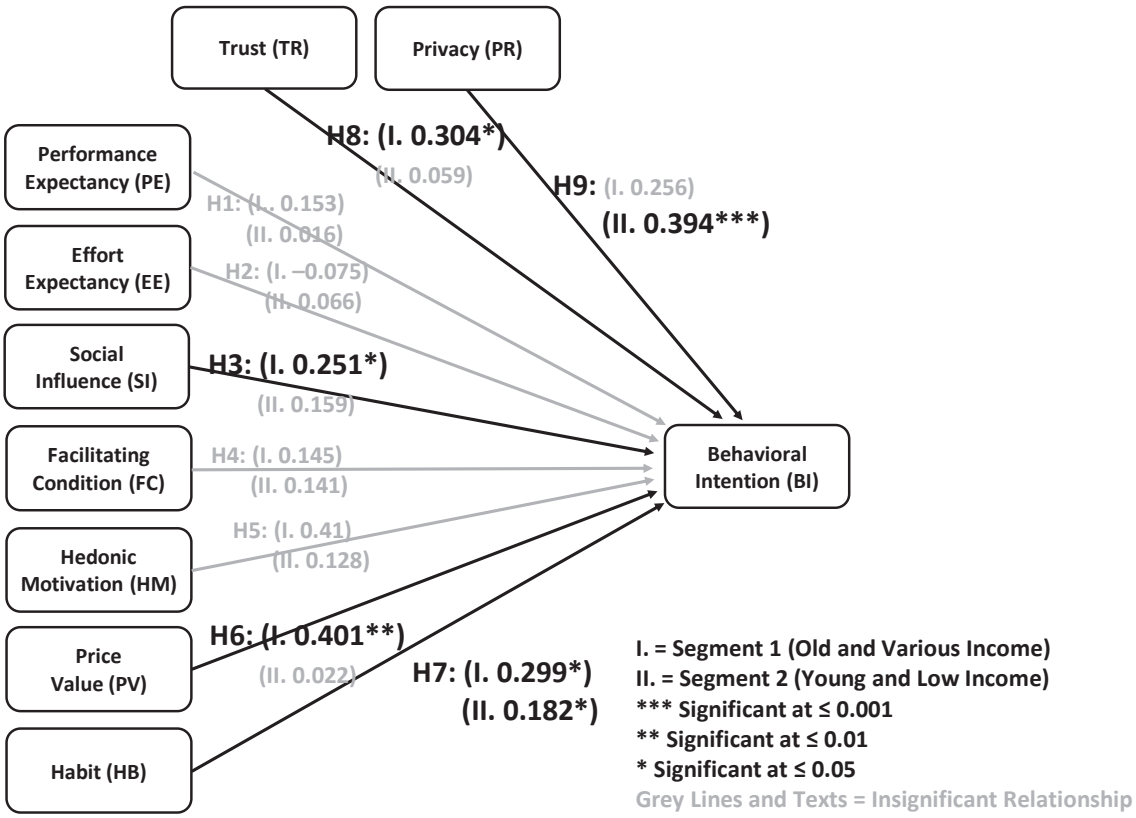

Figure 3. Multigroup structural model. Source: Figure created by authors (2023).

5. Discussion

Based on the statistical results from the SEM and MGA (Segment 1 vs. Segment 2) analyses, we can discuss the findings from the H1 to H9 tests as follows.

Hypothesis H1. *Performance expectancy positively influences users' behavioral intentions to use the circular agricultural waste management platform.*

The findings of the study revealed that the respondents' performance expectancy had no beneficial effect on their use of the platform (p-value = 0.403 > 0.05). This was because "performance expectancy" refers to providing benefits and possibilities that are valuable for users in agricultural waste management, yet most of them did not express a high level of perception of this performance expectancy. Additionally, they may have felt that adopting a platform did not increase their productivity. Consequently, the majority of the respondents did not place a great deal of importance on performance expectancy.

The study was not comparable to earlier research by Yeo et al. (2017) [41], who found that performance expectancy was the extent to which users' propensities to utilize online food-ordering systems were significantly influenced by the usability of the system.

Moreover, based on the results from MGA, the moderation effect of the demographic segments did not affect this relationship. The results revealed that neither Segment 1 (older and various incomes) nor Segment 2 (young and low incomes) moderated the relationship between performance expectancy and behavioral intentions, given the insignificant *p*-values of Segment 1 (*p*-value = 0.288 > 0.05) and Segment 2 (*p*-value = 0.852 > 0.05). In this respect, performance expectancy did not influence the intentions to use an agricultural waste management platform for the users of all ages and income statuses. This was contradictory to the previous findings of Yusof et al. (2019) [98], Bilgihan (2016) [106], and Naruetharadhol et al. (2022) [109].

Hypothesis H2. *Effort expectancy positively influences users' behavioral intentions to use a circular agricultural waste management platform.*

In line with findings from earlier research, this study's findings (*p*-value = 0.857 > 0.05) revealed that the level of expected effort did not have any impact on the platform utilization [9,44], because most of the respondents were unfamiliar with the technology. As a result, they may have found it difficult to utilize this platform, the interactions between the users and this platform may have been confusing, and the functioning was still problematic. Therefore, the respondents were not concerned about the effort expectancy of using the platform.

The MGA result revealed that the moderation effect of the demographic segments did not affect this relationship either. The findings indicated that the association between effort expectancy and behavioral intentions was not moderated by either Segment 1, which comprised individuals with diverse incomes and advanced ages, or Segment 2, which consisted of young individuals with low incomes. This was evidenced by the non-significant *p*-values of Segment 1 (*p*-value = 0.464 > 0.05) and Segment 2 (*p*-value = 0.474 > 0.05). It can be observed that the intention to utilize an agricultural waste management platform was not affected by the level of effort expectancy among the users in both segments. This assertion is in contrast with the earlier technology adoption research conducted by Yusof et al. (2019) [98] and Naruetharadhol et al. (2022) [109].

Hypothesis H3. *Social influences positively impact behavioral intentions to use the agricultural waste management platform.*

This gives credibility to the positive benefits that social influence has on behavioral intention (*p*-value < 0.001), which have been found in earlier research [21]. The result of this research implied that the information obtained from others around someone adds to their social influence. This influenced the inclination to use the platform more often, because the respondents may have been interested in a platform for disposing of agricultural waste management. This would also be a way for merchants and farmers to make more money and is expected to have a big impact on society.

Based on the MGA result, social influence (H3) appeared to affect the behavioral intentions in Segment 1 (loading = 0.251, *p*-value = 0.042 < 0.05), but was irrelevant for Segment 2 (loading = 0.159, *p*-value = 0.052). This result implies that the users in Segment 1 (older and various incomes) needed to have influences from their peers or third parties prior to actual use, while the users in Segment 2 (young and low incomes) did not need this. Because the older users in Segment 1 were not technology-oriented [98], social influence would play a critical role in attracting their intention.

Hypothesis H4. *Facilitating conditions positively influence users' behavioral intentions to use an agricultural waste management platform.*

This conclusion from the structural model revealed that previous research on the acceptability of the platform's facilitating conditions had a major influence on the users' intentions, given the *p*-value of 0.03 (<0.05 level of significance). This finding supports Lu et al. (2005) [52] and Naruetharadhol et al. (2023) [9]. However, when strictly analyzing this relationship using a *p*-value of 0.01, this hypothesis can be rejected and would lead to unsupported results for MGA.

However, the result of MGA revealed that the facilitating condition did not affect the userss behavioral intentions in both Segments 1 and 2, given the *p*-values of 0.139 (>0.05) and 0.134 (>0.05), respectively. Most of the respondents believed the platform having customer services to help customers and provide information was not necessary. They also expected that the platform would not be compatible with the other technologies that they used. Hence, the MGA results contradicted Lu et al. (2005) [52] and Naruetharadhol et al. (2023) [9].

Hypothesis H5. *Hedonic motivation positively influences users' behavioral intentions to use an agricultural waste management platform.*

The research results showed that the hedonic motivation of the respondents did not impact their intentions to use the platform (*p*-value = 0.227 > 0.05), which differed from previous studies by Venkatesh et al. (2012) [36] and Naruetharadhol et al. (2022) [109], wherein hedonic motivation was shown to be a crucial component of behavioral intentions to adopt mobile internet in a consumer setting.

The MGA result also revealed that demographic segments did not moderate this structural relationship. This was because most of the respondents assumed that the platform was not focused on entertainment or enjoyment enough to affect the users' intentions. According to the findings, the demographic segments did not have an impact on the relationship between hedonic motivation and behavioral intentions. Specifically, Segment 1, which included individuals with varying income levels and an older age (*p*-value = 0.681 > 0.05), and Segment 2, which was made up of younger individuals with lower incomes (*p*-value = 0.231 > 0.05), did not affect this association. These MGA results are unsupported by Venkatesh et al. (2012) [36] and Naruetharadhol et al. (2022) [109].

Hypothesis H6. *Price value positively influences users' behavioral intentions to use an agricultural waste management platform.*

The findings of the study revealed that respondents' price values had no effect on their use of the platform (*p*-value = 0.126 > 0.05). Users may have been uninterested in the platform because they perceived it to be a relatively new platform (farmers and sellers), making it difficult to generate money. Some responders may also have been concerned about the expenses associated with utilizing this platform. For this reason, this hypothesis had no significant effect compared to previous research [40].

When using the MGA approach, nevertheless, price value (H6) highly influenced the behavioral intentions in Segment 1 (loading = 0.401, *p*-value = 0.005 < 0.001), but not in Segment 2 (loading = 0.022, *p*-value = 0.827). Table 10 also indicates a critical ratio difference of $|-2.011|$, which is more than the threshold of $|1.96|$, confirming that the loading of Segment 1 was statistically greater than that of Segment 2. This reveals that the users in Segment 1 tended to pay attention to price value because they expected the platform to be reasonably priced to attract their behavioral intention [59]. On the other hand, the users in Segment 2 were not more likely to be concerned about price value.

Hypothesis H7. *Habit positively influences users' behavioral intentions to use an agricultural waste management platform.*

The findings of the SEM were consistent with previous studies by Venkatesh et al. (2012) [36], which discovered that habit affected behavioral intentions (*p*-value < 0.001).

This research identified that habit directly affected the behavioral intentions toward using the platform. Due to the platform information given to these potential users before each survey, most respondents are expected to use this platform and the platform is expected become a habituation for users to sell agricultural waste.

Furthermore, when considering the MGA result, habit affected the behavioral intentions in both Segment 1 (loading = 0.299, p-value = 0.020 < 0.05) and Segment 2 (loading = 0.182, p-value = 0.029 < 0.05). The impact was slightly higher in Segment 1 than in Segment 2. This shows that the users in both segments expected to use the platform often or as a part of their regular activities. This platform would be their first choice when it comes to working.

Hypothesis H8. *Trust positively influences users' behavioral intentions to use an agricultural waste management platform.*

The SEM result suggested that trust robustly enhanced the behavioral intentions to use a platform for agricultural waste management (p-value = 0.046 < 0.05). According to the survey results, both the farmers and sellers felt that the usage of this platform was dependable, that it maintained its promises to its users, and that the material on this platform was reputable. This is consistent with the earlier literature, which has demonstrated that trust has a noticeable effect on behavioral intentions [37].

The MGA result suggested that trust influenced the behavioral intentions in Segment 1 (loading = 0.304, p-value = 0.032 < 0.05), but not in Segment 2 (loading = 0.059, p-value = 0.575). The test result demonstrated that trust may have better influenced the users in Segment 1 (older users) than in Segment 2 (younger users).

Hypothesis H9. *Privacy positively influences users' behavioral intentions to use an agricultural waste management platform.*

The results indicated that privacy had a great impact on the users' behavioral intentions to use the platform (p-value < 0.001), comparable to prior research from Yuduang et al. (2022) [79]. According to the survey findings, the respondents believed that the privacy of this platform's users was protected and that the platform would keep the information of the participants safe. These findings are encouraging, because respondents' perceptions of privacy are a significant factor in their decision to use a platform.

For the MGA result, privacy also did not impact the behavioral intentions in Segment 1 (loading = 0.256, p-value = 0.063), but strongly affected them in Segment 2 (loading = 0.394, p-value = ***). Because the respondents in Segment 1 were mostly from Generation X and baby boomers, they may not place as much emphasis on data privacy in their use of online platforms as the respondents in Segment 2 do, which was made up of people in the age range with unlimited internet access, combined with the development of technologies and social media.

6. Research Implications

Primary stakeholders, such as farmers and retailers, were presented with the research findings. An agricultural platform is an application that acts as the intermediary that helps two parties (farmer/seller and organization) to make a deal through this platform. Thus, the users, involving fruit and vegetable farmers and sellers, can earn more income by selling agricultural and food leftovers through this application. The developers should create the best quality platform features that are user-friendly and facilitating, adaptable to user habits, trustworthy, and privacy-concerned. Additionally, this platform should involve marketing features that enhance its social influence, such as referencing and testimonials, because these can impact user intentions to use the platform. This research has clear benefits for marketing and development teams, who would benefit from having access to and knowledge of user behavior intentions and the user types in specialized markets for selling and buying food waste as a result of this study.

In addition, marketers should utilize different strategies for attracting users in different demographic segments: (1) older users with various income ranges, and (2) younger users with low incomes. Marketers may create advertisements to attract older people with various income ranges to use the platform, focusing on social influence by utilizing peers or celebrities as influencers. More than that, the developer should allow older people with various incomes to set their selling prices, attracting more utilization. The developer should create a platform with features similar to other everyday-use platforms in order to create familiarity with using the platform for both Segments 1 and 2. The developer should establish reliable content, because older people pay attention to reliability. Concerning younger users, the team developer should be concerned about privacy and security to attract their utilization.

7. Research Limitations and Future Research

This study contributes significantly to academic and business processes. However, there are still certain limits to this research. The questionnaire was only administered to residents in the northeast of Thailand; hence, the results may not be representative of sample groups in other regions of the country. Data may be collected from other regions of Thailand to ascertain and compare them with the present study's results.

Future research may adapt the variables of the UTAUT2 by adding more variables to this structural model to understand users' behavior intentions. These additional variables may include environmental awareness, perceived risk, personal innovativeness in IT, and resistance to change. In addition, it may shift the moderator of the user segment to farmers and sellers, in order to analyze the specific behaviors of these users. Finally, after the actual platform is launched, it is possible to utilize different research designs, for instance, exploring the actual use behavior through a quasi-experimental design with regard to the platform's features, user interface (UI), and user experience (UX).

8. Conclusions

The purpose of this study was to identify the different demographic segments of users, as well as the significant factors that influence the behavioral intentions to utilize a circular-economy-based digital platform for fruit and vegetable waste management, based on the Unified Theory of the Adoption and Utilization of Technology 2 (UTAUT2). The study found two user segments: (1) older and various-income users, and (2) young and low-income users. Our data suggest that social influence, price value, habit, trust, and privacy are essential elements impacting these user behavioral intentions when using a fruit and vegetable waste management platform. Contrary to the UTAUT2, there was no substantial relationship between performance expectancy, effort expectancy, facilitating condition, hedonic incentive, and behavioral intentions towards adopting the technology. The results show that the attitudes and behaviors of surrounding society influence consumers' adoption of waste management platforms, especially for older and various-income users. When motivated by a group of people who influence beliefs or feelings, such as a colleague or a person who has the same or a similar occupation, the more probable it is that the Segment 1 users would be driven, convinced, and followed by them. Additionally, the results revealed that price value tended to influence the users in Segment 1, but did not affect those in Segment 2. Moreover, the data revealed that consumers wanted to engage in online behavior owing to habit in both segments, as familiarity influenced the propensity to use the platform. Its intended use is equally vital to directing its usage behavior. Therefore, the platform developers should promote the benefits of its use and encourage continuing use by, for example, customer service, a user-friendly and straightforward platform, or more services. Furthermore, the results demonstrated that users have online behavioral intentions due to trust. Explicitly, trust increased interest in using the platform for Segment 1 users. This might establish credibility and influence behavioral intentions. Hence, the platform developers should provide clear information and contact options to increase the platform's credibility. Additionally, the results demonstrated that users have online

behavioral intentions due to privacy, especially the younger users in Segment 2; thus, the platform developers should create the most secure platform possible to safely store user information without publishing it. Therefore, this study suggests that the platform developers should promote users' behavioral intentions differently through specific target groups for fruit and vegetable sellers and farmers from various age and income groups.

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Appendix A

Appendix A.1. Questionnaire—Demographic Questions

(1) Gender: a. Male b. Female
(2) Age: a. Gen Z (20–27 years old) b. Gen Y (28–41 years old) c. Gen X (42–56 years old) d. Baby Boomer (57 years old and above)
(3) Income: a. Less than BHT 15,000. b. BHT 15,000–20,000. c. BHT 25,001–30,000. d. More than BHT 30,000.

Table A1. Answers in sub-questions are on a 1 to 5 Likert scale; 1 as strongly disagree and 5 as strongly agree.

Constructs	Items	Measurement	Reference
Performance Expectancy (PE)	PE1	I expect that using this platform will increase my chances of success at work, which is important to me.	[36]
	PE2	I expect using this platform will help me accomplish tasks more quickly.	[36]
	PE3	I expect using this platform will increase my productivity.	[36]
Effort Expectancy (EE)	EE1	I expect learning how to use this platform will be easy.	[36]
	EE2	I expect that my interaction with this platform will be clear and understandable.	[36]
	EE3	I expect this platform to be easy to use.	[36]
	EE4	I expect it will be easy for me to become skillful at using this platform.	[36]
Social Influence (SI)	SI1	People who matter to me suggest that I should use this platform.	[36]
	SI2	People who influence my behavior think that I should use this platform.	[36]
	SI3	People whom I respect desire that I employ this platform in agriculture production.	[36]
	SI4	People who use this platform have more prestige in my society.	[36]
Facilitating Condition (FC)	FC1	I expect to have the resources necessary to use this platform.	[36]
	FC2	I expect to have the knowledge necessary to use this platform.	[36]
	FC3	I expect that this platform will be compatible with other technologies I use.	[36]
	FC4	I expect that I can get help from others when I have difficulties using this platform.	[36]
Hedonic Motivation (HM)	HM1	I expect that using this platform is interesting.	[36]
	HM2	I expect that using this platform is enjoyable.	[36]
	HM3	I expect that using this platform is entertaining.	[36]
	HM4	I expect that using this platform is pleasurable.	[21]

Table A1. *Cont.*

Constructs	Items	Measurement	Reference
Price Value (PV)	PV1	I expect that this platform will be reasonably priced.	[36]
	PV2	I expect that this platform is good value for the money.	[36]
	PV3	I expect that at the current price, this platform provides good value.	[36]
	PV4	I expect this platform fee does not significantly affect my monthly bill for services.	[36]
Habit (HB)	HB1	I expect that using this platform has become a habit for me.	[127]
	HB2	I am addicted to using this platform.	[21]
	HB3	I expect using this platform will be a regular activity for me.	[127]
Trust (TR)	TR1	I believe that using this platform is trustworthy.	[36]
	TR2	I believe that this platform can fulfill its task.	[36]
	TR3	I believe that this platform keeps its promises to its users.	[36]
	TR4	I believe that the content of this platform is reliable.	[21]
Privacy (PR)	PR1	I believe that the privacy of users of this platform is protected.	[21]
	PR2	I believe that personal information stored in this platform system is secure.	[21]
	PR3	I believe that this platform keeps participants' information secure.	[21]
	PR4	I believe this platform does not use GPS or track mobile phone locations after use.	[21]
Behavioral Intention (BI)	BI1	I am interested and expect to use this platform in the future.	[36]
	BI2	I will always try to use this platform in daily life.	[36]
	BI3	I plan to use this platform in the future.	[36]
	BI4	I predict I will use this platform in the future.	[17]

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Research on Blockchain-Based Cereal and Oil Video Surveillance Abnormal Data Storage

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Abstract: Cereal and oil video surveillance data play a vital role in food traceability, which not only helps to ensure the quality and safety of food, but also helps to improve the efficiency and transparency of the supply chain. Traditional video surveillance systems mainly adopt a centralized storage mode, which is characterized by the deployment of multiple monitoring nodes and a large amount of data storage. It is difficult to guarantee the data security, and there is an urgent need for a solution that can achieve the safe and efficient storage of cereal and oil video surveillance data. This study proposes a blockchain-based abnormal data storage model for cereal and oil video surveillance. The model introduces a deep learning algorithm to process the cereal and oil video surveillance data, obtaining images with abnormal behavior from the monitoring data. The data are stored on a blockchain after hash operation, and InterPlanetary File System (IPFS) is used as a secondary database to store video data and alleviate the storage pressure on the blockchain. The experimental results show that the model achieves the safe and efficient storage of cereal and oil video surveillance data, providing strong support for the sustainable development of the cereal and oil industry.

Keywords: blockchain; cereal and oil; storage; traceability; deep learning; video surveillance

1. Introduction

Cereal and oil are necessities of human life and, therefore, it is important to ensure their quality and safety [1]. The large production scale of cereal and oil and their extended temporal and spatial span from cultivation to sale make it difficult to implement effective regulations [2]. Cereal and oil reserves are a key link in the supply chain, and the implementation of a national cereal and oil security strategy requires that the granary be well-guarded and -managed [3]. At present, most grain depots are equipped with omnidirectional video surveillance cameras. Through the remote monitoring of key areas and key grain depots, the information of depots can be viewed at any time to achieve visual supervision.

The grain depot video monitoring system has many monitoring nodes, large video storage, and contains a large amount of detected information [4,5]. Currently, the main problems are as follows: First, most grain depots store data in a centralized way, which forms an information island between different departments and grain depots, making it difficult to effectively share information. Second, cases of tampering, falsification, deletion, etc. can occur during the process of entering the information into the local database, which makes it difficult to ensure the data's integrity. Third, the massive amount of video surveillance data occupies a large amount of storage space, which can very easily cause a wastage of

resources [6,7]. Blockchain technology can effectively solve the aforementioned problems, and research on the storage of video data on a blockchain has become a current hot topic.

Blockchain is a new type of distributed database with the underlying use of hash encryption algorithms, consensus mechanisms, smart contracts, peer-to-peer networks and other core technologies. Consequently, the data uploaded to the blockchain have the characteristics of openness and transparency, tamper resistance, traceability, permanent preservation, etc. [8]. In recent years, many researchers have combined blockchain technology with the food industry [9–14]. The use of blockchain to store data can not only ensure data security, but also promote information interaction between nodes on the blockchain and solve the trust problem caused by centralization. However, the highly redundant storage mechanism of blockchain will cause problems such as a low throughput rate and difficulty in scaling [15–17], which will restrict its development. At present, researchers mainly study the storage scalability of blockchain from two aspects: on-chain capacity expansion [18–20] and off-chain capacity expansion [21–24]. It has been shown that the model incorporating the latter storage scheme enhances the scaling effect of the blockchain more than the former scheme.

Therefore, this paper proposes a blockchain-based cereal and oil video surveillance abnormal data storage model to ensure the security, traceability and anti-tamper robustness of video surveillance data storage. First, a dual storage model based on blockchain and InterPlanetary File System (IPFS) is designed to ensure the safe storage of data and relieve the storage pressure in the blockchain. Second, we study the target detection algorithm based on YOLOv7 [25], and design and implement the anomaly detection model for the video surveillance data of the grain depot. We extract and store the frames with abnormal behaviors in the video, and quickly obtain the video summary while reducing the data redundancy. Last, the FISCO BCOS [26] is deployed and relevant data are uploaded to the chain.

2. Materials and Methods

2.1. Blockchain

Blockchain is a chained data structure that sequentially combines data blocks in a chronological order. Each block is composed of a block header and a block body [27], as shown in Figure 1. Each block header contains the hash value of the previous block, and it is connected to the current block from the genesis block to form a chained data storage structure. The block body includes the number of transactions in the current block and all transaction records generated during the block creation process. These records undergo the Merkel tree hash process to generate a unique Merkel root and are stored in the block header, which ensures that each block is connected chronologically and the transaction data cannot be easily tampered with.

Blockchain is essentially a decentralized database. It is a new application model of computer technology such as distributed data storage, peer-to-peer transmission, consensus mechanism, encryption algorithm and so on. It can ensure the safe storage, transmission and sharing of data, and solve the problems of data silos and information barriers. Currently, there are three main types of blockchains: public, private and consortium blockchain [28]. Table 1 shows the differences between them. Among them, the consortium blockchain is widely used as it is more private and secure compared to the public blockchain, and data sharing is more efficient compared to the private blockchain [29]. In this study, FISCO BCOS consortium blockchain technology is used as the basis for model design and development.

2.2. IPFS

IPFS [30] is a new hypermedia transport protocol based on content addressing. It generates a corresponding hash fingerprint based on the file contents, which serves as a unique identifier for the file and provides the file storage location. The IPFS has the feature of automatic de-duplication, which considerably reduces the data storage cost. As the

IPFS network has servers over many geographic locations, the failure of some servers can be overcome using the backup files of other nodes and, therefore, permanent storage can be achieved.

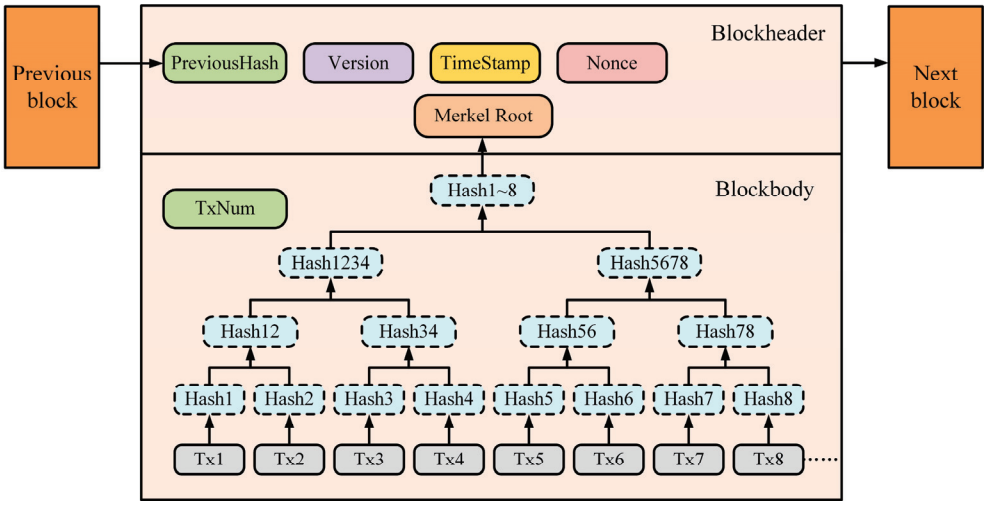

Figure 1. Structure of blocks.

Table 1. Classification of blockchain.

	Public Blockchain	Consortium Blockchain	Private Blockchain
Participant	Anyone	Alliance members	Inside individual organizations
Degree of centralization	Totally decentralized	Partially decentralized	Centralized
Performance	Slow	Fast	Fast
Transaction efficiency	Low	Higher	High
Consensus algorithm	POW, POS	Raft, PBFT	Paxos
Representative Examples	Bitcoin, Ethereum	Hyperledger Fabric, FISCO BCOS	ConsenSys

The files in IPFS use the form of objects to store data, where each object contains data items and link arrays, and the data size is no more than 256 KB [31]. If the data size exceeds 256 KB, it will be split into multiple objects, and subsequently, an upper-level object will be established to summarize the split objects and form a link, as shown in Figure 2.

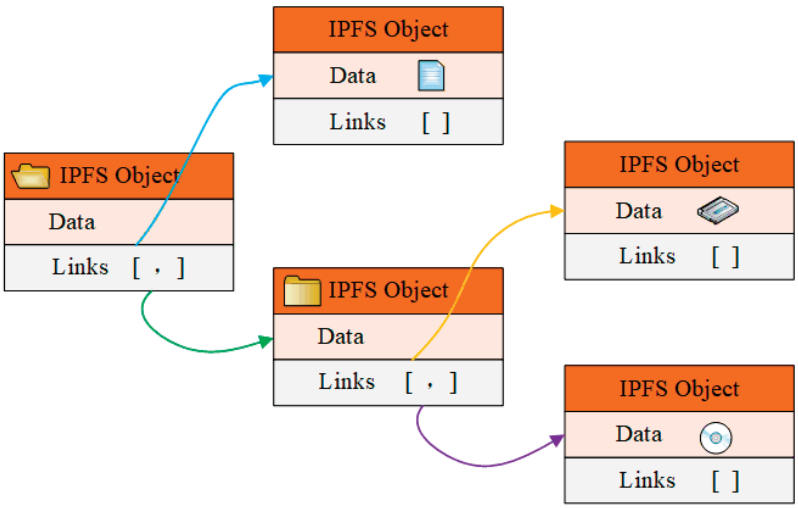

Figure 2. Storage structure of IPFS.

2.3. Inter-Frame Difference

Motion target detection is a very important research direction in video sequence analysis, and also plays an important role in intelligent video surveillance. Various researchers have conducted extensive research on motion target detection methods, and the commonly used methods include inter-frame difference, background subtraction and optical flow analysis [32–34]. Table 2 shows the differences between these algorithms.

Table 2. Comparison of methods for object detection.

Algorithm	Inter-Frame Difference	Background Subtraction	Optical Flow Analysis
Result of the operation	Outer contour of the moving target	Entire area of the movement target	Entire area of the movement target
Complexity of operation	Small	Determined by algorithm complexity	Big
Scope of use	Fixed camera	Fixed camera	Fixed or moving camera
Robustness	Good	Common	Bad

Inter-frame difference method selects two or more adjacent frames in a video image sequence and performs a difference operation to obtain the contour of a moving target. It achieves target detection by utilizing the results of the difference operation of pixels at the corresponding positions in different images [35]. Figure 3 shows the main workflow.

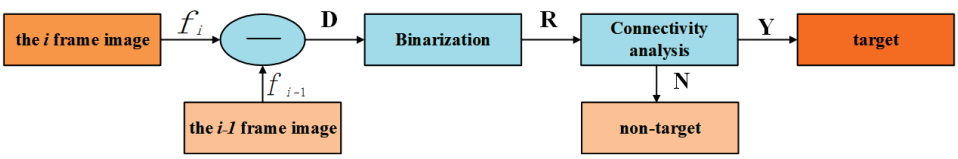

Figure 3. Flowchart of inter-frame difference.

In Figure 3, $f_i(x, y)$ and $f_{i-1}(x, y)$ are the two images collected at time i and time $i - 1$, respectively. The difference image can be obtained as the following:

$$D_i(x, y) = |f_i(x, y) - f_{i-1}(x, y)| \tag{1}$$

The binarization formula of D_i (x,y) is as follows:

$$R_i(x, y) = \begin{cases} 255, D_i(x, y) < Th \\ 0, D_i(x, y) \geq Th \end{cases} \tag{2}$$

where the points with a gray value of 255 and 0 are the foreground and background points, respectively, and Th is the threshold value. The inter-frame difference method is simple in calculation, fast in detection, has good adaptability to the dynamic environment, and detects distant moving targets effectively in real-time.

2.4. YOLOv7

YOLO is the most typical representation of one-stage target detection algorithms, which uses deep neural networks for object recognition and localization, and runs fast enough to be used in real-time systems [36]. YOLOv7 is the more advanced algorithm of the YOLO series, surpassing the previous YOLO versions in terms of accuracy and speed. The YOLOv7 algorithm framework is mainly composed of input, backbone and head [37], and its structure is shown in Figure 4. At the input, different preprocessing operations such as mosaic data enhancement, adaptive anchor frame computation and image scaling are performed on the input image. The backbone network consists of several CBS modules, ELAN modules and MP modules [38]. The CBS module consists of a Conv layer, BN layer and SiLU layer, and its purpose is to extract features from the image.

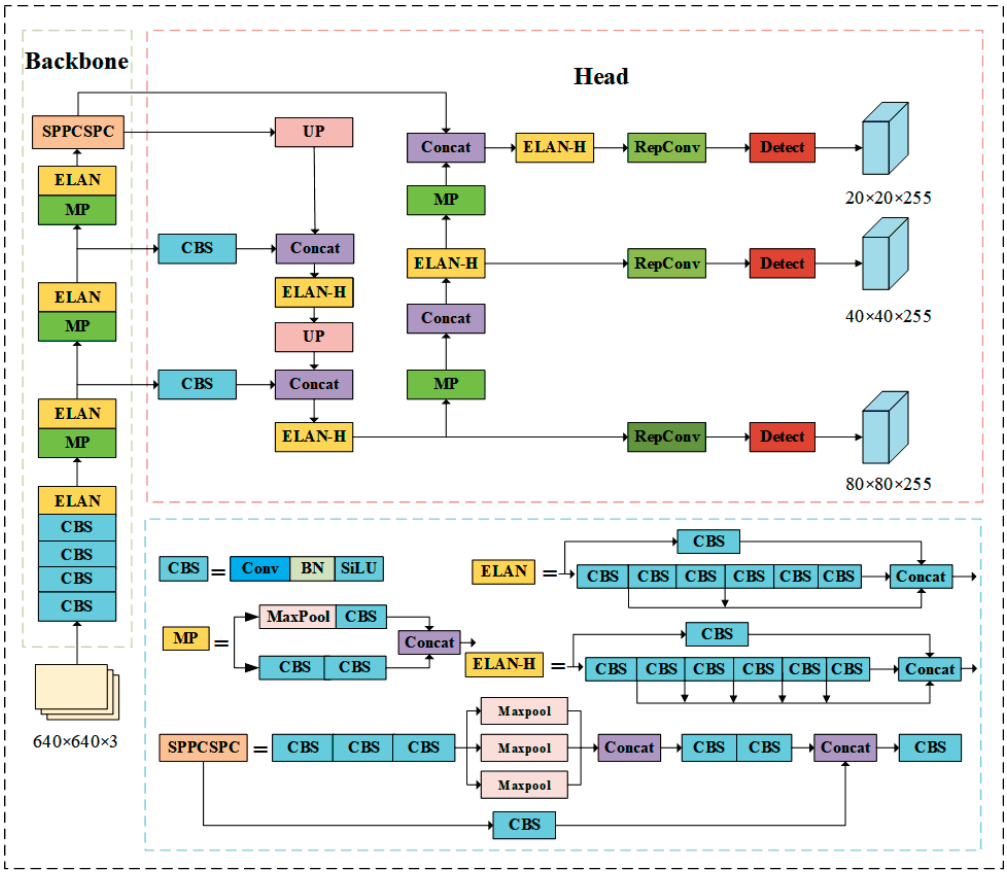

Figure 4. Overall network architecture of YOLOv7.

The ELAN module consists of several convolutional modules and can learn more features by controlling the shortest and longest gradient paths. The MP module has two branches that perform downsampling. It utilizes max pooling operations to reduce the spatial dimension of the feature maps, effectively capturing essential information at different scales, improving the feature extraction ability of the network. The SPPCSPC structure is composed of spatial pyramid pooling (SPP) and contextual spatial pyramid convolution (CSPC). It divides the features into two parts, one of which is processed by the conventional CBS module, the other part is processed by CBS and max pooling. Finally, these two parts are merged together, which can obtain a higher precision. The head network performs feature processing on the image output from the backbone network. It also uses a path aggregation pyramid network to pass the bottom level information to the higher level along a bottom-up path to efficiently fuse features at different levels [39]. Finally, the number of channels is adjusted by the RepConv structure for features of different scales, providing results of three different sizes.

2.5. Cereal and Oil Video Surveillance Abnormal Data Storage Scheme Based on Blockchain

In this section, a cereal and oil video monitoring abnormal data storage scheme based on blockchain is proposed. The scheme studies the granary video monitoring data in the cereal and oil supply chain. It includes the model construction, target detection model based on the improved YOLOv7, and the dual storage model based on blockchain and IPFS. Table 3 illustrates the symbols used in the scheme and their respective meanings.

Table 3. List of symbols and their meanings.

Symbol	Meaning of Symbol
GVSD	Grain video surveillance data
KF	KeyFrames of video
DU	Data user
SD	Supervision department
IPFS	InterPlanetary File System
CID	Unique identifier of the file returned by IPFS
ID	Identity of block
Hash(.)	Hash value of data
PK(.)	Public key
SK(.)	Private key
Sign_SK(.)	Sign with the private key

As Figure 5 shows, the model consists of five entities: the monitoring device, the data user, the FISCO BCOS, the IPFS and the regulator. The surveillance device consists of a wireless self-organizing local area network of camera sensor nodes, which transmit the video stream to the data client. The data user represents the person within each depot who manages the video surveillance data of the grain depot. The FISCO BCOS and IPFS provide a decentralized storage platform for data users. The supervision department has the right to view the video monitoring data of each library point in the case of emergencies.

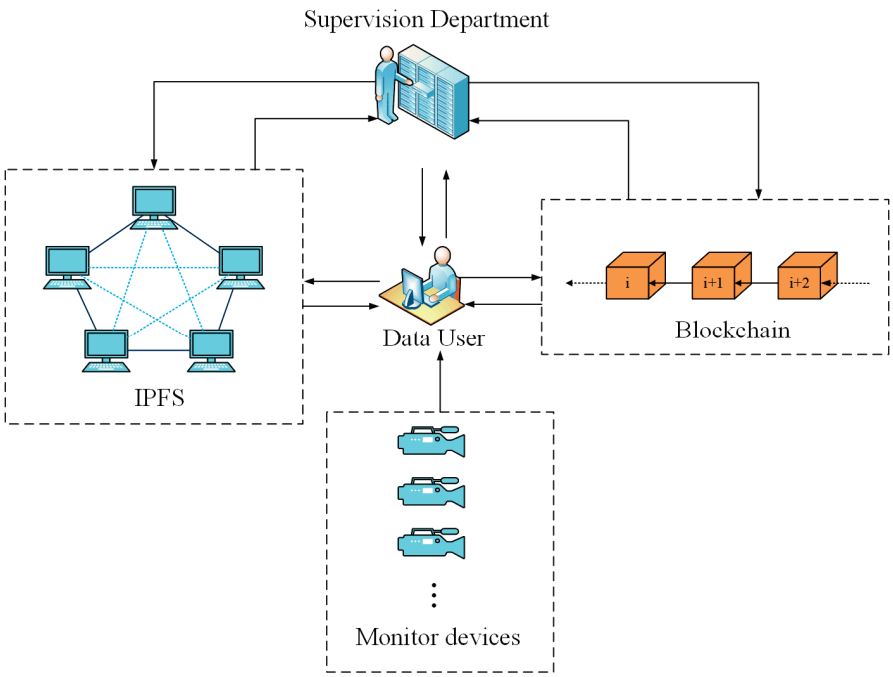

Figure 5. Model structure.

There are a variety of abnormal behaviors in grain depots such as not wearing a safety helmet, unauthorized personnel entering and exiting, and the unsafe operation of equipment. Hazards such as unstable grain accumulation and operation of machinery and equipment may cause accidental injuries to operators. As head protection equipment, safety helmets can effectively protect workers from falling objects, splashing debris and other injuries, reduce or avoid potential safety hazards to the workers' safety, and help to maintain the safe operation of grain depots. Thus, this paper takes the abnormal behaviors of not wearing safety helmets as the research object. This scheme uses the improved YOLOv7 algorithm to process the video surveillance data. It extracts and encrypts the video frames with abnormal behavior, i.e., without safety helmet, without tooling, etc., and stores the encrypted summarized information on the blockchain without storing the all the

video data, which can effectively reduce the storage pressure on the block. The IPFS system stores the original video data and ensures its security. The proposed scheme achieves the safe and efficient storage of video surveillance data in the grain depot through a variety of technologies, which can effectively assist the supervisory authorities in investigating and handling emergencies.

2.5.1. Target Detection Model Based on Improved YOLOv7 Algorithm

Figure 6 shows the basic flow of the model. The data user first extracts the key frames in the grain depot video surveillance data using the inter-frame difference method. Subsequently, it uses the improved YOLOv7 algorithm to construct a target detection model, through which the images of personnel without helmets in the surveillance video are obtained.

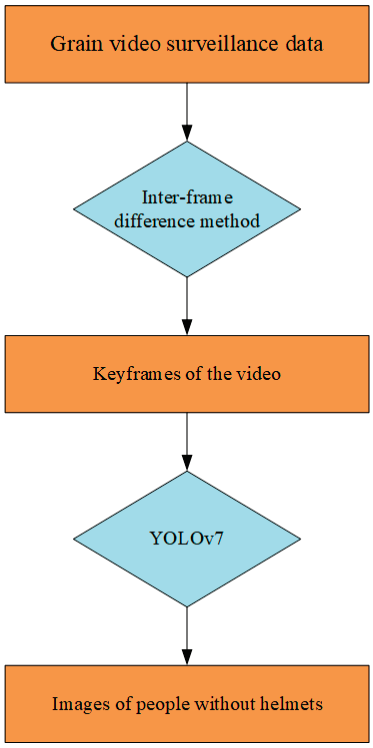

Figure 6. Process of extracting video summaries.

Due to the existence of a large amount of redundant information in video surveillance, this experiment uses the target detection method based on inter-frame difference to extract the key frames in the video, which improves the detection efficiency. There are three methods for threshold selection in the inter-frame difference, which are the maximum value of the difference intensity, the preset difference intensity, and the local maximum value of the difference intensity.

In order to intuitively compare the extraction performance of the above methods, some of the detected images are selected for comparison, as shown in Figures 7–9. The threshold selection methods are used to extract video data with a length of 32 min and 8 s, and the corresponding times are 26.91 s, 32.83 s and 23.63 s. Figure 9 shows that the extraction results obtained using the differential intensity local maxima as the threshold are the best: They are evenly dispersed in the video, and are representative to a certain extent. Therefore, in this paper, the frame with an average inter-frame differential intensity local maximum is selected as the key video frame.

Figure 7. The extraction performance of using differential intensity maxima.

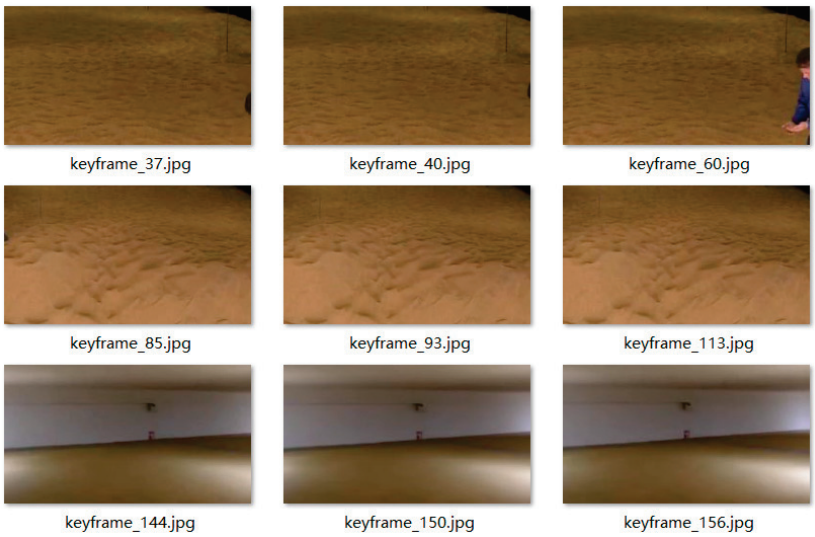

Figure 8. The extraction performance of using preset differential intensity.

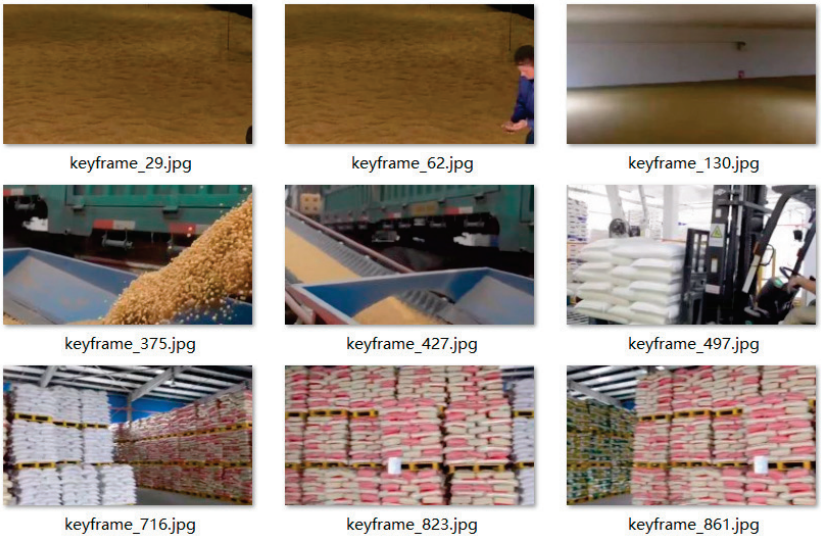

Figure 9. The extraction performance of using differential intensity local maxima.

In this study, the personnel without safety helmets in the grain depot are considered as the research target. A target detection model based on the improved YOLOv7 algorithm is proposed to meet the real-time requirements and improve the detection accuracy. The YOLOv7 loss function contains the classification loss, the confidence loss and the localization loss. Out of these, the classification loss and confidence loss adopt the binary cross-entropy loss function, and the localization loss adopts the CIoU loss function, which is defined in (3) and (4).

$$\mathrm{CIoU} = \mathrm{IoU} - \frac{\rho^2\left(b, b^{gt}\right)}{c^2} - \alpha v \tag{3}$$

$$\mathrm{Loss}_{\mathrm{CIoU}} = 1 - \mathrm{IoU} + \frac{\rho^2\left(b, b^{gt}\right)}{2} + \alpha v \tag{4}$$

where $\frac{\rho^2\left(b,b^{gt}\right)}{c^2}$ is the penalty term, b and b^{gt} represent the center point of the prediction box and the real box, respectively, ρ represents the Euclidean distance between the two points, and c represents the diagonal distance of the minimum external matrix formed by the prediction box and the real box. Furthermore, α is a balance parameter, and v is used to measure the consistency of the width-to-height ratio. These parameters are defined as follows:

$$\alpha = \frac{v}{1 - \mathrm{IoU} + v} \tag{5}$$

$$v = \frac{4}{\pi^2}\left(\arctan\frac{w^{gt}}{h^{gt}} - \arctan\frac{w}{h}\right)^2 \tag{6}$$

It can be gathered from (6) that when the difference between the aspect ratio of the predicted box and the real box is not large, the CIoU loss function cannot express the penalty term of the aspect ratio in a stable manner. At the same time, the model has a slower convergence speed because the CIoU loss function only considers the distance between the real box and the predicted box, overlapping area and aspect ratio, and ignores the angle between the real box and the predicted box. In YOLO, the commonly used loss functions also include SIoU, DIoU, GIoU and EIoU. Among them, EIOU replaces the aspect ratio by calculating the difference value of the width and height, respectively, on the basis of CIOU, which solves the fuzzy definition of aspect ratio. Therefore, in this study, the EIoU loss function is used instead of the CIoU loss function as the localization loss function of the YOLOv7 algorithm, which is defined as the following:

$$\mathrm{Loss}_{\mathrm{EIoU}} = 1 - \mathrm{IOU} + \frac{\rho^2\left(b, b^{gt}\right)}{\left(w^c\right)^2 + \left(h^c\right)^2} + \frac{\rho^2\left(w, w^{gt}\right)}{\left(w^c\right)^2} + \frac{\rho^2\left(h, h^{gt}\right)}{\left(h^c\right)^2} \tag{7}$$

The EIoU loss function includes the IoU loss, distance loss and position loss. On the basis of CIoU, the width and height influence factors of the prediction and real boxes are split and calculated separately, which minimizes the difference between their widths and heights. This improves the regression performance, the convergence speed and positioning. It also introduces the focal loss to reduce the imbalance of positive and negative samples, and the imbalance of difficult and easy samples.

2.5.2. Time-Division Storage of Cereal and Oil Video Surveillance Data Based on Blockchain

Considering grain depot video surveillance data (GVSD) as the research object, the acquired GVSD are processed in segments of two hours, and stored on the blockchain in batches in order to improve the storage access efficiency. The specific steps are as follows:

Step 1: The data user uploads the original GVSD data and the image data of the personnel without helmets together in a file to the IPFS. The IPFS generates a unique hash value based on the file content and returns the CID, which can be used by the CID to find the corresponding file in the IPFS.

Step 2: The data user uses the SHA256 hash function to encrypt the image data (KF) of the personnel without wearing helmets, and obtain the hash value h_{KF}, i.e., hash(KF)→h_{KF}.

Step 3: The data user uses the private key SK_d to sign the CID and the hash value h_{KF} of the image data obtained in step 2 as S_{IK}, i.e., S_{IK} = Sign_SK_d(CID, h_{KF}). Subsequently, S_{IK} is recorded in the consortium blockchain and broadcasted in the form of a transaction, and the blockchain will return the transaction receipt storing the data.

Step 4: The regulator needs to view the GVSD data for a certain time period, and obtain the corresponding S_{IK} record from the blockchain based on the index of the string containing the video time.

Step 5: The regulator performs the first decryption using the data user's public key PK_d to confirm that the S_{IK} record was uploaded by the same data user, i.e., Decrypt(PK_d, S_{IK})→(CID, h_{KF}).

Step 6: The regulator locates the storage node for the video surveillance data by content addressing in the IPFS based on the hash address CID, and downloads the original GVSD record and the image data of personnel without helmets.

Step 7: In the last step, hash operation is performed on the images of personnel without helmets and the corresponding calculation results are compared with h_{KF} on the chain. This completes the process of storing and the management of GVSD on the chain.

3. Results and Discussion

The operating systems of the experiments presented in this paper are Windows and Ubuntu. The deep learning framework Pytorch is utilized to build, train and test the target detection model, and the improved YOLOv7 algorithm is used to carry out the detection on the cereal and oil video surveillance data. The simulation deployment of alliance chain nodes is achieved on the virtual machine to construct the blockchain network based on FISCO BCOS. Table 4 shows the specific operating environment of this system.

Table 4. System operating environment.

Experimental Environment	Version
Virtual machine	VMware Workstation 16.2.1 build-18811642
Operating system	Windows10 64 bit, Ubuntu-16.04.7
CPU	11th Gen Intel(R) Core(TM) i7-11800H
GPU	NVIDIA GeForce RTX 3060 Laptop
Memory	32 GB
Python	v3.8.2
Deep learning framework	Pytorch 1.12.1 CUDA 10.2
FISCO BCOS	v2.9.1
Go-ipfs	v0.4.14
OpenSSL	V1.0.2

3.1. Target Detection Based on Improved YOLOv7 Algorithm

In this study, the personnel in the grain depot without helmets are considered the research target, and the YOLOv7 algorithm is chosen to construct the target detection model. The helmet datasets used in this paper are obtained from the web via Python scripts. A total of 2800 personnel samples are screened, and the images are labeled using Labelimg and saved in YOLO format. The datasets are randomly divided into the training set, the test set and the validation set, according to the ratio of 8:1:1. The datasets consist of two categories: one without a helmet and the other with a helmet. The initial learning rate during training is 0.01, momentum is 0.937 and batch size is set to 8. The training image sizes are all set to 640 × 640 pixels, and training is carried out over 100 epochs.

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}} \tag{8}$$

$$mAP = \frac{1}{m}\sum_{i=1}^{m} AP_i \tag{9}$$

$$Precision = \frac{TP}{TP + FP} \tag{10}$$

$$AP = \sum_{i=1}^{n-1} (r_{i+1} - r_i)p(r_{i+1}) \tag{11}$$

The performance of different loss functions is analyzed by replacing the loss function CIoU of the original YOLOv7 with SIoU, DIoU, GIoU and EIoU. Table 5 compares the performance of the above five loss functions applied to YOLOv7.

Table 5. Performance of five loss functions.

Loss	mAP/%	Precision/%	Recall/%	Training Time/h
CIoU	93	90.8	86.6	2.99
SIoU	94.4	93.5	89.3	2.71
DIoU	92.9	90.6	87.0	2.81
GIoU	79.2	85.2	72.0	2.69
EIoU (ours)	94.5	93.7	90.0	2.67

It can be gathered based on Table 5 that compared with CIoU, the mAP, Precision and Recall of the EIoU loss function model are 1.5%, 2.9% and 3.4% higher, respectively, and the training time is shortened by 0.32 h. Compared with SIoU, the mAP, Precision and Recall of EIoU loss function model are 0.1%, 0.2% and 0.7% higher, respectively, and the training time is 0.04 h less. Compared with DIoU, the mAP, Precision and Recall of EIoU loss function model are 1.6%, 3.1% and 3% higher, respectively, and the training time is shortened by 0.14 h. Compared with GIoU, the mAP, Precision and Recall of EIoU loss function model are 15.3%, 8.5% and 18% higher, respectively, and the training time is decreased by 0.02 h. The above analysis shows that the comprehensive advantages of the EIoU loss function for model training are more obvious and the detection precision is the highest.

In order to objectively evaluate the performance of the improved YOLOv7 model for helmet detection in this study, the same number of training sets is used under the same configuration conditions. Comparative experiments are carried out using several popular target detection networks: YOLOv3-Tiny, YOLOv5s and YOLOv7. The experimental results are evaluated using Recall, Precision and mAP and FPS, which are shown in Table 6.

Table 6. Experimental results comparison of five algorithms.

Model	mAP@0.5/%	Precision/%	Recall/%
YOLOv3-Tiny	83.7	90.1	74.6
YOLOv5s	91.9	94.6	85.2
YOLOv7	93	90.8	86.6
Ours	94.5	93.7	90.0

Table 6 shows that YOLOv7 outperforms the YOLOv3 and YOLOv5 models in terms of the mAP and Recall rate, which has certain advantages. Compared with the basic YOLOv7 model, the mAP, Precision and Recall are increased by 1.5%, 2.9% and 0.4%, respectively. Therefore, the improved algorithm proposed in this study can increase the precision of helmet wearing inspection.

In order to better verify the algorithm proposed in this paper, some frames of the video monitoring data of the grain depot are selected for testing, and the detection performance of the benchmark model YOLOv7 before and after the proposed improvement is compared and analyzed, as shown in Figure 10. Figure 10a,c,e show the detection results with the

reference model. Figure 10b,d,f show the detection results with the proposed algorithm. In the environment with dense intersection, false detection occurs in Figure 10a,c. In the environment with weak light, false detection also occurs in Figure 10e. In Figure 10b,d,f, each target is accurately detected and has a higher detection accuracy. Therefore, the improved YOLOv7 model has good robustness in a more complex environment, showing better performance and higher detection accuracy.

Figure 10. Comparison of detection results.

3.2. Surveillance Video Data Storage Based on FISCO BCOS

This experiment builds an IPFS and deploys a blockchain network using the FISCO BCOS platform. The visualization WeBASE platform is used to complete the development, deployment and invocation of data storage smart contracts and other operations, as shown in Figures 11 and 12.

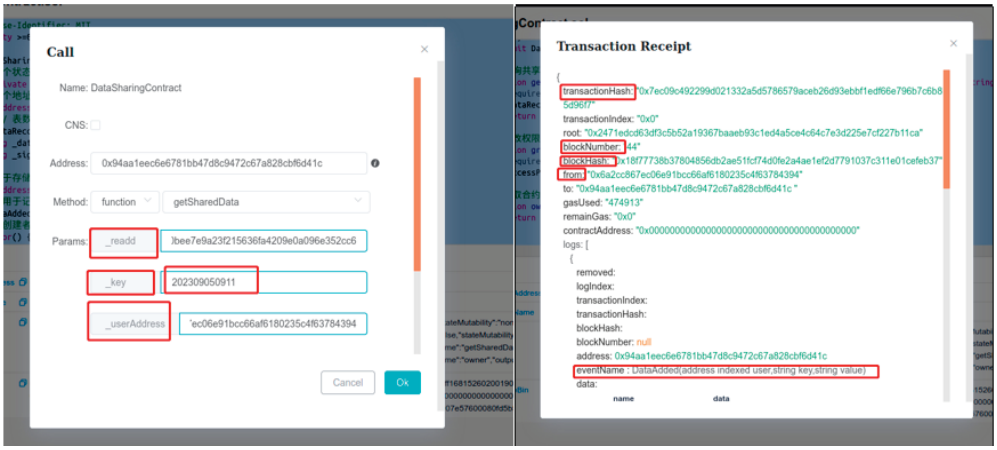

Figure 11. Process of writing data on-chain.

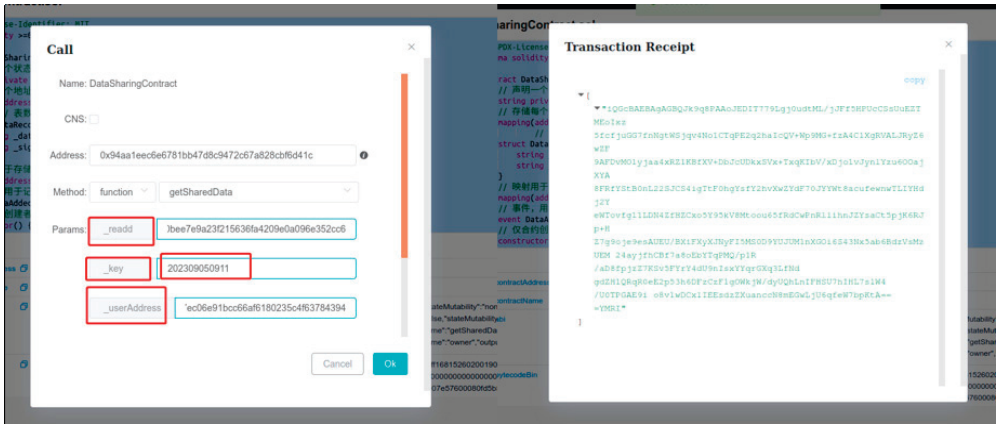

Figure 12. Process of reading data on-chain.

In this study, the SHA256 algorithm is used to encrypt the frames of the grain depot video where personnel are without helmets. The contract deployer has the right to call the function of setting the shared data, and sign the encrypted picture abstract h_{KF} and the video data storage address CID in IPFS with its own private key to obtain the data. Subsequently, the deployed contract uploads the data to the chain. Algorithm 1 shows the data upload algorithm.

Algorithm 1. Algorithm for setSharedData

Input: _wusr(address),_key(time of video),_value(data)

```
function setSharedData
    if hasAccess(_wusr)= =True
        _value=Sign _SK_wusr(data)
    if bytes(_key).length>0 and bytes(_value).length >0
        dataMap[_wusr] [_key] = DataRecord(_date: _key,_signdata: _value)
     emit DataAdded(_wusr, _key, _value)
```

When the regulator wants to view the video data in a certain period of time, they call the Get Shared Data function in the contract, and enters their own address and video index. If it has access rights, the system will return the corresponding block information. Algorithm 2 shows the data access algorithm.

Algorithm 2. Algorithm for getSharedData

Input: _rusr(address),_key(time of video), _wusr(address)

```
function getSharedData
    if hasAccess(_rusr)= =True
        DataRecord storage record = dataMap[_userAddress][_key]
    return record._signdata
```

Next, we test the stability of video files with different sizes. When the size of the stored video file is less than or equal to 5 GB, this system can complete a data-sending transaction in 5 s and return the block ID. When the uploaded file is larger than 10 GB, it is still able to complete the sending of a transaction at a faster speed. Considering the video file with a size of 3.2 GB as an example, 248 frames of key information are finally obtained using the target detection algorithm. Out of these frames, 34 abnormal images where personnel are not wearing helmets are extracted. The total size of these abnormal images is about 1.1 MB, which is considerably smaller than that of the original video file, and the whole process can be completed within 10 s. This analysis from the perspective of distributed storage shows that the way of storing data in this study improves the system scalability.

4. Conclusions

In this study, a dual storage model of "Blockchain + IPFS" was designed to address the problems of the reliability, security and resource wastage of traditional cereal and oil video surveillance data storage. The use of IPFS in this model was not only suitable for the decentralized characteristics of blockchain, but also mitigated the problem of the insufficient storage capacity of blockchain. The improved YOLOv7 algorithm exhibited a 1.5%, 2.9% and 3.4% higher mAP, Recall and Precision, respectively, than the original YOLOv7 model. Thus, it could obtain the abnormal information in the cereal and oil video surveillance data from the complex grain storage environment more accurately. This study replaced the complete video data with video summaries for on-chain storage, which effectively reduced the storage burden on the blockchain while ensuring the integrity and security of the cereal and oil video surveillance data storage, and significantly improved the query efficiency of the on-chain data. The model proposed in this paper is of great significance for ensuring cereal and oil safety, which is a fundamental issue linked to the survival of human beings.

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Comparison of Carbon Footprint Analysis Methods in Grain Processing—Studies Using Flour Production as an Example

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Abstract: Rational energy management in food production is one of the key actions in the context of reducing greenhouse gas emissions. Ongoing rapid climate change and global warming are making energy consumption an increasingly critical point in food production, throughout the "farm-to-table" manufacturing chain. The carbon footprint (CF) can be used to assess the amount of greenhouse gas (GHG) emissions in the area of food cultivation, production and distribution. The work purpose was to characterize the CF methodology on the basis of literature data, to analyze manufacturing processes in production plants to determine the shares of each type of emissions for selected products and to identify directions for optimizing technology (the scope of analysis—from raw material input to product output). A literature analysis of agriculturally important grain products was undertaken. Methods of carbon footprint analysis were analyzed. There is no standardized methodology for a given product group, with individual approaches designed for each product group existing in the literature. PAS 2050 is the most common standard focused on quantifying GHG emissions created during the life cycle of specific goods/services, without considering potential environmental, social and economic impacts.

Keywords: carbon footprint calculation; greenhouse gas emissions; grain industry; climate change; food production

1. Introduction

The development of sustainability indicators, based on benchmarking of actual data on products, companies and investments, and their consistent application is essential for reducing the negative impact of human activities on the environment [1,2]. The agri-food branch includes two inseparable sectors of the economy: the agriculture sector, which is the source of plant and animal raw materials, and the food processing sector, which is the main consumer of agricultural crops and is also responsible for directing the production of agricultural raw material. The term food industry refers to food production and to all activities related to the production, processing, distribution, preparation, and consumption of food, taking into account socio-economic and environmental aspects [3,4]. Food production is a major contributor to greenhouse gas emissions and biodiversity loss. Identifying emissions in agriculture and identifying directions for their reduction is a complex issue. Any action must be targeted so as not to jeopardize food security. This research should be conducted, as there is no one-size-fits-all solution, by applying universal instruments depending on regional or national conditions [5].

In Poland, the agri-food industry has been in a continuous phase of development for several decades. Of great importance in this regard was Poland's accession to the European Union (EU), which resulted in the restructuring and modernization of agriculture, associated, among other things, with subsidies that allowed production enterprises to adapt to EU standards. As a result, the Polish agri-food sector has become competitive in both domestic and international markets [6].

One of the best-known indicators of human activity on the environment is the ecological footprint, which expresses in units of area the ecosystem services that are necessary to sustain the production and consumption that occur. The value of the ecological footprint takes into account the consumption of raw materials, energy, as well as waste emissions. This indicator represents human demand for raw materials and services [7,8]. Another indicator that determines the environmental impact of humans is the carbon footprint, characterized as the sum of the products of the amount of gases emitted and their GWP ratios, expressed in kg or Mg of carbon dioxide equivalent (CO_{2eq}) and related to the functional unit of the product [9]. Environmental pollution and depletion of natural resources negatively affect climate security and the future of our planet. Among the most dangerous global threats are excessive CO_{2eq} emissions. An indicator for estimating the emission of greenhouse gases into the atmosphere over the life cycle of a product, process or technology is called the carbon footprint (CF). Greenhouse gases (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride) contribute differently to the greenhouse effect, which is measured on a per-particle CO_2 basis. Global warming potential (GWP) is an indicator comparing the global warming potential of a given greenhouse gas to that of carbon dioxide. GWP is calculated based on the climate warming effects of one kilogram of a given gas over 100 years compared to the effects of one kilogram of CO_2 [10,11].

The carbon footprint calculated using global warming potential (GWP) can be expressed in terms of organizational units, production process, performed services, product and consumer. In CF analysis, two types of emissions are considered [12,13]:

- direct greenhouse gas (GHG) emissions resulting from, i.e., fuel combustion, manufacturing and natural processes that generate these gases emissions;
- indirect GHG emissions resulting from the use of energy media (electricity, heat) and/or raw materials in the production of a product.

The primary objective of our research was to conduct a comprehensive literature review focusing on existing methodologies for calculating the carbon footprint. This involved examining scholarly articles, reports, and publications to gain insights into the various approaches and tools used in quantifying carbon emissions. As part of this study, an analysis of flour production was conducted as an example. The rationale behind this was to apply and adapt the reviewed methodologies in a real-world context, specifically with the aim of developing national standards for assessing the carbon footprint in the flour production industry.

2. Materials and Methods

The study was focused on the analysis of flour, with key information on the production process and logistics provided by the partnering production facility. The various stages of production, from the selection of raw materials, through the processing process, to the final product, were thoroughly analyzed. In addition, aspects of flour transportation were explored, including means of transport, storage conditions and any practices to safeguard product quality as it moved through the supply chain. Collaboration with the production facility provided a unique perspective on internal processes, as well as insight into the measures the company takes to maintain high quality standards. The data analysis also focused on identifying possible areas for optimization or implementation of improvements, with the goal of increasing the efficiency of the flour production and logistics process. Technological process analysis and the preparation of unit process diagrams in production cycle was the scope of work. The issue analysis approach was presented as a research method. After characterizing technological processes, CF measurement ranges, functional unit and boundary of measurement system were determined. The input–output analysis within a specified range and throughout the life cycle was carried out. A method was developed for counting the process' CF and with an extension of the range to include the ingredients' CF. The conception of process line metering feasible for CF calculation was planned. Relevant emissivity data were collected with production volumes and the

recording of number of cycles. Based on this, a database was created for calculating CF, depending on production volume.

The carbon footprint (CF) value was given in equivalent quantity (CO_{2eq}). The CF calculation of a product, process, and technology required adding up all emissions (direct and indirect) identified throughout the life cycle (LCA) of the product, process and technology. The carbon footprint was calculated from the formulas in Table 1.

Table 1. Equations for calculating carbon footprint.

CF value	$CO_{2eq} = GHG \cdot GWP_{GHG}$
CF of product, CF of process, CF of technology	$CF = \sum_{i=1}^{n} (CO_{2eq})_i + \sum_{j=1}^{m} (CO_{2eq})_j$
CO_{2eq}—equivalent emission volume expressed in kg (or other mass units) of CO_2, GHG—the emission volume of a given greenhouse gas expressed in kg (or other mass units), GWP_{GHG}—GWP (Global Warming Potential) value of a given greenhouse gas (kg CO_{2eq}/kg GHG), CF—carbon footprint of the product [kg CO_{2eq}/kg product], $(CO_{2eq})_i$—the amount of direct emissions from the i-th source expressed in CO_2 equivalent [kg/kg product], $(CO_{2eq})_j$—the amount of indirect emissions from the j-th source expressed in CO_2 equivalent [kg CO_{2eq}/kg product].	

Detailed principles of CF analysis and directions on how to calculate CF values are described in relevant normative documents [14–18]. Life cycle analysis (LCA) is a tool used to determine the carbon footprint. It is an environmental management technique, which is an analytical study in a comprehensive assessment of the environmental impact of a product, service or process. The LCA analysis considers all inputs and raw materials throughout the production, pre-production and operational cycles of a product, service or process. The methodology for LCA analysis is given in ISO 14040, 14044: 2009 [14,15]. These standards define the structure of an LCA analysis, which includes the following steps: defining the purpose and scope of the analysis, analyzing the dataset, assessing the environmental impact [16–18].

The first step in the analysis is to determine the purpose and scope of the analysis and the type of potential environmental impact of the product, service or process. In determining the CF of agricultural products, potential sources of carbon dioxide, methane and nitrous oxide emissions (kg CO_{2eq}) are assessed. The scope of the analysis is defined as the boundaries within which the resources realistically used in the production process and the energy inputs involved are considered. A mass and energy balance of the process has to be carried out based on unit processes, taking into account emissions and losses between these processes [11,19,20].

For certain production processes that result in several products, it is not possible to determine the environmental burden attributed to a specific product. In such situations, GHG emissions of the entire production process are determined by assigning their emissions proportionally to individual products. These proportions are determined based on the following criteria: mass balance, commercial value or energy value. It is particularly difficult to determine the allocation of the indicated GHG emissions to individual products, on farms with a wide spectrum of activities, including multigenerational crop production as well as animal production [21].

An important step in the LCA analysis is to determine how to obtain data on emissions of individual GHGs. In order to obtain emission values, measurements should be made in a given process to develop databases. The next element of this step is to determine the functional unit of the product, service or process. For agricultural production, this unit is usually a kilogram of product obtained with a standardized chemical composition. The next step is a harvest analysis, which is the quantification of greenhouse gas emissions associated with the total number of all raw materials entering the production cycle and energy inputs

entering the production process. Harvest analysis in agricultural production most often includes emissions associated with the production of fertilizers, crop protection products, feedstuffs, animal husbandry and agrotechnical treatments. Determination of greenhouse gas emissions for a product was performed in an identical manner. Similarly, using all the steps described above, the entire supply chain including processing, distribution and packaging should be considered [18].

Methodology comparison for estimating the carbon footprint was performed. The demands of the market are forcing businesses around the world to take action to reduce greenhouse gas emissions. Entrepreneurs who work with international companies are required to calculate the carbon footprint for their operations and/or products. In order to properly determine the CF, it is important to choose the right methodology. To date, many different methods have been developed for counting the environmental impact of pollutants and greenhouse gases, the most popular ones are presented in Table 2.

Table 2. Methodologies of carbon footprint analysis.

Methodology	Description
IPCC—Task Force on National Greenhouse Gas Inventories, 2006 IPCC Guidelines for National Greenhouse Gas Inventories [10]	Methodological guidelines for national greenhouse gas inventories
WRI GHG Protocol [13]	Specification for estimating greenhouse gas emissions of goods and services
ISO 14040 [14]	Product life cycle assessments (LCA)
ISO 14044 [15]	
ISO 14067 [22]	Principles, requirements and guidelines for quantifying and reporting product carbon footprint (CFP) based on ISO 14040 and ISO 14044 standards for life cycle assessment (LCA)
PAS 2050 [23]	Determines the environmental impact of a company's operations, products and services, and enables measurement of greenhouse gas (GHG) emissions over their life cycle
PAS 2060 [24]	Specification for demonstrating carbon neutrality; sets out the requirements needed to achieve and demonstrate carbon neutrality in all areas, including buildings, transportation, production, production lines and events

The most common method for calculating the CF is the PAS 2050 ("Publicly Available Specification 2050") [23] which was developed by the BSI (British Standard Institute). The PAS 2050 specification defines requirements for assessing the life cycle greenhouse gas emissions of goods and services based on key life cycle assessment techniques and principles. It is used by the BSI to update the quantification of life cycle GHG emissions of any goods and services in accordance with the latest technical developments. It makes it possible to measure the environmental impact of the activities of a company's products and services and to measure GHG emissions over their life cycle. The PAS 2050 specification is mainly based on ISO 14044 (Environmental Management; Life Cycle Assessment; Principles and Structure) and ISO 14044 (Environmental Management, Life Cycle Assessment; Requirements and Guidelines) [18].

Personalized approaches designed for specific product groups are encountered in the subject literature. They provide the opportunity to compare different production systems, regions and products, according to the requirements of the standardization approach. This methodology makes it possible to compare GHG emissions between products, identify GHG emissions from the field to the gate of the production facility, and identify those

areas where there is potential to reduce GHG emissions if they are particularly high. The approach combines various aspects of existing standards and specifications (Table 1) and is called the attribution or outcome method for calculating the carbon footprint. The LCA method is directed at describing the actual flows to and from a product or process relating to environmental impacts. The method is also useful for planning strategies to reduce or mitigate GHG emissions at specific stages. The attribution method uses average data, for example, for electricity or other commodities traded, not specifically linked to their supplier. The approach was evaluated as both sufficient and practical to develop a common CF methodology. The development of a methodology for calculating the carbon footprint is directed at setting uniform standards for CF analysis and enabling the evaluation of dairy products using the developed bases. These efforts are aimed at supporting the development of sustainable food production that enables ongoing reductions in GHG emissions [16,17,21].

The food product groups analyzed are grain products. The carbon footprint analysis methodologies for the selected product group (i.e., bread) were analyzed (Table 3).

Table 3. Carbon footprint estimation methodologies for agriculture and on-farm processing.

Product	Methodology and Characteristics of the Study	Source
Bread	The carbon footprint was estimated according to the PAS 2050 methodology. The results were also calculated according to the ISO 14044 methodology to identify any differences in the two approaches and results.	[25]
	The attribution method was used.	[26]
	The carbon footprint (CF) was assessed using a life cycle assessment (LCA) methodology.	[27]

British researchers collected primary data of the bread supply chain according to the PAS 2050 methodology. Secondary data came from UK statistics, life cycle databases and other published sources. They estimated the bread CF produced and consumed in the UK. Sliced and wholemeal white bread were considered for these purposes, and the functional unit was defined as "one loaf of sliced bread (800 g)". The effects on the carbon footprint of several parameters were analyzed, including the country of origin of the wheat (UK, Canada, France, Germany, Spain and the US), the type of flour (white, brown and wholemeal) and the type of packaging (plastic and paper bags). CF results ranged from 0.977 to 1.244 kg CO_{2eq} per loaf of bread. Coarse-cut wholemeal bread packaged in plastic bags has the lowest carbon footprint, while medium-cut white bread in a paper bag has the highest. The main critical points are wheat cultivation and bread consumption (refrigerated storage and toasting), which contribute 35% and 25%, respectively. The CF can be reduced by an average of 25% by avoiding toasting and storing bread in the refrigerator. Further reductions (5–10%) can be achieved by reducing the amount of bread waste discarded by consumers. The contribution of transportation and packaging to the overall results is small. Similar trends in results were also found in a study based on secondary data and following ISO 14044 methodology. The main methodological differences between the two standards relate to the PAS 2050 specification [23], which defines requirements for assessing life cycle GHG emissions of goods and services based on key life cycle assessment techniques and principles. It distinguishes between "the cradle-to-gate" and "cradle-to-grave" boundaries of the scope of the study, while the scope of measurement included in ISO 14044 depends on the purpose of the study [25].

The CF of rye bread produced on an industrial scale in Denmark was determined by identifying the steps that significantly contribute to the generation of the carbon footprint. Using an attribution approach, the CF of 1 kg of rye bread was estimated at 0.731 kg CO_{2eq}. The supply chain was considered in order to estimate the carbon footprint. The main source of carbon emissions was the raw material stage, especially agricultural production (culti-

vation), with processing and distribution as secondary sources. The waste management stage was considered an important and previously overlooked opportunity for process optimization [26].

Chiriacò et al. compared the impact of organic and conventional agriculture on climate change in terms of GHG emissions from organic and conventional agriculture. They compared the production process of organic and conventional whole grain bread produced in central Italy by a small- and medium-sized bakery company. The carbon footprint was assessed using LCA methodology. It was determined that the CF of 1 kg of conventional whole-grain bread was 24% lower compared to the same organic bread, and was 1.18 and 1.55 kg CO_{2eq}, respectively. If CF is evaluated per unit of cultivated area (ha), the organic wheat crop showed better performance in terms of GHG emissions than the conventional one by 60%, with CFs of 1150 and 2870 kg CO_{2eq} per ha, respectively. The higher CF per unit of organic product is due to the lower yield per unit area grown in organic agriculture and the resulting attribution of fewer GHG emission products generated in the field phase of the life cycle. In contrast, the CF per hectare is higher when conventional practices are used due to the higher use of raw materials (higher seed density, agrochemicals for fertilizer and crop protection) for the same organic system. Organic farming for wheat in Italy is a low-carbon agriculture with a smaller contribution to climate change in terms of GHG emissions per hectare compared to conventional wheat farming, although reduced crop yields and the resulting need for more farmland should be considered. A more comprehensive assessment of the actual GHG emitted to the atmosphere from organic and conventional farming systems can be obtained when the CF is assessed per unit area, in addition to the CF per unit product [27]. The carbon footprint is a measure of a farm's climate warming potential due to its high GHG emissions from agri-food processes. It is measured in kg CO_2 equivalents (eq.) and calculated as the sum of the products of the climate warming potentials for individual GHGs (kg CO_{2eq} per kg GHG) and emissions (kg) from all direct and indirect sources [28]. For the case of bread production, the CF was estimated in accordance with the PAS 2050 methodology and in accordance with the ISO 14044 methodology, while the life cycle assessment (LCA) methodology was used to compare the carbon footprint of organic and conventional whole grain bread production processes produced by small- and medium-sized enterprises.

3. Results and Discussion

An analysis of processes to determine the shares of each type of emissions for selected products and to identify directions for optimization of technology was performed. A carbon footprint can be used to assess the amount of greenhouse gas emissions in the food production and distribution area. The CF indicator is increasingly used with the development of low-carbon economy assumptions and the introduction of social responsibility strategies for the agri-food industry. Ongoing research should be aimed at analyzing existing technological processes, identifying solvable problems and developing new technological solutions that significantly affect the carbon footprint of food production [29].

Grain processing characteristics with identification of unit processes were performed. Crop production is one of the main directions of agricultural production in Poland. In recent years, the share of cereals in the global value of agricultural production is at 20%. In the structure of sown crops, cereals account for about 74% of the total area. In 2014–2018, the total grain harvest was at the level of 26.5–31.8 million tons. In 2022, the wheat harvest was as high as 13.5 million tons. Grain is one of the most important plant raw materials used for food production [30]. Grains in milling processes are processed into different types of flour, groats and flakes. The largest part is flour, which can be divided by purpose into bread flours, market flours, pasta flours and confectionery flours [31]. Each flour is characterized by a certain baking value, i.e., the balance between the gluten mesh's ability to produce and retain gases in wheat bread and the protein mucous membranes in mixed and rye bread. Standardization and improvement of flour quality is based on the correction of the fermentation gas production and retention capacity with appropriate enzymes and

with ascorbic acid acting synergistically with the added enzymes and improving the gluten structure. This action improves the fermentation capacity of the flour, strengthens (or weakens) the gluten protein structures, increases the water absorption capacity, resulting in improved dough and crumb quality, increased bread volume and prolonged freshness. The properties of the flour used in baking determine fundamentally, the quality of the resulting bread and the applicability of mechanized and continuous production systems. In processing, we produce different types of flour depending on demand. These are determined by the content of mineral substances in the flour. Thus, for example, type 450 specifies a content of 4.5 g of ash/1 kg of flour, type 750 a content of 7.5 g of ash/1 kg of flour, and type 2000 a content of 20 g of ash/1 kg of flour. Wheat grain is used to produce flours for a variety of products, so it is first necessary to determine the purpose of the flour and, based on this, select a grain with quality characteristics suitable for its production [32]. For the milling industry, it is important, for example, the shape and size of the grain (accuracy, alignment, weight of 1000 grains), the structure of the endosperm and its bonding to the casing (vitreousness, hardness), and the ash content (the maximum ash content in grain for the production of light flours must not exceed 1.80–1.85%) [33].

Each kind of confectionery bread requires flour with different quality parameters. Flour for yeast dough production should have the same quality parameters as flour for bread production, so it should be produced from grain with the same quality parameters, while flour "for cakes" should have lower than average water absorption (50–56%), and the dough should be elastic, "flowing", inelastic and weak [34]. The best raw material for pasta production is semolina obtained by milling hard wheat. It should be characterized by a yellow color with an amber tint, high protein content (not less than 15%), the amount of gluten not less than 30%, which should be strong, but at the same time stretchy and malleable. Common wheat milling products (flour or porridge) are also used to make pasta [35]. Wheat flakes are one of the products obtained during three-grain milling of wheat. It can be produced in a wide range of granulations, depending on the intended use. For the production of wheat flakes, whole wheat grain is used. In corn milling, it is very important to extract the germ, which contains large amounts of fat, so that the quality and shelf life of milling products deteriorates. Maize milling products in the form of flours are used mainly as an additive in the production of bread, confectionery bread and in the production of pasta. Various types of groats are used to make corn flakes or in the brewing industry [36].

On the basis of data from the manufacturing plant, flour production has been characterized and schematically depicted in two figures to ensure clarity of the identified processes (Figures 1 and 2). The equipment used at the various stages of production is presented in Table 4. The process begins with the preparation of grain for milling in the cleaner. The first step in preparing grain for milling is cleaning. After the grain is cleaned, conditioning must be carried out, which involves moistening and aging the grain. The next stage is cleaning. Its purpose is to remove impurities adhering to the surface of the grain and some parts of the grain, for example, parts of the fruit and seed coat. After these preliminary steps, grain milling is carried out in the mill proper. It involves milling the grain (previously cleaned and subjected to the conditioning process) and then also sorting between the different milling products. As a result, a final product is obtained through screening. The grain passes through the milling machines many times, and each time the milk is sifted to separate the coarse particles from the fine ones. The resulting products are sorted into flours, porridges, middlings and bran. In order to separate adhering fragments of the fruit and seed coatings, porridge and middlings are sorted and cleaned on porridge separators before being sent for further grinding. The product coming out of the creamer is not homogeneous and requires sorting. Sorting between milling products is based on the particle size on sifters (screens). Porridge sifters or flat sifters are used for sifting by quality. The basic multispecies milling is a three-species milling. This milling results in light flour type 550 (to extract 65%), bread flour type 750 (to extract 75–80%) and semolina (1.5%), crisp flour (2%) and cake flour (0.5%) [31,37].

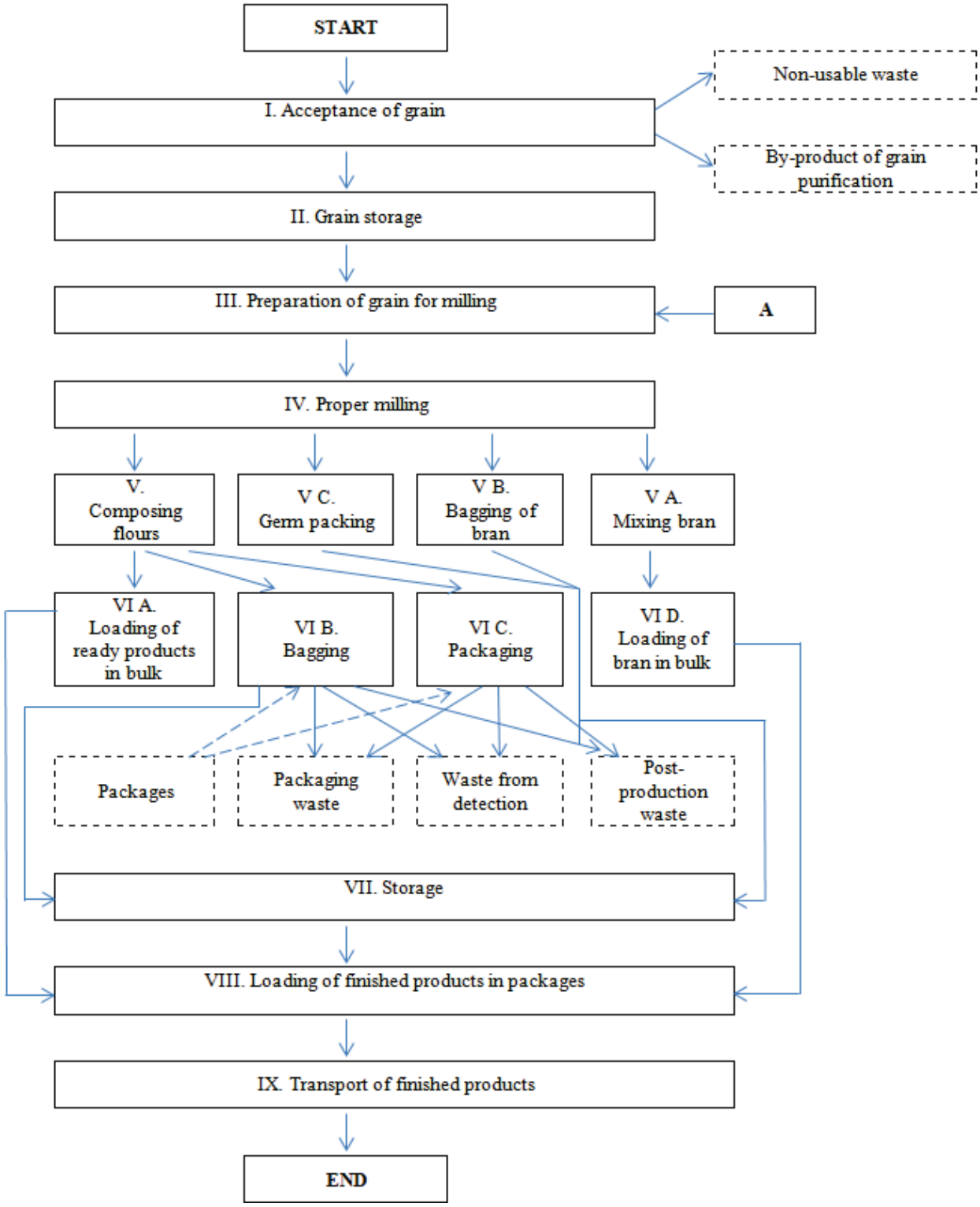

Figure 1. Scheme of flour production according to the selected plant—without preliminary preparation of grain for milling (stage A in diagram) (own description).

A detailed description of the calculation methodology is presented in the works [38,39]. In order to take into account the CF of applied energy media, appropriate conversion indicators were used, the values of which are shown in Table 5. The data on energy media consumption and production volume (Table 6) were collected at the production plant.

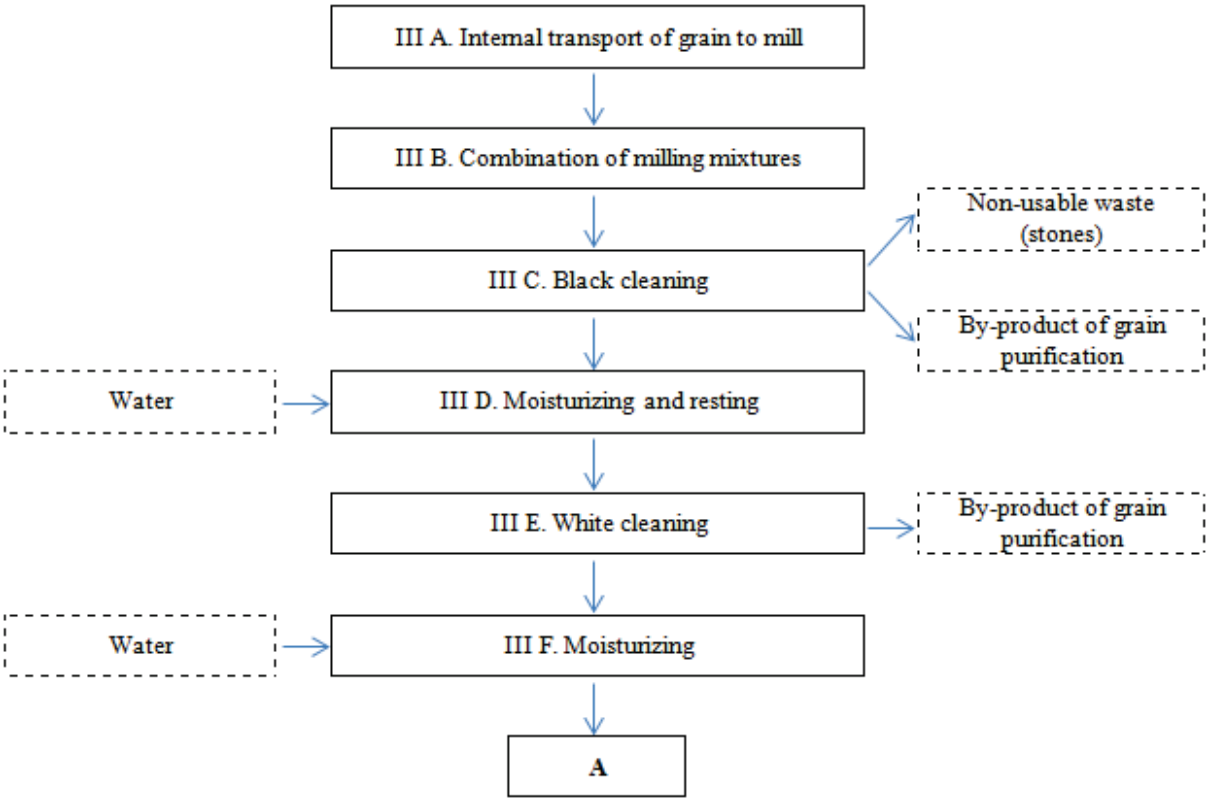

Figure 2. Preliminary preparation of grain for milling (stage A in Figure 1) (own description).

Table 4. Flour production stages and equipment used.

Process Steps	Devices
I. Acceptance of grain	
II. Grain storage	Chain conveyors, bucket conveyors, grain separator, filter cyclones, gravity transport, grain tanks, scales.
III. Preparation of grain for milling	Bins, tanks at the mill, percenters, horizontal transport conveyors (augers and redlers), aspiration fans, aspiration filter cyclones, vertical transport conveyors (bucket elevators), billing scales with dams, combo cleaning device including aspiration channels, sortexes, wheat humidifiers, devices controlling the measurement of water dosage to the amount of wheat, scrubbing machine, air channel, dowilizer, water pumps, beater mill.
IV. Proper milling	Scales, milling roller unit, flat pass sifters, pneumatic transport entollectors (sterilizers), porridge scale unit, porridge and bran projectors, filter cyclones, pass augers, check sifters, air locks with pneumocyclones, matadors (sterilizers), finished product transport sluices with crossovers to chambers, samplers (devices that take flour samples directly from production), pneumatic transport blowers.
V. Composing flours	Flour chamber selectors, batching scales, horizontal transport, homogenizer, flour sifter including magnet dam, blower, matador (sterilizer), pneumatic transport including crossovers to chambers.
V C. Germ packing	Gravity transport.
V B. Bagging of bran	Gravity transport.
V A. Mixing bran	Auger pickers, hydraulic pump, horizontal transport of bran, vertical transport (bran elevator), blower, aspiration filter cyclone, pneumatic crossovers.
VI A. Loading of ready products in bulk	Bulk flour chamber selectors, horizontal transport (augers), screening machines including magnet dams, horizontal pass-through hopper (redler), pass-through loading sleeves, quantity scales.

Table 4. *Cont.*

Process Steps	Devices
VI B. Bagging	Flour chamber selectors, horizontal transport (augers), sifters including magnet dams, weigh valve packer with metal detector, horizontal transport (conveyor belts), palletizer, wrapping machine.
VI C. Packaging	Flour chamber selectors, horizontal transport (augers), screening machines including magnet dams, unit packers with metal detectors, conveyor belts, heating tunnels, palletizer.
VI D. Loading of bran in bulk	Auger selectors from the bran chambers, horizontal transport (bran redler), drive-through loading sleeve, magnet dam, filter cyclone, blower.
VII. Storage	-
VIII. Loading of finished products in packages	High-bay forklifts, battery trucks, fuel combustion internal forklifts.

Table 5. Indicator values for conversion of applied energy media for CF analysis.

Energy Media	Indicator Value	Source
Heating oil [L]	2.54 kg CO_{2eq}/L	[40]
Diesel [L]	2.66 kg CO_{2eq}/L	
Gasoline [L]	2.35 kg CO_{2eq}/L	
Gas [kWh]	0.2 kg CO_{2eq}/kWh	
Electricity [kWh]	0.708 kg CO_{2eq}/kWh	[41]

Table 6. Characteristics of energy media consumption in 2022.

Month	Production Volume	Energy	Diesel	Gasoline	Gas
	t	kWh	L	L	kWh
January	16697	1,047,000	5862	511	46,760
February	12949	828,000	5862	511	34,720
March	17771	1,085,000	5862	511	35,440
April	15724	945,000	6191	572	25,310
May	16521	949,000	6191	572	6916
June	14839	842,000	6191	572	1151
July	16176	954,000	5905	649	1006
August	14686	869,000	5905	649	970
September	15470	957,000	5905	649	4041
October	17232	1,070,000	7878	525	7160
November	16977	1,043,000	7878	525	22,810
December	15268	966,000	7878	525	41,860
Sum	190310	11,555,000	77,508	6771	228,144

On this basis, CO_{2eq} emissions related to consumption of energy media were determined (Table 7) and the carbon footprint for each month was estimated (Table 8). The determined carbon footprint of flour production at the plant (scope of analysis: production and transportation) with respect to unit weight was 0.041–0.047 kg CO_{2eq}/kg. The average carbon footprint of flour production was 0.044 kg CO_{2eq}/kg. It was found that there was a dependence of the carbon footprint of poppy production on the season. The lowest value was in the summer months (June) and the highest in the winter months (February). In

addition, there was no significant relationship between carbon footprint and monthly production volume. Production-related CO_{2eq} emissions came mainly from indirect emissions from electricity consumed, which accounted for 96.8% of total emissions. CO_{2eq} emissions related to transportation were constant throughout the year analyzed, averaging 2.63%.

Table 7. CO_{2eq} emissions related to consumption of energy media for 2022.

Month	Electricity		Diesel		Gasoline		Gas		Emission
	Emission	Share	Emission	Share	Emission	Share	Emission	Share	
	Mg CO_{2eq}	%	Mg CO_{2eq}	%	Mg CO_{2eq}	%	Mg CO_{2eq}	%	Mg CO_{2eq}
January	741.276	96.59	15.593	2.03	1.201	0.16	9.352	1.22	767.422
February	586.224	96.11	15.593	2.56	1.201	0.20	6.944	1.14	609.962
March	768.180	96.98	15.593	1.97	1.201	0.15	7.088	0.89	792.062
April	669.060	96.69	16.468	2.38	1.344	0.19	5.062	0.73	691.934
May	671.892	97.22	16.468	2.38	1.344	0.19	1.383	0.20	691.087
June	596.136	97.06	16.468	2.68	1.344	0.22	0.230	0.04	614.178
July	675.432	97.48	15.707	2.27	1.525	0.22	0.201	0.03	692.866
August	615.252	97.25	15.707	2.48	1.525	0.24	0.194	0.03	632.678
September	677.556	97.41	15.707	2.26	1.525	0.22	0.808	0.12	695.597
October	757.560	96.98	20.955	2.68	1.234	0.16	1.432	0.18	781.181
November	738.444	96.50	20.955	2.74	1.234	0.16	4.562	0.60	765.195
December	683.928	95.72	20.955	2.93	1.234	0.17	8.372	1.17	714.489
Sum	8180.940	96.83	206.169	2.44	15.912	0.19	45.628	0.54	8448.651

Table 8. Monthly values of carbon footprint.

Month	CF [g CO_{2eq}/kg]
January	46.0
February	47.1
March	44.6
April	44.0
May	41.8
June	41.4
July	42.8
August	43.1
September	45.0
October	45.3
November	45.1
December	46.8
CF_{AV}	44.4

Expanding the analysis of the CF for the entire range (from the field to the table) requires taking into account primary production as well. Climate change has a negative impact on agriculture, which can be seen in the level of variability in yields. Agriculture is subjected to climate conditions, and the greenhouse effect affects food production. Direct GHG emissions associated with agricultural production combined with the expansion of

agricultural areas, packaging, distribution, transportation, disposal, emissions from food production and consumption processes can exceed 40% of total global emissions [42].

Factors influencing changes in agricultural carbon dioxide emission levels include soil cultivation technology, the absorption capacity of the soil, the adopted farm profile, as well as state environmental protection measures. The possibility of reducing soil carbon dioxide emissions is carried out through such measures as the plowing of organic fertilizers or their substitutes of properly prepared straw, residual crop residues and green manures, which lead to an increase in the proportion of humus, resulting in the prevention of large amounts of carbon dioxide emissions into the atmosphere [43].

Reducing the use of chemical fertilizers, modern cultivation of agricultural land, more efficient farming technology, and reducing livestock numbers are all measures that significantly reduce GHG emissions in the agricultural sector. Performing farm work with new, less energy-intensive machinery and equipment has allowed farmers to farm more efficiently, both technologically and environmentally [43].

Currently, the development of the agri-food industry is striving to fully automate production processes. Smart greenhouses, intelligent sensor networks and closed production systems, in which human participation is not directly required, are increasingly being used. It is characterized by the implementation of a variety of tools that enable the digitization of food production systems, striving to reduce labor costs as much as possible while maintaining the quality and safety of the products produced, as well as introducing sustainability principles by reducing water, fuel and fertilizer consumption and promoting the use of renewable energy [42,44].

When considering the problem of GHG emissions in agriculture, special attention should be paid to the issue of production technology. Farmers' investments in modern machinery and adherence to cross-compliance and good agricultural practices have played an important role in leveling emissions of harmful compounds into the atmosphere. Nevertheless, the threat of maintaining food security on a global scale will continue to significantly affect the level of natural resource intensity of the agricultural sector, which will translate into the level of greenhouse gas emissions in this sector of the economy [45]. Expanding the scope of farm-to-table CF analysis requires considering GHG emissions throughout the food production chain, adding up primary production and other stages of the supply chain. A complete CF analysis of flour should include all stages of production; however, in this paper it was narrowed to the stages of processing and transportation (Table 9).

Table 9. GHG emissions at different stages of food production [43,45].

Stages of Food Production	Greenhouse Gas Emissions
Land use change	Above-ground changes in biomass due to deforestation and below-ground changes in soil carbon
Farms	Methane emissions from cows, rice, fertilizer, manure and agricultural machinery
Animal feed	On-farm emissions from crop production and processing for animal feed
Processing	Emissions from energy consumption in the processing of raw agricultural products into final food products
Transport	Emissions from energy use in transportation of food products at home and abroad
Retail	Emissions from energy use in refrigeration and other retail processes
Packaging	Emissions related to the production of packaging materials, transportation of materials and disposal of used packaging

In recent years, the European Commission has carried out a series of activities to develop uniform methods for measuring the environmental impact of products and companies in different industries. The food sector has included pasta, bottled water, dairy products, wine, beer, olive oil, coffee, marine fish and meat, and pet and livestock feed, among others. In the near future, manufacturers will be required to include environmental footprint information on labels to give consumers the opportunity to make an informed choice among products that affect the environment in varying degrees [46].

4. Summary and Conclusions

The CF provides a measurable and rational basis for starting a discussion on a strategy to increase the efficiency of production processes while reducing energy consumption and developing its optimal distribution. A detailed analysis must be carried out for each production and the method of calculating the CF must be tailored to specific needs. An individual approach is required when analyzing the CF of each product, but it has to take into account the life cycle of the product. The CF is one of the best and most reliable tools for verifying processes and reducing business GHG emissions. CF analysis also allows for a reduced scope, e.g., only the manufacturing process (cradle to gate), which must be detailed in the analysis. Such a broad scope requires more work but allows for a transparent representation of processes throughout the life cycle.

Calculating CF is not yet mandatory, but it is becoming more widely used with the development of low-carbon economy assumptions and the introduction of social responsibility strategies for food producers. Dissemination of the methodology for calculating the carbon footprint can provide an effective stimulus for the implementation of efficient solutions aimed at optimizing energy consumption. Closed-loop economy refers to the constant interaction of the entire chain of actors: starting from farmers, food producers, suppliers and retail chains to consumers, as well as taking environmentally conscious actions.

The life cycle assessment (LCA) methodology was used to compare the CF of organic and conventional bread production processes. There is no unified methodology for a given product group, with individual approaches designed for specific product groups existing in the literature. To date, it has not been possible to finally globally standardize the methodology for calculating the carbon footprint. Therefore, there are many ways/versions of measuring and calculating the CF, which differ significantly from one another. It has been shown that for each production and product, a detailed analysis must be carried out and the CF calculation method must be adapted to specific needs, taking into account their characteristics. Appropriate CF analysis methods and universal metering systems are necessary to identify the individual steps responsible for GHG emissions in food production. CF reduction is possible by shortening the supply chain, optimizing production equipment, and modifying food technology and production planning.

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Effects of Biochar and Cattle Manure under Different Tillage Management on Soil Properties and Crop Growth in Croatia

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Abstract: The negative environmental impact of conventional agriculture threatens agroecosystem stability and food security. Therefore, searching for optimal soil management practices is crucial for maintaining and improving soil functions. This work aims to determine the impact of conventional and conservation tillage on Stagnosols in a semi-humid environment in Marija Magdalena (Croatia) during 2021 and 2022. Under each tillage treatment, subplots were biochar, cattle manure, and control (split-plot design). The conservation tillage exhibits lower compaction in addition to conventional tillage. In 2021, at 0–15 cm and 15–30 cm depths, control plots had the highest bulk density (BD), while biochar plots had the lowest. In 2022, biochar and manure treatments under conventional tillage had significantly higher BD than those under conservation tillage. Penetration resistance did not exceed 2 MPa in all treatments. Soil water content was high in conservation treatments at 0–15 cm. Water-stable aggregates were higher in biochar and manure plots under both tillage treatments. Maize yield was higher in conservation treatments in 2021 and in conventional during 2022. Manure and biochar in the conventional system showed a better impact on grain yields than under conservation. Conservation tillage in rain-fed farming maintains crop yields and reduces soil compaction.

Keywords: reduced tillage; soil amendments; soil compaction; grain yields; sustainable agriculture

1. Introduction

Soil is a limited natural resource essential for human life. Soils support numerous ecosystem services. Soils provide food, wood, and fiber. They support the purification of water and the delivery of other diverse ecosystem services like transforming nutrients, substances, and water, the provision of a physical and cultural basis for humans and their activities, and the function of geological and archaeological archives [1,2]. In the context of food security, global threats like climate changes and wars, and the importance of soils in sustaining human life, soil provisioning services became the main focus in the scientific literature [3–6].

In acknowledgment of agricultural systems' importance, the food provided by soils still reaches more than 95% globally [7], providing about 90% of food calories and 80% of proteins and fats [8]. The sustainability of agricultural systems nowadays presents a significant issue of concern. Long-term conventional soil management in annual and perennial croplands significantly exacerbated land degradation processes [9,10]. According to Löbmann et al. [11], at least one-third of the global land is considered moderately

to highly degraded, while in the European Union (EU), 60–70% of soils are considered degraded [12].

The leading causes of soil degradation in croplands were identified: frequent invertive tillage, wheel traffic, overuse of pesticides and mineral fertilizers, lack of organic amendments, and proper crop rotations [13]. Conventional agricultural practices decrease aggregate stability, biological activity, and soil fertility [14]. Frequent machinery traffic during tillage, sowing, and plant protection increases soil compaction and overland flow [15], often increasing diffuse pollution [16,17]. Conventional tillage negatively affects soil structure [18] and decreases hydraulic conductivity [19], which inhibits root development and reduces grain yields [20].

Distorted structure and elevated soil compaction in conventionally managed croplands are responsible for disturbed aeration and increased CO_2 emissions [21], increasing the negative impact on the climate crisis [22,23]. On the other hand, conservation management appears as an interesting alternative to conventionally managed soils. Conservation agriculture is a system of agronomic practices that include reduced tillage or no tillage, permanent organic soil cover by retaining crop residues, and crop rotations, including cover crops [24]. Conservation agriculture management is proven to reduce compaction [15], mitigate overland flow and sediment losses [17], reduce fuel and labor costs [25], and increase carbon sequestration [24].

Conservation agriculture regularly uses organic amendments to reduce soil degradation and improve soil properties [24]. Farmyard manure and biochar in the scientific literature are associated with positively impacting soil physical and chemical properties, and they can help in reducing nitrogen fertilizer losses [26,27]. Their impact on soil is mainly related to enhanced soil structural stability, higher porosity, reduced compaction, erosion, and overland flow, and elevated carbon. In contrast, benefits like higher nutrient availability, reduced toxic chemical load, facilitated biodiversity, reduced emission of greenhouse gases, and better water storage capabilities are also documented [28,29]. Root and microbial activities are also positively impacted [30]. Biochar use in some soils can be used as a crop residue strategy in a conservation agriculture system [31]. Choice of soil management can affect the loss of soil organic carbon content and the proportion of soil degradation and determine the soil production level and duration of its exploitation. The influence of soil management on soil physical properties and yields is well documented. Still, the results are frequently inconsistent, mainly because soil responses to agronomic practices are also influenced by climate, soil texture, and soil organic matter (SOM) [31]. Due to the primary use of universal solutions to site-specific conditions, the farmers often failed to obtain stable yields. Then, they reversed to transition into conservation agricultural practices. The solutions of conservation agriculture practices should be tested for specific pedological, geomorphological, and environmental conditions. Otherwise, the results will not support the easy transition of farmers toward sustainable practices. Hence, adopting site-specific soil conservation practices in croplands is extremely important to reduce the negative impact of conventional agriculture. The effect of the management of tillage and organic amendment (biochar, manure) on maize grain production in loam Stagnosols under semi-humid conditions needs to be better documented. Moreover, biochar trials are mainly set up in glasshouses, accelerating the need for more experiments under field conditions [31]. We thus hypothesized that (i) the conservation treatments enable the preservation of soil physical quality, preventing compaction; and (ii) adding organic amendments will provide a better soil structure and higher crop yields. This work aims to study (i) the impacts of tillage and amendment treatment on compaction, structure, and soil water content and (ii) to identify the most appropriate soil management for maize grain yields.

2. Materials and Methods

2.1. Study Site

The study area is located in northwestern Croatia (45°55′ N; 15°44′ E; elevation—211 m above sea level) in the village of Marija Magdalena (Figure 1). It is predominantly a hilly area, and land besides natural forests is covered mainly by croplands and orchards. The slope inclination in the study area is 11°. The climate of the study area is temperate continental. The mean annual temperature is 11.2 °C, and the total average precipitation is 970 mm. The studied years (2021 and 2022) are similar to the average 1995–2020 (Figure 2). The study area's soil is classified as Stagnosols [32] loam in topsoil and clay loam in subsoil (Figure 1). The general properties are shown in Table 1.

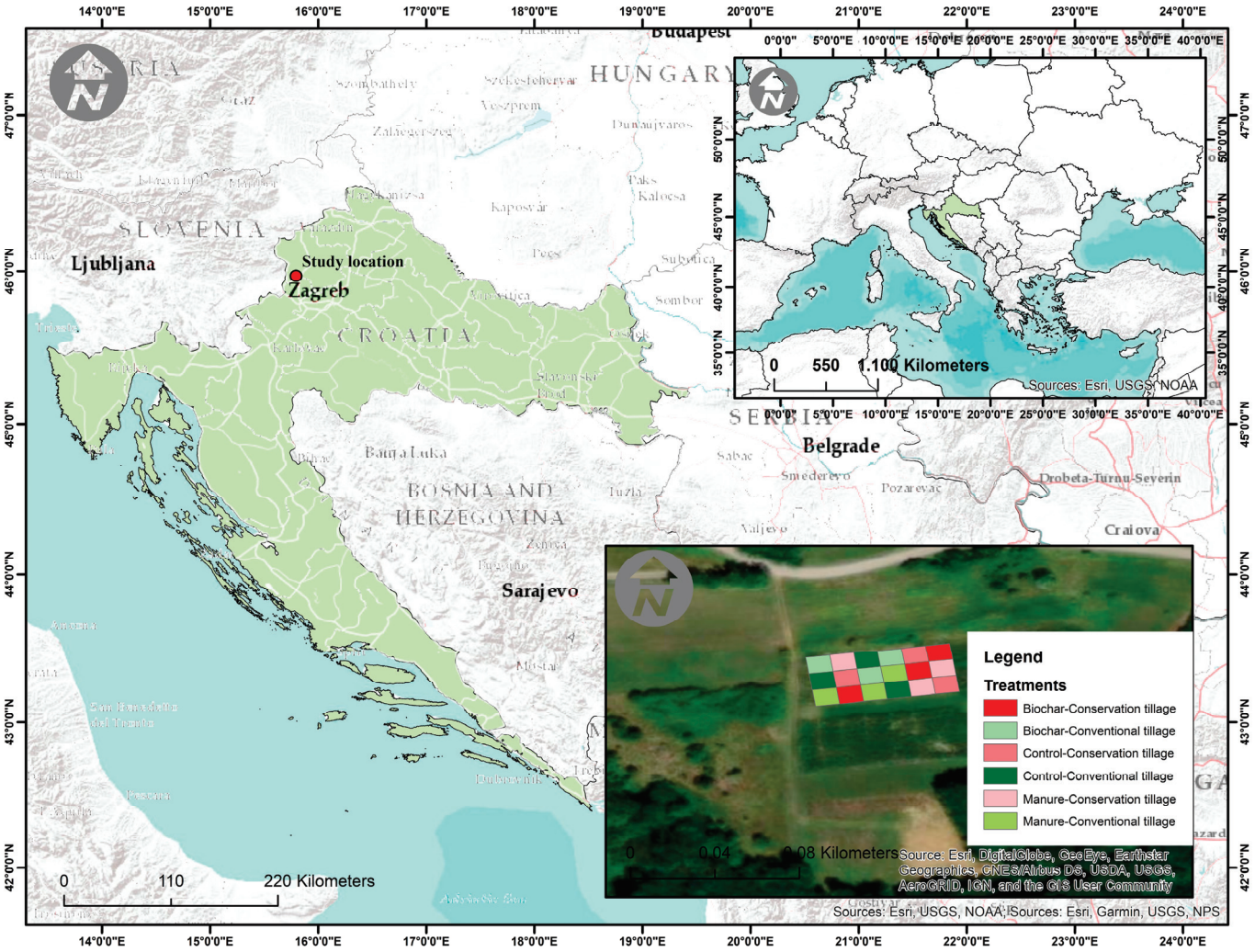

Figure 1. Location and design of the experiment in Croatian and Central European relations.

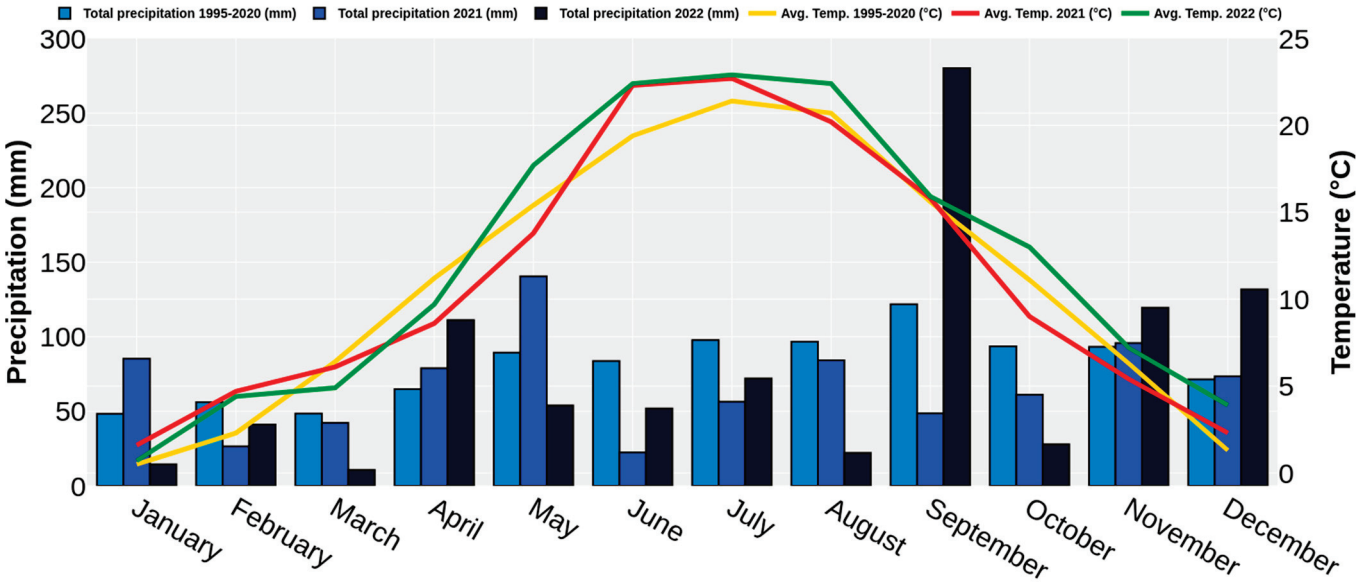

Figure 2. Monthly precipitation and temperature throughout the experimental period along the long-term average.

Table 1. Soil properties at 0–35 and 35–70 cm depths.

Soil properties	0–35 cm	35–70 cm
pH in H_2O	7.29	5.10
P_2O_5 (mg kg^{-1})	163	42
K_2O (mg kg^{-1})	282	79
Organic matter (%)	3.37	1.9
Bulk density (g cm^{-3})	1.26	1.34
Water holding capacity (%)	44.04	30.68
Clay (%)	23.2	39.9
Silt (%)	30.4	21.0
Sand (%)	46.4	39.1
Texture	Loam	Clay Loam

2.2. Experimental Design and Management Practices

The experimental plots were established in the autumn of 2020 and consisted of a split-plot design with tillage as the primary treatment and amendment application as sub-treatment (Figure 1). Two tillage treatments were considered (8 m wide and 18 m long): conventional and conservation tillage (Figure 1). Conventional tillage involves moldboard plowing to a depth of 30 cm and preparation of the seedbed with a roto-harrowing to an 8 cm depth before seeding. Conservation tillage treatments consist of loosening (non-invertive) to a depth of 30 cm and harrowing to a depth of 8 cm. Both treatments incorporated plant residues into the soil. The crops grown on each experimental plot were maize (*Zea mays* L.) during both seasons (2021–2022), as well as 2020 under non-irrigated cultivation.

Primary tillage (plowing and loosening) for maize was implemented during November in the previous autumn, and supplementary tillage followed in April before planting. Between-row cultivation measure was not performed during the research period. In each tillage treatment, three sub-treatments (8 m wide and 6 m long) (Figure 1) were established: without any addition—control, biochar, derived from wood, with a dose of 40 t ha^{-1}, and the addition of cattle manure (40 t ha^{-1}). Biochar and manure were added only during primary tillage performed in November 2020. Their basic properties are presented in Table 2.

Table 2. Basic properties of used manure and biochar.

Property	Cattle Manure	Biochar
H_2O	79.67	66.24
Dry matter (%)	20.33	33.76
pH	8.85	8.33
Organic matter (%)	81.93	91.64
N (%)	0.85	0.33
P_2O_5 (%)	0.232	0.15
P (%)	0.101	
K_2O (%)	0.665	0.46
K (%)	0.552	
Ca (%)		1.37
Mg (%)		0.09
Fe (mg kg^{-1})		223
Mn (mg kg^{-1})		360

2.3. Penetration Resistance and Yield Measurements, Soil Sampling, and Laboratory Analysis

We determined soil sampling in all plots during May 2021 and 2022. Each plot was sampled with six cores. In total, 18 random points were selected for sampling at each treatment. Soil was sampled at 0–15 cm and 15–30 cm depths using 100 cm^3 cylinders. Overall, a total of 108 soil samples were collected per sampling date (2 tillage × 3 amendment × 3 replicates × 2 depths × 3 repetitions). The undisturbed soil samples were transported to the laboratory and dried in the oven at 105 °C for 48 h to measure bulk density (BD) and determine soil water content (SWC). Penetration resistance (PR) measurements were carried out simultaneously in the vicinity of the sampling point using a cone penetrometer (Penetrologger, Eijkelkamp, Giesbeek, The Netherlands), which measures PR at each cm. The PR data were grouped in soil layers 0–15 and 15–30 cm, respectively. In total, 15 sampling points per treatment (90 per sampling date) were measured at 0–15 cm and 15–30 cm depths.

Additional undisturbed soil samples (0–15 cm) were collected and stored in rectangular plastic boxes to determine soil structural properties. Undisturbed soil samples were prepared by hand [33] and, after air-drying for one week at room temperature (25 °C), were dry-sieved in a sieve shaker for 30 s [34] to obtain particular aggregate size fractions (<0.25, 0.25–0.5, 0.5–1.0, 1.0–2.0, 2.0–4.0, 0.4–0.5, and 0.5–0.8 mm) and calculate mean weight diameter (MWD) using the following formula for calculation after weighting each aggregate size:

$$\mathrm{MWD} = \sum_{i=1}^{n} x_i \times w_i, \quad (1)$$

where x_i is the mean diameter of any particular size range of aggregates separated by sieving, and w_i is the weight of aggregates in that size range as a fraction of the total dry weight of soil used. Eijkelkamp's wet sieving method derived from Kemper and Rosenau [35] was used to determine water-stable aggregates (WSAs) with Eijkelkamp's wet sieving apparatus on all previously dry-sieved samples in the particle size range 1.0–2.0 mm. The percentage of WSAs was received with the equation:

$$\mathrm{WSA} = \frac{W_{ds}}{W_{ds} + W_{dw}} \times 100, \quad (2)$$

where WSAs is the percentage of stable water aggregates, W_{ds} is the weight of aggregates dispersed in dispersing solution (g), and W_{dw} is the weight of aggregates dispersed in distilled water (g).

Samples and penetration measurements were collected/measured from non-traffic areas on each plot. Each year during the harvest, six passes of the harvester per treatment were performed to determine the maize grain yields. Afterward, the grain was cleaned and weighed, and the obtained values were corrected to a 14% grain moisture content.

2.4. Statistical Analysis

Before statistical analysis, data were checked for normality with the Kolmogorov—Smirnoff test. Normal distribution of the data was considered at a $p > 0.05$. Bulk density, WSA, and PR followed the Gaussian distribution, while SWC, MWD, and crop yield data were box-cox- and logarithmic-transformed to meet normality requirements, respectively. A two-way ANOVA design was applied. If significant differences were identified at a $p < 0.05$, Duncan's post hoc test was applied. Statistical analyses were computed with SAS 9.3 software package (SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. Soil Water Content, Bulk Density, and Penetration Resistance

Over two years of management practices consisting of tillage and amendment management, our experiment showed significant interactions on several soil physical properties in each soil depth layer (Table 3). During 2021, conservation tillage improves SWC and soil compaction properties at the topsoil layer. At 0–15 cm depth, significantly higher PR was measured at control than at manure plots under conservation tillage. Control plots at conservation tillage had significantly higher PR than control under conventional tillage. At 15–30 cm depth, biochar and control have significantly higher PR than at manure plots under conservation tillage. Under a conventional tillage system, differences are insignificant, with the PR highest at the biochar (1.23 MPa) and the lowest at the manure (1.04 MPa) plots.

Table 3. Results of two-way ANOVA considering penetration resistance (PR), soil water content (SWC), and bulk density (BD). Different letters after mean values in the columns represent significant differences at $p < 0.05$.

Depth	Tillage	Amendment	PR (MPa)		SWC (% vol)		BD (g cm^{-3})	
2021				$\bar{x}$		$\bar{x}$		$\bar{x}$
0–15 cm	Conventional	Biochar	0.71 abc	0.77 c	40.2 a	40.4 ab	1.32 ab	1.35 a
		Control	0.86 bc		40.3 a		1.37 a	
		Manure	0.76 bc		40.8 a		1.35 ab	
	Conservation	Biochar	0.92 ab	0.89 c	42.8 a	42.0 a	1.29 b	1.31 b
		Control	1.07 a		42.1 a		1.34 ab	
		Manure	0.66 c		41.1 a		1.30 b	
F			8.700		1.12		4.76	
p			0.0003		0.331		0.012	
15–30 cm	Conventional	Biochar	1.23 b	1.15 b	37.8 ab	38.5 bc	1.37 ab	1.38 a
		Control	1.15 b		36.7 b		1.40 a	
		Manure	1.04 b		41.0 ab		1.37 ab	
	Conservation	Biochar	1.58 a	1.40 a	30.9 c	37.5 c	1.28 c	1.29 b
		Control	1.50 a		39.8 ab		1.32 c	
		Manure	1.11 b		41.6 a		1.27 bc	
F			6.800	1.404	2.843	1.618	0.06	3.56
p			0.010	0.028	0.035	0.021	0.033	0.031
2022								
0–15 cm	Conventional	Biochar	0.76 a	0.74 c	36.5 a	35.74 a	1.30 a	1.29 c
		Control	0.72 a		35.1 a		1.27 ab	
		Manure	0.74 a		35.6 a		1.31 a	
	Conservation	Biochar	0.92 a	0.87 c	36.5 a	35.17 a	1.20 b	1.21 d
		Control	0.85 a		33.8 a		1.22 b	
		Manure	0.86 a		35.2 a		1.22 b	
F			0.769		0.062		0.351	
p			0.383		0.940		0.041	

Table 3. *Cont.*

Depth	Tillage	Amendment	PR (MPa)		SWC (% vol)		BD (g cm^{-3})	
15–30 cm	Conventional	Biochar	1.02 c	1.11 b	35.6 ab	34.36 a	1.41 ab	1.42 a
		Control	1.16 abc		34.3 abc		1.44 a	
		Manure	1.14 bc		33.2 bc		1.42 a	
	Conservation	Biochar	1.53 a	1.43 a	38.7 a	34.75 a	1.37 ab	1.37 b
		Control	1.50 ab		29.9 c		1.39 ab	
		Manure	1.25 abc		35.7 ab		1.34 b	
F			13.310	2.589	4.104	0.184	0.390	0.58
p			0.0004	0.011	0.021	0.668	0.028	0.037

In 2021, at 0–15 cm depth, conservation tillage seems to conserve more water in the soil, although the differences are insignificant. At 15–30 cm depth under conservation tillage, manure plots recorded significantly higher SWC than biochar plots (Table 3). Bulk density differs between treatments in both depths. Generally, the conservation tillage exhibits lower compaction in addition to conventional tillage. More specifically, control plots have the highest BD at 0–15 cm and 15–30 cm depths, while biochar plots have the lowest BD.

During 2022, the tillage and amendment treatments significantly impacted BD at 0–15 cm depth. Biochar and manure treatments under conventional tillage have significantly higher BD than those under conservation tillage. At 15–30 cm depths, BD at manure plots is significantly higher at conventional tillage than at conservation. Regarding the PR and SWC at 15–30 cm depth, significant differences in SWC occur under conservation tillage where control plots recorded significantly lower SWC than biochar and manure plots. Differences among amendments in PR did not occur under both tillage managements. Biochar plots under conventional tillage recorded significantly lower PR than those under conservation tillage.

3.2. Soil Structural Properties

Soil structural properties during 2021 and 2022 are presented in Figure 3. In 2021, only non-significant differences between treatments in the cases of MWD and WSAs occur. Biochar and manure plots recorded higher MWD and WSAs than control plots on both tillage treatments (Figure 3a,b). Conservation tillage plots recorded slightly higher WSAs than conventional plots (Figure 3b). During 2022, on both tillage treatments, the amendment did not significantly modify the MWD (Figure 3c). Conventional tillage has a slightly higher MWD than conservation tillage plots. Biochar and manure plots at conventional tillage management recorded significantly higher WSAs than control plots (Figure 3d). In the conservation tillage system, manure treatment recorded significantly higher WSAs than other treatments in the conservation tillage system. Generally, the stability of the soil in 2022 is on a higher level compared with 2021.

3.3. Maize Grain Yields

The yields are presented in t ha^{-1} at 14% moisture content. In 2021, the highest maize yield was detected in conventional tilled manure plots (8.86 t ha^{-1}), followed by conservation control plots (8.47 t ha^{-1}) (Figure 4). The lowest was noted at conventionally tilled biochar plots (5.98 t ha^{-1}). Comparing the tillage effect, the maize grain yields did not significantly differ. Conventional tillage recorded 7.04 t ha^{-1} and 7.63 t ha^{-1} at conservation tillage. In 2022, conservation-tilled control and conventional-tilled biochar reached the highest yield (10.50 t ha^{-1}; 10.08 t ha^{-1}), followed by conventional-tilled control (9.54 t ha^{-1}) and manure plots (9.24 t ha^{-1}). The lowest yields were noted at conservation manure plots (8.29 t ha^{-1}). The tillage effect was not significant. Conservation tillage plots (9.20 t ha^{-1}) recorded lower yields than conventional (9.62 t ha^{-1}).

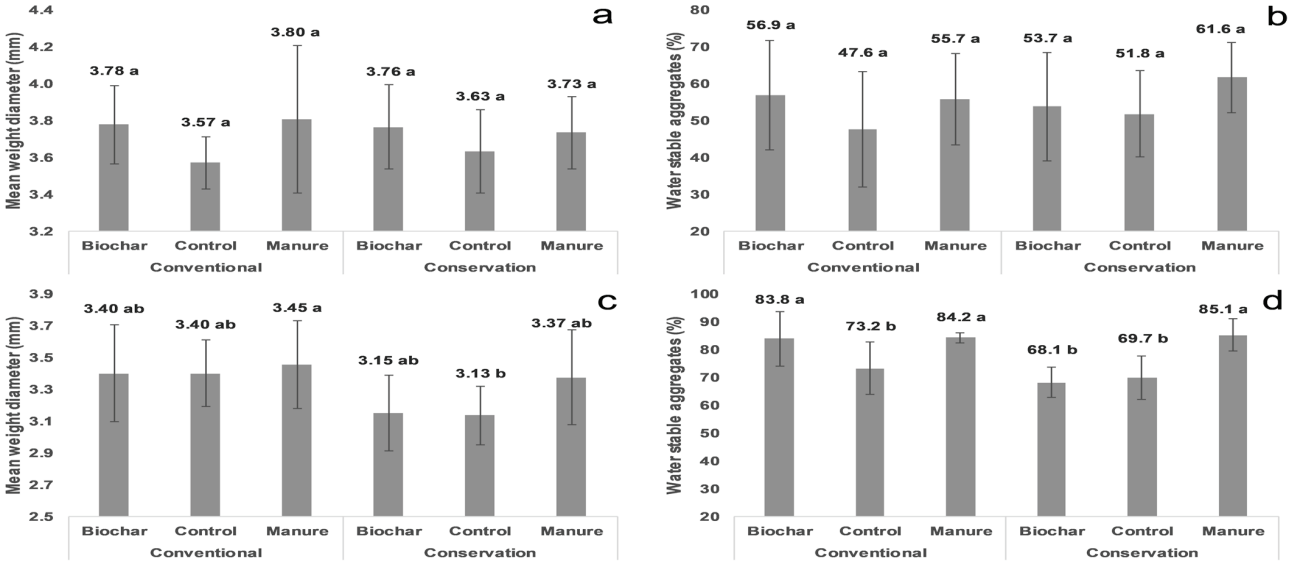

Figure 3. Effect of tillage and amendments treatments on (**a**) mean weight diameter in 2021, (**b**) water-stable aggregates in 2021, (**c**) mean weight diameter in 2022, and (**d**) water-stable aggregates in 2022. Different letters represent significant differences at $p < 0.05$. Hanging bars represent standard deviation.

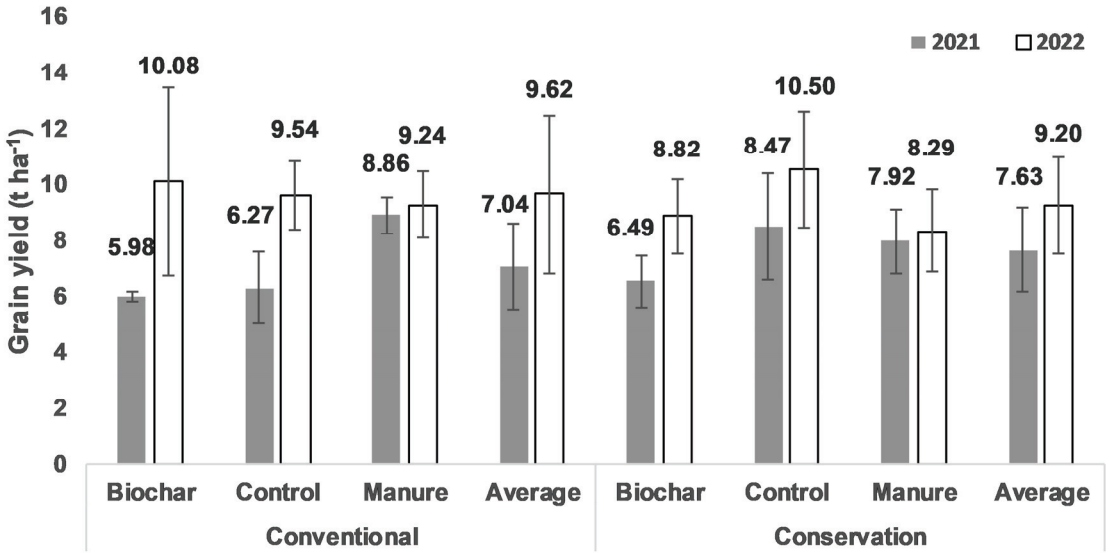

Figure 4. Maize grain yield on different treatments in the 2021 and 2022 agricultural year. Hanging bars represent standard deviation.

4. Discussion

4.1. Impact on Soil Properties

Conventional agriculture in continental European conditions, specifically the Pannonian region, produces food (second-most significant region regarding the share of agricultural land use in Europe but first in productivity) for international markets in croplands, for the most part, covered by bare soils due to frequent use of conventional practices, i.e., conventional tillage and herbicides [10,36,37]. Conservation agricultural practices are rarely applied and cover small areas. Proper soil management practices are critical aspects of the sustainability of agroecosystems, and there is a need to research which conservation management strategies are sustainable. The frequency and severity of climate and weather extremes are increasing, making the last two decades to have far-reaching effects inside and outside of the European Union. Further, economic losses from more

frequent climate-related extreme events are increasing, averaging over EUR 12 billion annually [38]. In order to raise the climate challenge, climate neutrality by 2050, and an emissions reduction target of at least 55% by 2030, there are mechanisms to combat what the European Council sees as "an existential threat". The present research is focused on adapting regional agriculture solutions in a "no regret" manner, as the Global Commission on Adaptation sees them—solutions worth pursuing regardless of the ultimate climate path [38]. Soil degradation is one of the consequences of conventionally managed soils, and soil carbon loss, soil compaction, and erosion contribute to soil degradation [39] but also result in variable and decreased yields, negatively impacting farmers' incomes [40–42]. At the same time, another type of damage (floods, downstream sedimentation of lakes and rivers) significantly damages infrastructure, the environment, and society [43].

This study demonstrates that conservation tillage practices (soil layers were kept at the same level throughout the year) applied in continental Croatia on rain-fed croplands resulted in lower soil bulk density, while the maize grain yields were not decreased. The measurements during 2021 and 2022 confirmed that conventional tillage on the experiment increased compaction levels (measured by BD) by 3% and 7% on 0–15 cm and 15–30 cm depths, respectively, making these land management practices less sustainable. Soil tillage is seen as a key factor for growing conditions and crop performance, and it is performed mainly to optimize soil productivity by modifying its properties [44]. Tillage has been a major cause of soil degradation since the first agricultural revolution [45]. Several researchers confirm the fact that conventional tillage with frequent invertive tillage operations leads to elevated soil compaction levels [9,15,36,37,46]. Such negative soil status reduces the long-term productivity of soils since it negatively influences the various physiological processes in soil and modifies soil properties such as organic matter or microbial properties [47]. Conventional tillage often decreases the bulk density of soil in the early stages of plant growth [44]. However, until the end of the vegetation season, the compaction level in conventional tillage systems is several times higher due to settling, unstable soil structure, and additional traffic events [48,49]. Our results were consistent with previous studies that reported higher compaction under conventionally plowed than under conservation loosening tillage [21,37,50]. However, the significant justification between treatments is often missing [51] due to the low sensitivity of BD properties to tillage treatments. Penetration resistance is generally low during both years of research and does not exceed values higher than 1.6 MPa on both tillage treatments. The low PR level is primarily due to the high SWC in the soil during both years of research since their relation is usually highly correlated. Such PR values do not inhibit normal growth when using the accepted limit of 2 MPa for normal root development [52]. Lower PR at topsoil and higher at subsoil is similar to other studies [37,53] and is very likely a consequence of the tillage depth that can affect soil structure, pore system, and water retention. Finally, tillage management's impact on SWC was insignificant in the present study. High SWC can explain this during the hydrologically good years 2021 and 2022. It is already noted that conservation tillage management reveals a higher beneficial effect on water conservation in arid environments on textured lighter soils than on heavy soils in humid environments [54].

In the Pannonian Croatia research area, biochar and manure caused several advantages in both tillage management systems. Farmyard manure, over millennia, and biochar, over the last several decades, have been used as examples of good agricultural practices in several agricultural production types like carbon farming, regenerative agriculture, or organic farming. Present research here confirms the same. The plots with the addition of biochar or manure recorded a more favorable structure and lower compaction. A similar idea is noted in several other studies in continental [55] or Mediterranean [56] environments on silty clay [21], clay [56], sandy loam [55], and sandy [57] soils. When used regularly, organic sources from biochar and manure elevate soil carbon concentrations, making several beneficial impacts on soil like higher aggregate stability [56,58], which increases soil resistance to settling and traffic. Secondly, manure and biochar increase water retention, infiltration, and aggregate stability [59], although several improved soil properties in

the present study record insignificant positive changes in addition to control plots. This situation may be due to the duration of the experiment. Some authors indicate that manure effects are often small or insignificant in short-term studies (less than four years) under field conditions [60–62]. This may explain some of our non-significant relations in soil physical properties between manure and biochar in addition to control plots. When looking at the whole, present research shows that biochar has similar benefits to manure for enhancing soil physical properties and can complement other organic amendments for improving soil structure and reducing soil compaction. These findings are important not only for provisioning services but also for land degradation mitigation. At the research site in Pannonian Croatia, conventional tillage was the only management strategy used by farmers, while mineral fertilizers dominated in addition to organic ones. Such management occurred from the 1960s. Such improper management can increase total erosion and facilitate sediment transport downstream; this has already been proven in several erosion and rainfall simulation studies on the same soil type and environment as in the present research [15,63–65]. As demonstrated in the current research, it is necessary to revise the study's focus. This work did not follow potential erodibility or soil erosion. Still, the positive impact of conservation tillage on soil structural properties and soil compaction level can support the conclusion that sustainable management practices that can halt and reverse land degradation in present pedological and environmental conditions are using organic amendments and non-invertive tillage.

4.2. Impact on Maize Grain Yields

Grain yield was generally high compared to the world average of 5.8 t ha^{-1} in 2021 [66]. As reported previously, conventional farming produces higher yields than organic farming [67]. In the present research, tillage and amendments had implications on maize grain yield during both years. No significant differences were observed during both years. During 2021, conservation tillage plots (7.63 t ha^{-1}) have higher yields in addition to conventional (7.04 t ha^{-1}), and vice versa in 2022 (9.20 t ha^{-1} and 9.62 t ha^{-1}). Previous works reported that maize crop yields increase under conservation loosening tillage compared to conventionally plowed tillage [68] and vice versa [54]. The results suggest that crop yields were more affected by climate factors than tillage management. The crop yield depends on the interaction between rotation, management practices, soil properties, genotype, environment, and their complex interactions [54,69]. Climate is likely responsible for differences in maize grain yields. In dry environments, crop yields are usually higher under conservation tillage management because of the high water retention compared to conventional tillage management. In contrast, in semi-humid conditions, conventional tillage treatments can produce higher crop yields [70]. Despite extensive research, the impact of tillage management on maize crop yields remains unclear to date.

A similar scenario occurs when studying the amendment's impact on maize grain yields. In conventional tillage plots, the manure plots have the highest yields in 2021, and the biochar in 2022. In conservation plots, the control treatment has the highest yields during both years. We hypothesize that this could be attributed to the initial high nutrient content in the investigated field and the high organic matter content (Table 1). Together with sufficient rainfall during the vegetation season, it is very likely that a treatment effect is overlapped. An adequate supply of nutrients for maize plants in the study soils is achieved, considering the mean plant P and K uptakes of 24 kg P ha^{-1} and 120 kg K ha^{-1} [71]. However, this situation needs to be investigated further.

5. Conclusions

The Stagnosols in rain-fed croplands in Pannonian Croatia are less sustainable when conventionally tilled. The absence of organic amendments like biochar and manure aggravates the situation, increasing the compaction rates and decreasing the aggregate size and stability. Vertical non-inversion tillage in rain-fed farming maintains crop yields and reduces soil compaction. However, biochar and farmyard manure are recommended in stud-

ied croplands where the soil is conventionally tilled since it improves soil properties regardless of the tillage management. Those findings show that the tillage management types studied here can be classified as conservation > conventional and manure > biochar > control among amendment treatments from a soil conservation and land degradation mitigation perspective. Implementing conservation tillage could also achieve efficient management for stable yields since it significantly does not differ from conventional management. In conventional tilled soils, amendment shows an increase in yields, while for conservation tilled soils, more research is desirable. It can be concluded that non-invertive conservation tillage and organic fertilization contribute to better land use management in annual croplands in Pannonian Croatia.

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Colombian Crop Resilience: Evaluating National Yield Stability for Fruit and Vegetable Systems

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Abstract: In recent years the yield of fruits and vegetables has been decreasing, threatening Colombia's food security. Analysis of crop production data may lead to identifying cropping systems that have shown better adaptability to changes in climatic and non-climatic factors associated with agricultural production. The open database AGRONET keeps data on the agricultural activities conducted in Colombia, allowing us to find the information organized by crops, regions and years. Aiming to identify resilient crop systems in Colombia, agricultural data on fruits and vegetables were analyzed. First, trends in crop production were studied by year and location, detecting the regions and crops with the highest yields in the period from 2006 until 2020. Then, mixed linear regression and principal components analysis were applied to elucidate the relation between non-climatic factors and crop yield. In Colombia, vegetable production was more efficient than fruits, observing yields of 10.23 and 13.33 t ha^{-1}, respectively. On the other hand, the Colombian central region showed high yields for vegetables, while for fruits this was exhibited in northern and eastern locations. In the present study, yield variation responded to changes in the location of crop systems, while years had no effect on vegetable production. Furthermore, the price of the agricultural product and the cost of fertilizers were associated with the yield of the analyzed crop systems. In Colombia, carrots, cabbage, tomato papaya and pineapple are resilient crops whose yield increases, especially in the regions where they are cultivated.

Keywords: crops production; agricultural management; food security; open database

1. Introduction

Colombia is one of the most biodiverse countries in the world and has the third most plant species. This biodiversity is represented in the different crops grown nationally as well. In recent years, the fruit and vegetable species with higher export amounts have been lemon, pineapple, onions and tomato, generating earnings of USD 36 million [1]. In 2021 Colombia's GDP increased by 11% compared to 2020 and agricultural activities sharing from 2005 to 2021 has been 7.0% on average [2]. In the country, around 50 million hectares are used for cattle, forest and crop production and cultivated area in 2019 was about 4.6 million. For the same year, the fruits and vegetables system covered approximately 505.164 and 288.212 hectares, respectively [3].

Since fruit and vegetable production is very important for the country to improve economic development and national food security, a comprehensive knowledge of these crops is crucial, especially a description of the yield trends during this time. Recently, this is becoming predominant to understand how food and crops are produced and to determine the impact of environmental, social and economic factors on the cultivation system [4]. Furthermore, it is important to consider the challenges imposed by climate change, which have affected agricultural activity worldwide and are threatening global food security [5,6]. It has been estimated that by 2050, crop yield should increase up to 60–110% to fulfill food needs, while negative impacts of agriculture on the environment and climate changes must be reduced [7–9].

The improvement of national agricultural activities may start by analyzing historical data on crop yields [10,11], leading to identifying the resilience of agricultural systems based on climate and non-climate changes [12]. Most of this type of research has been conducted with cereals, where it has been found that yield reductions respond to rainfall and temperature variability resulting from CO_2 increases, which produces agricultural management changes, mainly in sowing and harvest time [13,14].

Since climatic and non-climatic factors affect crop development and yield, optimal crop management must improve agricultural productivity by increasing the efficiency of the cultivated area. For instance, Deryng et al. [15] simulated the effect of climate and agricultural management on global agricultural production, modeling global crop yield and demonstrating the effect of planting and cultivar choices avoiding productivity losses. Colombia has a large environmental variability along its land extension and crop yields may change when different locations are compared since a location's productivity is determined by both climatic and non-climatic factors [16]. It is crucial to elucidate the effect of climatic and non-climatic variables on fruit and vegetable productivity, achieving a deeper knowledge of the different factors that induce variability in crop yields. In Colombia, several fruits and vegetables are produced in hillside areas, where the environmental and social conditions are quite different from the lowlands. Hillside agricultural systems deal with technical, technological, environmental, social and economic challenges [17]. For instance, the Colombian Andes show steep slopes, heavy rainfall, fragile soils, adverse geographic conditions for tillage and low incomes in the population [18]. The most determinant factors on crop productivity on hillside systems are degraded soils and soil erosion, which increase with the slope inclination and inappropriate agricultural practices [19]. Although hillside farming is one of the oldest agricultural techniques, there are practical challenges. For instance, cultivation systems have low technification, and farmers still use simple tools, low inputs and local traditional practices, which increase the labor requirement in agricultural management. Hillside farming shows low yields compared to highly technified farming systems in flat areas, resulting in low incomes for the smallholders and poor economic and social development [20].

The assessment of yield stability may be used to determine the importance of a crop system and its resilience over time. This evaluation reflects the effect of agricultural and environmental factors on crop production, which can be used to make important decisions for improving farmers' practices [21] and identifying the influence of climate change on crop performance [22,23]. Yield stability can be evaluated using several methods, which are mainly focused on the analysis of plant–environment interaction and its effect on productivity. For instance, the yield variable has been used to evaluate crop stability over time and responses to climatic and non-climatic parameters. Yield means and variance of maize, soybean and wheat in Canada were calculated to examine the effect of agricultural practices on the cultivation system. The analysis showed that input amounts and technification levels have impacts on crop yields [23]. Research in this field is focused on understanding the effect of climate variables on crop yield, especially in cereal species [22,24,25]. Also, the effect of temperature, rainfall and solar radiation on crop productivity and stability has been analyzed and predicted using database analysis [26–28].

Crop yield prediction under climate change is crucial for food production [29]. This kind of information is quite important for national food security and might be used to make decisions about food distribution and the import and export rates of agricultural products. Agricultural databases are widely distributed and implemented to uncover trends and design national crop management strategies based on data analytics. Farmers may use this information to improve agricultural practices and investment decisions [25]. The information on the national crop productivity is crucial in other industries such as seed, fertilizer and agricultural machine production [11,30]. Linear regression models are an approach to examine crop production data. These are extensively used to predict yields and observe the effect of different variables [21]. Furthermore, mixed linear models (MLM) are utilized to understand crop–environment interactions, determining the outcome of fixed and random

effects on productivity. Mixed linear models are used to visualize crop yield stability and the impact of associated factors, as well [26]. Recently, multivariate analyses have been used to analyze crop productivity, combining several climatic and non-climatic variables. Principal component analysis is implemented to understand productivity changes, identifying the effect of environmental variability on crop yields [31].

The objectives of the present research are: (i) characterize fruit and vegetable productivity in Colombia from 2006 to 2020; (ii) identify fruit and vegetable crops with high yield stability; and (iii) determine differences among national regions and the effect of non-climate variables on crop productivity.

2. Materials and Methods

2.1. Description of the Database and the Collected Information

Colombian agricultural data on crop productivity by farms were collected from the AGRONET database [32]. This database was developed and administered by the National Agricultural Ministry. The variables available in the database were: (i) crop agricultural productivity; (ii) agricultural commodity prices; and (iii) agro-inputs prices of fertilizers, fungicides, herbicides and insecticides. This information is grouped by regions, locations and crop species, and it is also organized by years from 2006 until 2020. Since the database contains information for all the crop species produced in Colombia, the data was filtered by crop species category, selecting only fruits and vegetables. The data was analyzed using the R software [33] as described as follows.

Data analyses were conducted using descriptive and inferential statistics. These were implemented to describe the agricultural productivity of fruits and vegetables crops in Colombia for 15 years, and also to uncover the trends of different non-climatic factors associated with the industry. Multivariate analysis was used to study the collected data. First, data variability was analyzed to identify outliers in the sample, which were filtered using an outlier test. The filtered data set was used to describe fruit and vegetable productivity in Colombia from 2006 until 2020.

An additional database showing agricultural practices in Colombia for the year 2018 [32] was used to validate the results observed when agricultural trends from 2006 until 2020 were analyzed. This database stores information on agricultural practices for 36 different major crops, showing the number of agri-inputs used by farms, crop yield and selling information of the agricultural products.

2.2. Description of Agricultural Productivity for Fruits and Vegetables in Colombia

Data variability of fruits and vegetables cropping systems was analyzed for the variables cultivated area (CAR), harvested area (HAR), total production (PRO) and yield (YIE). Then, trends of the agricultural productivity by type of crop were compared using annual means to display the current Colombia situation for fruits and vegetables. Comparisons among regions were conducted using the variable YIE to identify national regions with strengthened fruit and vegetable systems. The analysis was targeted at YIE because the result of this variable reflects the impact of climatic and non-climatic factors associated with the agricultural system [21]. Crop species contrasting was used to describe the local situation for fruits and vegetables in Colombia. Crops with the highest YIE were analyzed thoroughly. Similar analyses were conducted for the variables: commodity price (CPR), fertilizers price (FRP), fungicides price (FUP), herbicides price (HEP) and insecticides prices (INP). These variables were regarded as associated with the system production and used to explain the variation in crop productivity. Prices of the agricultural inputs are determinants of the practices applied by farmers in the system management, especially for smallholders, which have a lower accessibility to these products.

2.3. Evaluation of the Crop Yields to Analyze Agricultural Systems Stability

Yield data from 2006 until 2020 was used to determine the highest productive agricultural system in Colombia among regions. First, fruit and vegetable crops with the largest

means for the YIE variable over time were identified; then, those that were cultivated at least in 15 different regions, were selected. Mixed linear models (MLM) were applied to those crops previously selected to assess the stability of the cropping systems in the country. The variation caused by time (year) and location (department) in the agricultural systems was determined (Equation (1)). This methodology is described by Piepho [21]. The stability of the yield variable accounts for a random effect that is not considered by the model, high values imply low stability of the crop. The MLM for each selected crop was applied using the R lme4 package [34]:

$$\boldsymbol{yij} = \boldsymbol{\mu i} + \boldsymbol{vj} + \boldsymbol{eij} \tag{1}$$

where $\boldsymbol{yij}$ is the mean of the yield of a crop by a certain year and region, $\boldsymbol{\mu i}$ is the fixed effect caused by the region where the crop was cultivated, $\boldsymbol{vj}$ is the random effect due to the year when the crop was cultivated and $\boldsymbol{eij}$ is the residual effect of the model. Since agricultural practices used by farmers may be controlled but differ among regions, locations were considered as a fixed effect. On the other hand, changes in climate conditions by year may be stochastic, and then year was used as a random effect in the model.

2.4. Analysis of Non-Climatic Factors on Agricultural Productivity among Colombian Regions

Principal component analysis (PCA) was used to determine the impact of non-climatic variables, CPR, FRP, FUP, HEP and INP on crop variables CAR, HAR, PRO and YIE. The PCA merged all the data used in the analysis to calculate independent composite variables (principal components) that account for the variance in the original data set. PCA may be used to identify which variables are more related to them. Before the analysis, a database combining agricultural productivity and non-climatic variable prices was constructed. This was conducted assuming that CPR, FRP, FUP, HEP and INP are related to CAR, HAR, PRO and YIE by the crop cultivation region and year. Then, this database was used to conduct PCA on standardized data. Data standardization was done using the z-score [35]. The PCA was run in R software using the package Factominer [36]. This analysis was done to complete the fruit and vegetable data set and also to the previously selected crops.

The results obtained with the data set for agricultural production from 2006 until 2020, were compared to a data set of agricultural practices in Colombia for the year 2018. This data contains information on agricultural activity in Colombian farms, showing holders' practices about agri-inputs application. First, selected fruits and vegetables crops were analyzed by comparing YIE means among Colombia regions. Analysis of variance (ANOVA) was applied to determine the significant difference in crop productivity. Then, data on the amount of fertilizers, herbicides, fungicides and insecticides were correlated to yield. This data was collected and structured by Colombia's National Administrative Department of Statistics (DANE), selecting 1942 farmers and assessing yield and several agricultural practices by farm, like the amount of agricultural inputs used and management costs. The data set of 2018 was used to compare the results of the agriculture sector observed from 2006 to 2020 in the country.

2.5. Conceptual Framework Applied in the Study

The methodology applied in the present research is presented in the following conceptual framework, which shows the rationale used to identify resilient fruit and vegetable systems in Colombia and the impact of locations and non-climatic variables (Figure 1).

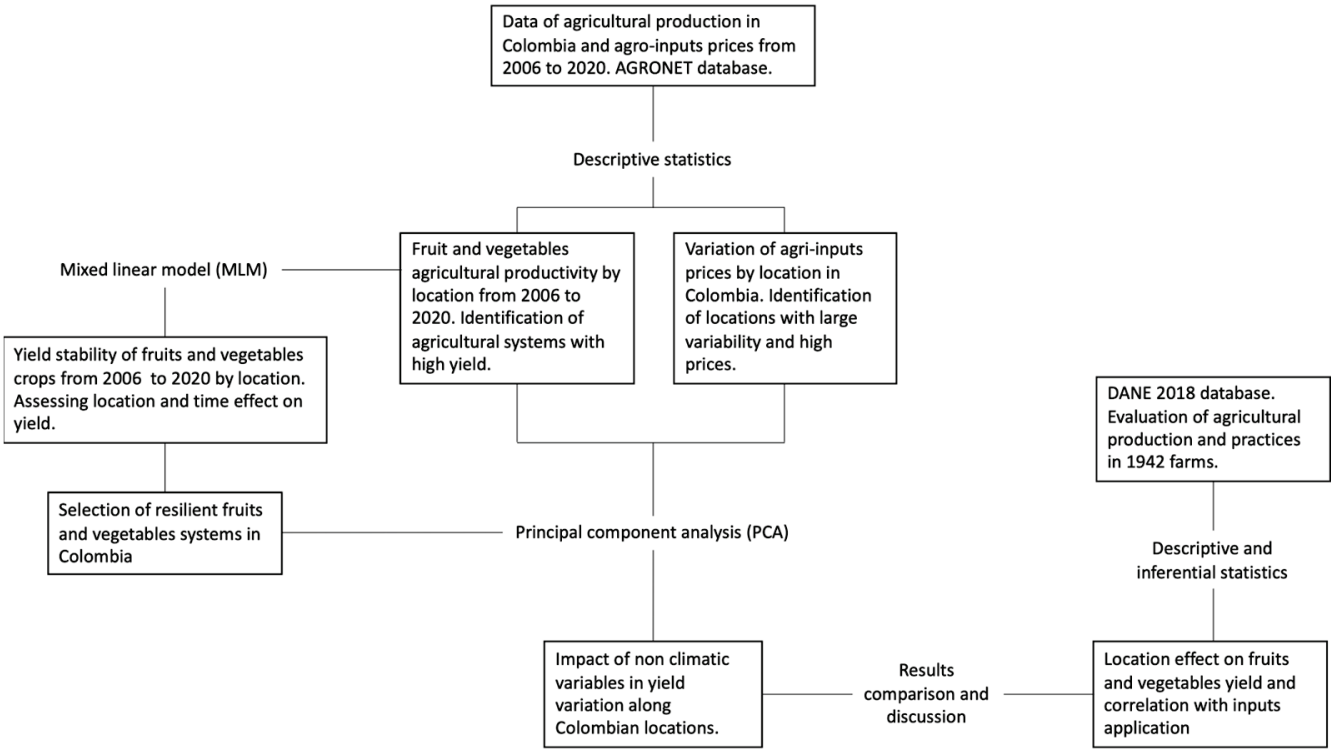

Figure 1. Conceptual framework of the research conducted to analyze fruit and vegetable agricultural productivity in Colombia.

3. Results

3.1. Decreases of Fruits and Vegetables Yield in Colombia

Data trends for vegetable and fruit systems were analyzed, initially, grouping the information by type of crop; then, variables were arranged by year and region, to understand agricultural tendencies in Colombia by time and location. Data distribution of the variables cultivated area (CAR), harvest area (HAR), production (PRO) and yield (YIE) show wide variability for fruits and vegetables in Colombia from 2006 until 2020 (Figure S1). In the last 15 years, it was observed that CAR in Colombian farms may diverge from one to more than 100 hectares for both fruit and vegetable cropping systems. This means that CAR, HAR and PRO have been higher for fruits than vegetables; however, YIE has been higher for the second at the same time. Furthermore, data shows that vegetable systems used less area than fruits for sowing (Figure S1). On the other hand, the means of analyzed variables decreased from 2006 until 2020, with a minor increase in 2018. Nonetheless, it is clear that the YIE of fruits and vegetables has widely decreased in Colombia, reaching values of 10.23 and 13.33 tons $\times$ ha^{-1}, respectively, in 2020. CAR and HAR showed similar trends during the time (Figure 2), which might be a national concern for the agricultural sector. In 2018 the amount of fruit and vegetable production increased in Colombia; however, YIE remains similar to previous years, indicating such increases relied on larger cultivated areas by farms (Figure 2).

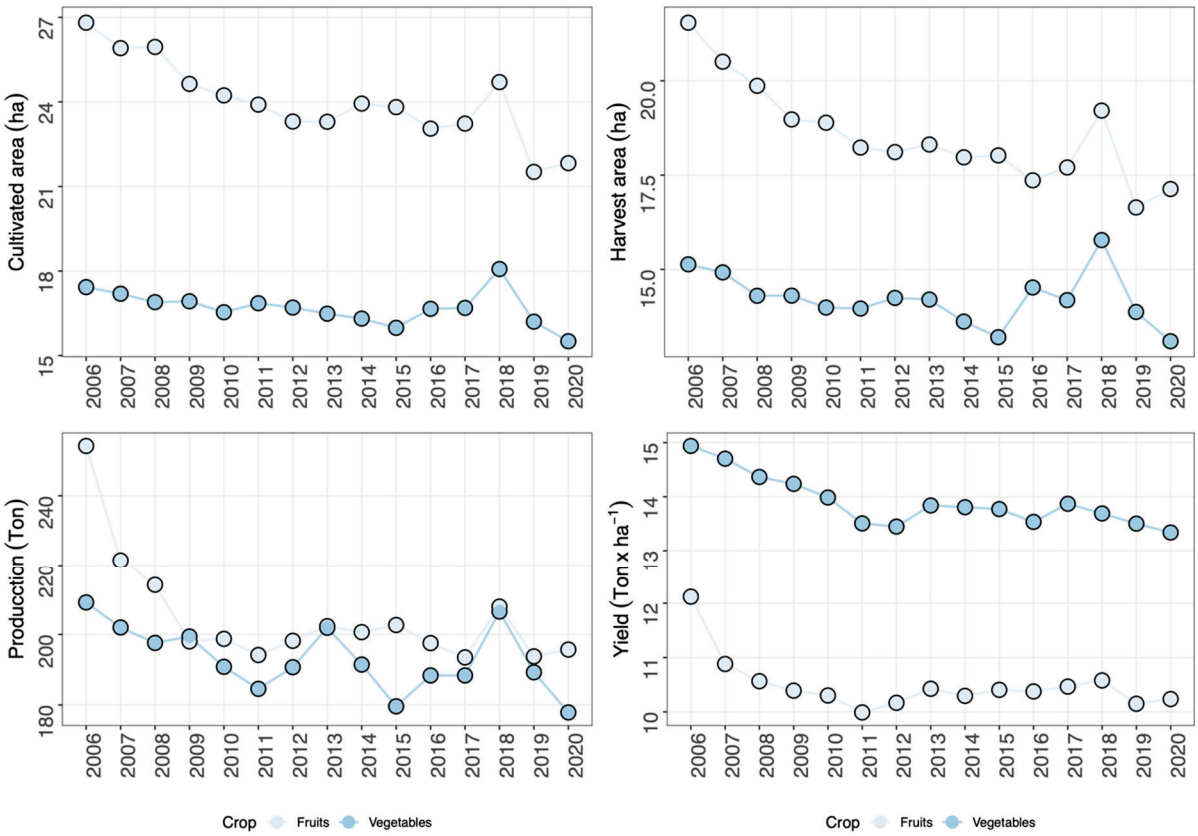

Figure 2. Trends for the means of cultivated area (CAR), harvest area (HAR), production (PRO) and yield (YIE) in fruits (light blue) and vegetables (gray-blue) in Colombia from 2006 until 2020 by farms.

3.2. Local Production of Fruits and Vegetables in Colombia

Yield analysis for fruit and vegetable systems in the last 15 years shows that farms in Arauca and Risaralda have the largest values, with an average of 18.25 y 20.08 tons $\times$ ha^{-1} for fruits and vegetables, respectively. Furthermore, farms at locations such as Valle del Cauca, Antioquia and Santander, among others, had higher YIE for both fruit and vegetable crop systems. Amazonas, Vaupes, Vichada and other regions located in south-eastern Colombia showed the lowest values for YIE. For fruit production, western locations showed higher YIE values, while for vegetables this was observed in central regions (Figure 3). In Colombia, the fruit crop with the highest yield is papaya with mean values of 17.57 tons $\times$ ha^{-1}, while cauliflower, with 20.63 tons $\times$ ha^{-1}, is the vegetable showing the largest values. Farms cultivating strawberry, grapefruit, pineapple, carrot, cabbage and tomato showed high yield values as well. Larger variabilities in YIE were observed for crops like carrot, cabbage, grapefruit, strawberry, melon and lime, while leek and badea showed less variation (Figure 4).

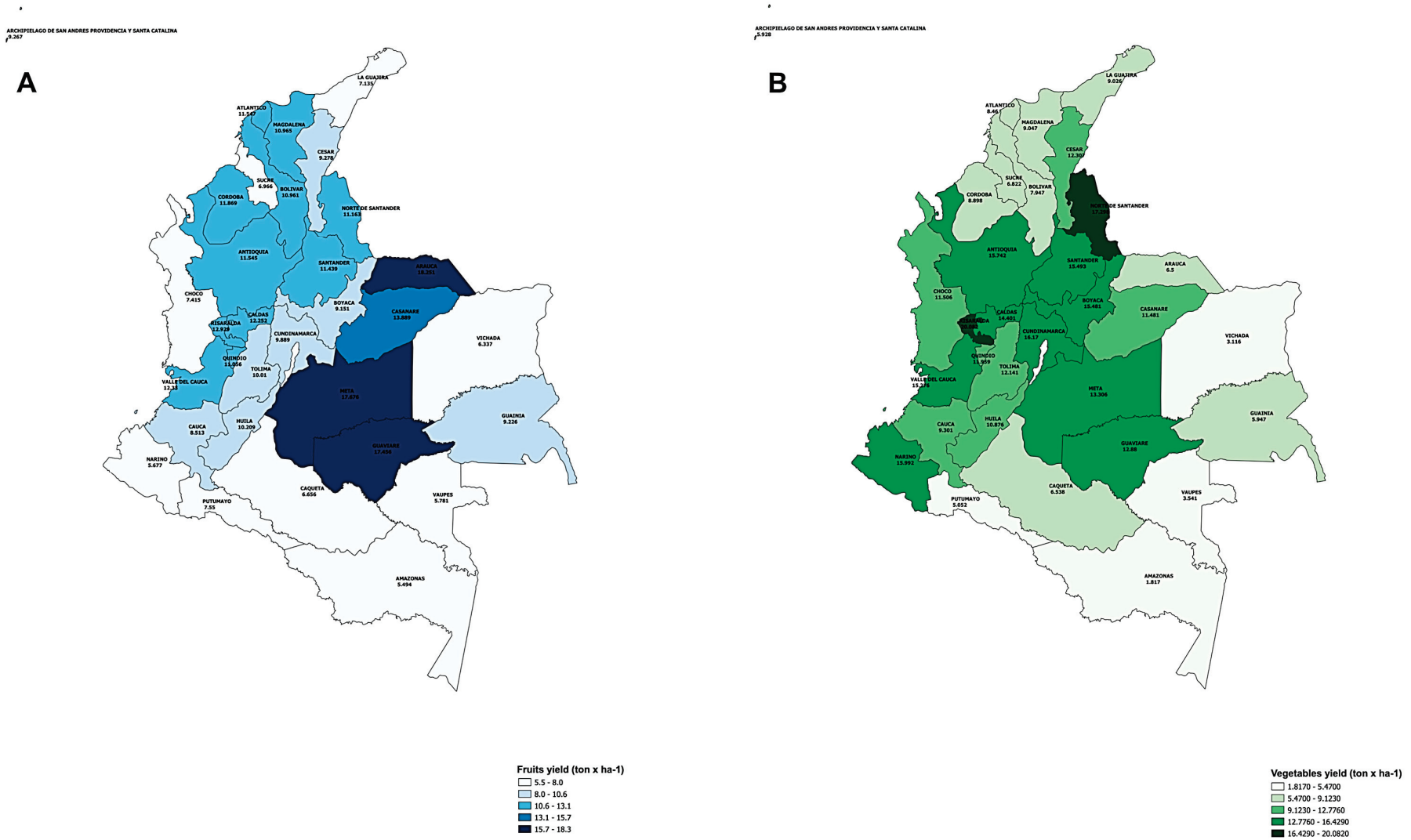

Figure 3. Colombia maps showing yields (ton $\times$ ha^{-1}) of the fruits (blue) and vegetables (green) by locations from 2006 until 2020. Values in the map indicate mean yield at every national location.

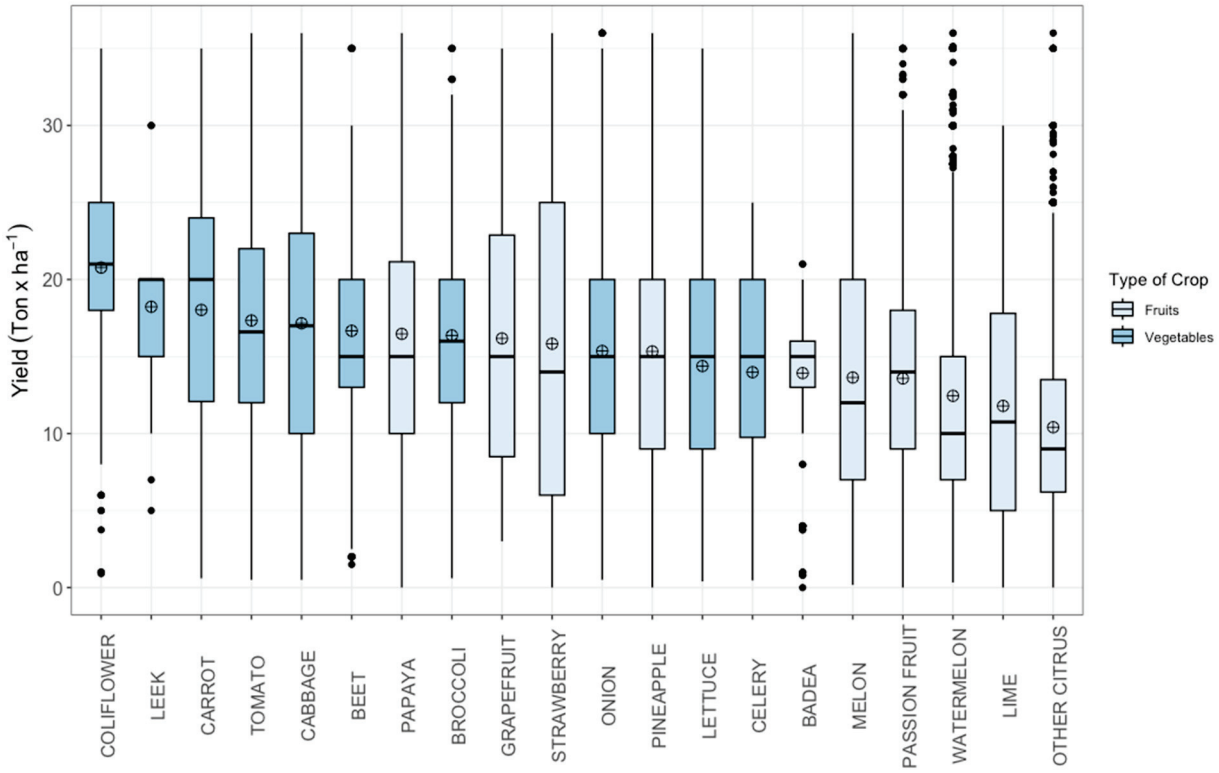

Figure 4. Boxplot of fruits and vegetables with highest mean for yield in Colombia from 2006 until 2020. Crossed circle indicates means for yield of each crop.

Yield comparison between fruits and vegetables exhibits a wide difference for these two kinds of crops. This result shows vegetable systems are more productive than fruit systems in Colombia, using the CAR more efficiently. On the other hand, fruit species with the highest YIE were those typically cultivated in farms of lowlands such as papaya, grapefruit and pineapple. The stability analysis, conducting a MLM for the productivity of Colombian farms, displays that time (random factor) had a small variance across the farms at different locations on YIE of fruit and vegetable systems. However, the fixed factor showed a large variance, indicating that the locations of the agricultural system considerably impacted the YIE augmentation. Model residual values were high and indicate that other factors should be used to understand the variability in the evaluated crops (Table 1). Locations showed a large positive impact on crops like tomato, papaya, pineapple and other citrus, which are mainly cultivated in lowlands. Departments such as Boyaca, Caldas, Cauca, Cundinamarca, Norte de Santander, Santander, Tolima and Valle del Cauca, had a diversity of agricultural systems; however, for some crops the impact of the location was negative. The largest negative effect was observed for cabbage in Cauca. For lettuce and passion fruit, location was a determinant in increases and decreases of YIE (Table 1).

Table 1. Values for the fixed (region) and random (year) effect of the mixed linear model adjusted to selected crops. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$ and ns, not significant. - indicates no data registered for the crop in the region for the evaluated years.

Predictors	Carrot		Cabagge		Tomato		Onion		Lettuce		Papaya		Pineapple		Passion fr		Melon		Lime		Other Citrus	
Antioquia	-	-	-	-	14.92	***	-	-	8.32	ns	12.24	ns	16.04	***	-	-	-	-	-	-	8.77	***
Arauca	-	-	-	-	6.74	ns	-	-	-	-	19.27	**	15.75	***	3.16	**	-	-	-	-	17.70	***
Atlantico	-	-	-	-	9.83	***	-	-	-	-	16.70	*	21.35	***	-	-	2.91	ns	2.47	ns	-	-
Bolivar	-	-	-	-	3.20	ns	-	-	-	-	17.91	*	16.46	***	-	-	4.21	ns	-	-	11.18	***
Boyaca	−4.34	***	−10.02	***	18.15	***	8.17	***	0.56	ns	10.65	ns	8.16	***	−2.38	*	7.99	ns	−12.86	ns	7.61	**
Caldas	−8.84	***	−11.69	***	18.55	***	−5.96	***	−2.13	ns	14.73	*	11.94	***	1.66	*	9.68	ns	−1.71	ns	14.09	***
Caqueta	−18.37	***	−10.07	ns	10.25	***	−9.55	*	−5.00	ns	4.35	ns	7.49	***	−4.49	ns	-	-	-	-	-	-
Casanare	-	-	-		11.58	***	-	-	-	-	18.44	*	24.54	***	1.44	*	−4.76	ns	−8.07	ns	8.62	***
Cauca	−15.18	***	−21.31	***	11.07	***	−6.55	***	−2.26	ns	14.15	*	9.57	***	−4.94	***	7.37	ns	−7.24	*	11.42	***
Cesar	−20.37	***	−13.29	*	16.20	***	4.63	***	−8.50	ns	13.24	ns	22.19	***	−5.73	***	2.33	ns	-	-	5.41	*
Choco	-	-	-	-	13.18	***	-	-	16.00	ns			15.96	***	−4.68	*	-	ns	-	-	-	-
Cordoba	-	-	-	-	10.97	***	-	-	-	-	17.12	*	19.13	***	−1.47	*	5.61	ns	2.14	ns	12.37	**
Cundinamarca	1.05	ns	−0.26	ns	14.34	***	6.57	***	6.45	ns	22.84	**	20.95	***	−4.37	***	−8.34	ns	−2.43	ns	5.45	*
Guainia	-	-	-	-			-	-	-	-			14.19	***	-	-	-	-	-	-	4.77	ns
Guaviare	-	-	-	-	11.89	*	-	-	-	-			25.75	***	-	-	-	-	-	-	-	-
Huila	-	-	-	-	15.16	***	−1.35	ns	3.08	ns	12.03	ns	14.61	***	1.50	**	9.09	ns	-	-	4.93	*
La Guajira	-	-	-	-	12.85	***	-	-	-	-	11.17	ns	6.64	ns	−8.73	***	1.68	ns	−5.92	ns	-	-
Magdalena	−7.93	ns	-	-	11.80	***	−1.13	ns	-	-	14.83	**	21.39	***	−6.29	***	−0.24	ns	-	-	14.87	***
Meta	-	-	-	-	16.08	***	−0.25	ns	-	-	24.37	**	26.45	***	3.93	***	14.08	*	-	-	14.64	***
Nariño	0.56	ns	−6.35	***	16.83	***	-	-	11.19	ns	6.03	ns	8.15	***	−3.64	***	−0.51	ns	−8.58	ns	2.20	ns
Norte de Santander	−2.52	**	−7.95	***	24.20	***	6.27	***	3.26	ns	11.73	ns	25.79	***	−3.94	***	12.94	*	−3.35	ns	7.83	**
Putumayo	−11.81	*	−20.33	**	13.61	**	-	-	−8.30	ns	7.08	ns	12.23	***	-	-	-	-	−10.05	*	14.18	**
Quindio	2.63	ns	−19.56	***	14.29	***	−0.02	ns	−2.58	ns	13.86	ns	27.03	***	−0.28	ns	-	-	-	-	18.40	***
Risaralda	−11.45	***	−0.36	ns	25.29	***	-	-	7.80	ns	13.11	ns	32.01	***	0.10	ns	-	-	8.96	***	-	-
San Andres y Providencia	-	-	-	-			-	-	-	-	12.24	ns	1.56	ns	−13.85	*	−2.03	ns	-	-	-	-
Santander	−1.38	ns	−0.04	ns	18.68	***	−0.89	ns	7.75	ns	15.22	*	24.08	***	0.28	ns	11.32	*	1.87	ns	8.53	***
Sucre	-	-	-	-		-	-	-	-	-	9.85	ns	8.55	***	−4.87	***	−1.59	ns	-	-	-	-
Tolima	−4.53	***	−5.91	**	11.76	***	7.97	**	−10.05	ns	12.04	ns	17.63	***	−3.97	***	4.97	ns	0.74	ns	7.95	**
Valle del Cauca	−10.05	***	−7.32	***	18.71	***	2.45	*	2.29	ns	20.23	**	19.74	***	3.42	***	14.47	**	2.14	ns	14.66	***
Vaupes	-	-	-	-	3.58	ns	-	-	-	-	-	-	9.57	***	-	-	-	-	-	-	-	-
Vichada	-	-	-	-	1.49	ns	37.36		-	-	0.88	ns	6.58	**	−6.86	*	−5.28	ns	3.36	ns	-	-
Year	0.14		0.12		0.40		0.04		0.00		0.08		1.51		0.18		1.46		1.75		0.35	
Residual	54.10		66.20		54.20		37.36		50.49		50.85		46.79		33.69		50.74		58.38		29.99	
r^2	0.24		0.22		0.21		0.28		0.26		0.33		0.43		0.24		0.33		0.17		0.47	

The database from 2018, which contains information about agricultural activities, practices and management of 1942 farms in Colombia, was used to contrast the trends observed in the data for fruit and vegetable production from 2006 to 2020. When the selected crops were compared, it was observed that the location of the farms had an effect on all the cropping systems, except for lime (Figure 5). Meta showed the highest YIE for papaya, melon and passion fruit, while Risaralda for tomato and pineapple. Arauca shows high values of production for passion fruit, papaya and other citrus. Large variability on YIE was observed in the cropping systems of onion, lime, melon, papaya and tomato located at Quindio, Narino, Caldas, Bolivar and Putumayo, respectively. For fruits, the highest YIE was obtained in pineapple, with values over 30 tons $\times$ ha^{-1}, while for vegetables, tomato reached yields over 25 tons $\times$ ha^{-1} (Figure 5).

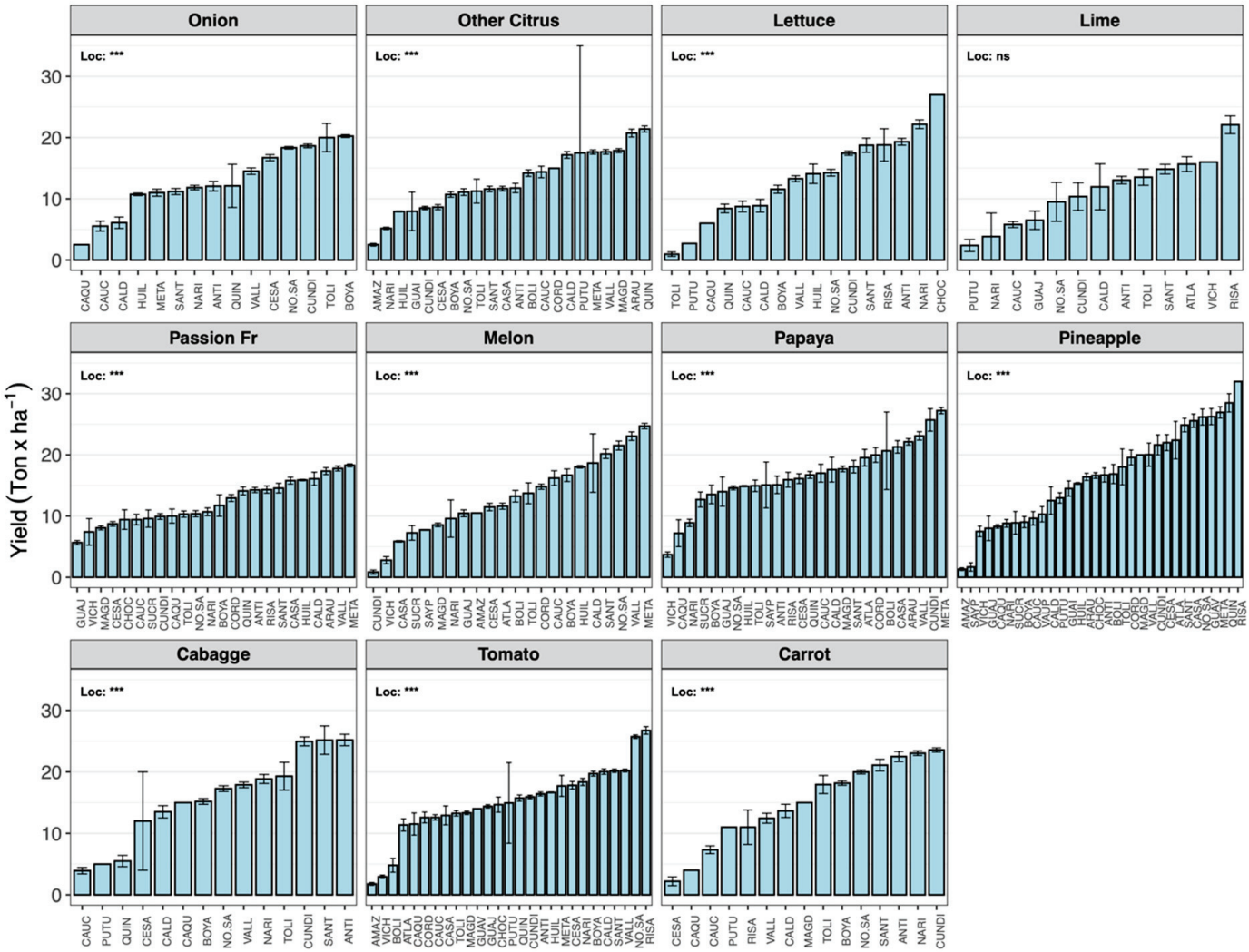

Figure 5. Comparison of yield means among farms in different Colombian locations of selected fruits and vegetables cropping systems. Black vertical lines indicate the standard error of the means. *** indicates significant differences for yield means at $p < 0.001$; ns indicates non-significant difference.

3.3. Yield Evaluation and the Impact of Non-Climate Factors on the Agricultural Systems

A large variability was observed for the crop prices (CPR) and the agri-input values in Colombia from 2015 to 2019. Crops such as lemon, onion and cantaloupe showed the largest variability in commodity prices during this time, due to the unsteadiness of markets (Figure S2). Otherwise, crops like pineapple and carrots had stability in commodity prices, even when they were low. The lowest prices were observed for papaya, green beans and tomato for the evaluated time in Colombia (Figure S2).

Agri-input prices in Colombia have large variability and several outliers in the evaluated locations. The highest prices were especially observed for biocide products. Arauca is the location with the largest mean for fertilizers and herbicides, while fungicides and insecticides were low. Locations such as Antioquia, Valle del Cauca and Cundinamarca showed middle values for prices of all the agro-inputs (Figure S3).

The analysis of the effect of these variables, described above, on the agricultural systems variables CAR, HAR, PRO and YIE was conducted using PCA. First, mean prices for all the agri-inputs and commodities were matched with the means for agricultural data based on the locations and years. The final data set comprised information for Antioquia, Cundinamarca, Norte de Santander, Risaralda and Santander y Valle del Cauca. After data standardization, the evaluated variables were merged into independent composite variables (principal components). The analysis shows that two principal components (PC1 and PC2) accounted for 46% of total variation in agricultural data. Crop production, sowing area and harvest area (PRO, CAR and HAR) showed a higher vector loading to PC1 (0.82, 0.93 and 0.95, respectively). Variables YIE, CPR, INP, HEP and FRP showed high vector loading to PC2 (0.12, 0.37, 0.38, 0.49 and 0.90, respectively) and were more related to each other. Vectors for agricultural input prices were larger than vectors for YIE, indicating higher variability for these variables. On the other hand, the results show that most of the locations change especially along the second dimension, while Antioquia, Cundinamarca and Valle del Cauca to the first (Figure 6). When crops were used to group along dimensions one and two, a particular trend was not observed (Figure S4).

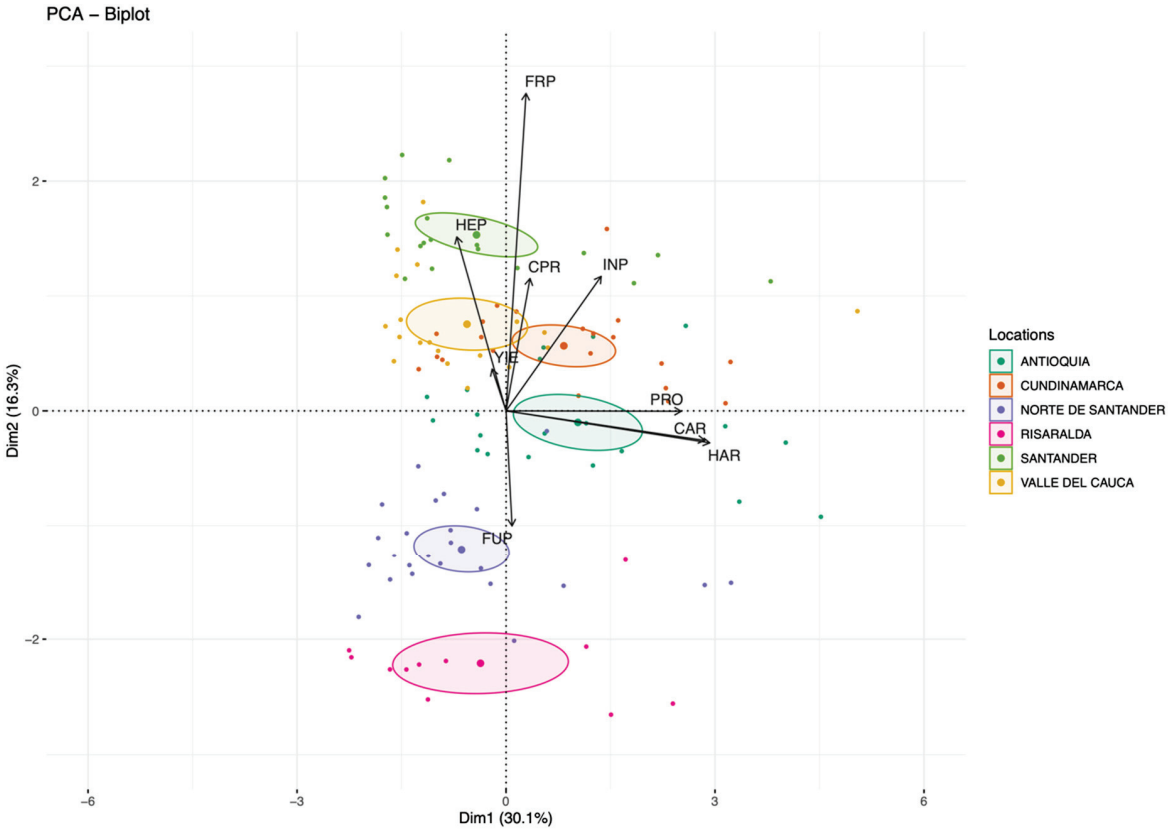

Figure 6. Biplots generated from PCA with the percentage of variance explained by the first two components for agricultural and non-climatic variables observed at different locations. Colors of the dots display the values grouped by Colombian regions. The analyzed variables were cultivated area (CAR), harvested area (HAR), production (PRO), yield (YIE), commodity price (CPR), fertilize price (FRP), herbicide price (HEP), insecticide price (INP), fungicide price (FUP).

These results, the direct influence of agri-input application on yield increase among locations in Colombia, were compared using a database with agricultural data for 2018. The selected crops were used for such validation, finding significant correlations of the yield with the amount of fertilizer applied before crop sowing and during cultivation (Figure 7A,B). The yield was also correlated with herbicide and fungicide applications during crop growth (Figure S5). Highest yields were observed for pineapple during 2018 as well as the amount of fertilizer used for the cropping system. The lowest amounts of fertilizer were used on lime and onion systems before sowing and during cultivation (Figure 7A,B).

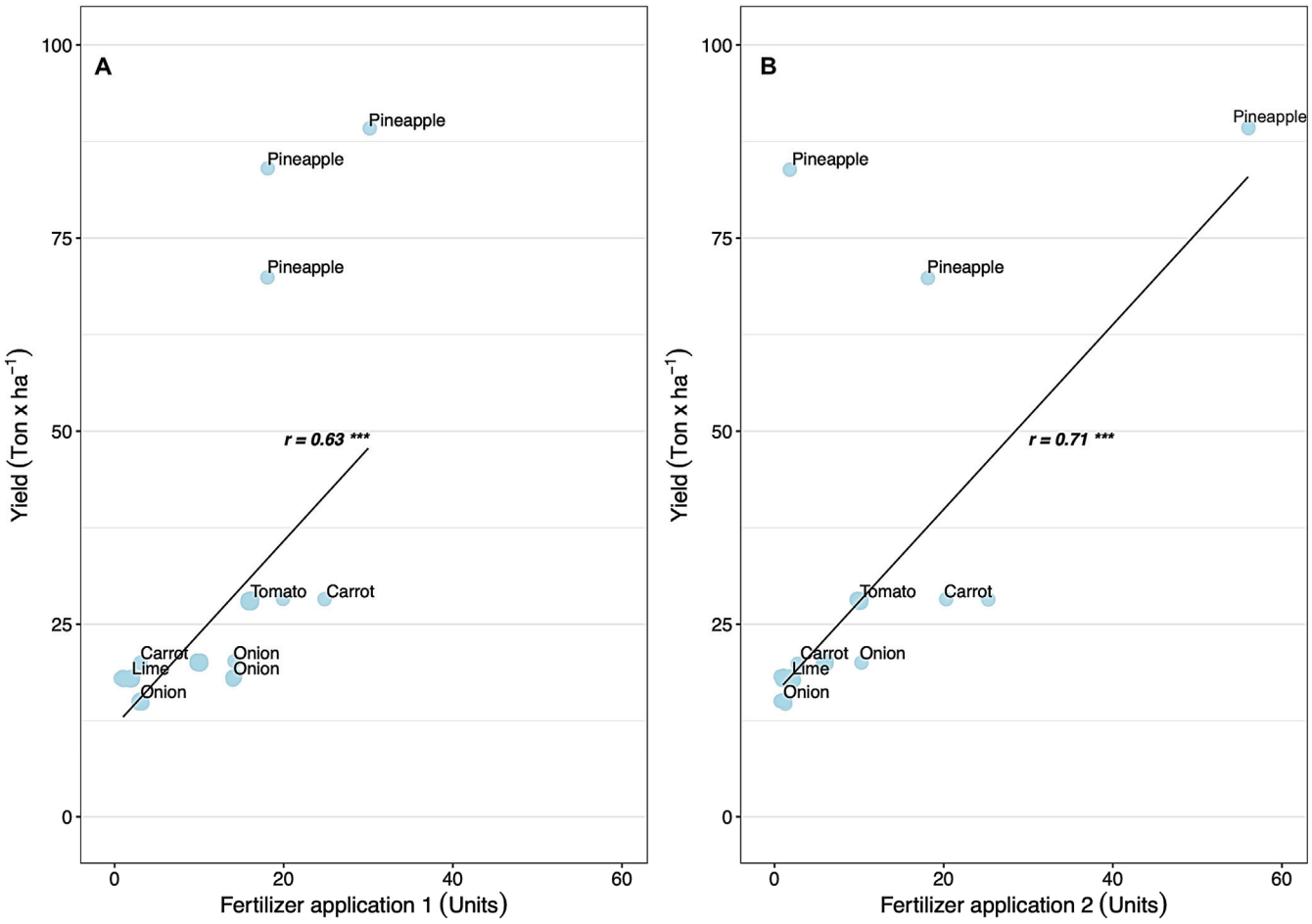

Figure 7. Yield and fertilizer application correlations for selected crops with Colombia agricultural data for 2018. First fertilizer application carried out before crop cultivation (**A**) and second fertilizer application carried out during cultivation (**B**). Pearson correlation coefficient (r) and significance test (***) with $p < 0.001$.

4. Discussion

Usually, the selection of a species for the establishment of an agricultural system is based on its economic importance. However, the identification of national strong crop systems may be developed by analyzing productivity trends and the influences of non-climatic variables. The analysis of the fruits and vegetables crops from 2006 to 2020 shows a large variation in agricultural data as a decreasing trend in the variables SAR, HAR, PRO and YIE as well (Figure S1). The described situation is opposite to the food security approach, and it could be an issue for the country in the mid and long term. Considering that the population is growing, the changes in diet habits and the agricultural area are limited, crop systems should be more efficient and productive, focusing on increasing yield [37,38]. For instance, in Colombia, the population has increased by 4.2% while the agricultural land 1.6% [39] in recent years,

escalating the pressure on the national food system. On the other hand, crop productivity and yield may be reduced by changes in the rural population in the country. It was observed that agricultural activity in Colombia is mainly done by adults between 41 and 64 years old, due to the migration of youths and young adults to urban areas who look for better academic and working options [40]. This situation is decreasing the agricultural activity in Colombia, especially fruit and vegetable crops.

When yield for crops like tomato and orange is compared to the yield in other countries such as Brazil and Chile, it is observed that Colombia had lower values in 2018; however, for lettuce and banana, the same variable is higher [39]. Then, a specific analysis for each crop was conducted, which allowed a comprehensive understanding of the yield stability of fruit and vegetable systems. The data analysis shows that vegetable systems are more efficient than fruit systems, reaching higher harvests in less sowing areas. Since agricultural land is a limited resource, crops with higher productivity in less cultivated areas are meaningful to solve agricultural issues. Even though yield increases can be achieved by enhancing the use of agro-inputs, developing more efficient crop cultivars that suitably grow under sub-optimal conditions is a long-term sustainable approach.

As it is shown by the AGRONET database, Colombia has a large diversity of fruits and vegetables agricultural systems. The foods obtained from these crops provide bioactive compounds to human nutrition, like flavonoids and carotenoids, which enhance human health, improving cardiovascular conditions and protecting against metabolic syndromes [41]. In developing countries, where diet is based on cereals, bioactive and micronutrient intake is deficient, resulting in a hidden hunger. One of the approaches to solve this issue might be nutritional-sensitive agriculture, which relies on the diversification of the agricultural systems and the cultivation of underutilized crops [41,42].

The fruit crops cultivated in the locations Arauca, Meta, Casanare, Guaviare and Risaralda had the highest yields, while for vegetables this situation was observed in Risaralda, Norte de Santander, Cundinamarca, Narino and Antioquia (Figure 3). On the other hand, the strongest crop systems, based on the mean of the yield observed for 15 years, were carrots, cauliflower, cabbage, papaya, strawberry and grapefruit (Figure 4). This calculation, developed using yield data, may reflect the impact of climatic and non-climatic data and agricultural practices. For instance, in Risaralda, where high yield was observed for fruits and vegetables, also the prices of fertilizers were low. A similar situation occurred in Arauca as well, where the yield for vegetables was high and the prices of fungicides and insecticides were low (Figure S2). Agricultural systems such as papaya and tomato had high yields, but the commercialization prices were low in the last years (Figure S1). The described situation displays the issues for analyzing the impact of individual non-climatic variables on crop productivity, which interferes with the identification of stable crop systems for the country's development. Then, a comprehensive description of fruit and vegetable crops was achieved with further analysis, where agricultural data and non-climatic variables were combined.

The MLM applied to analyze crop production stability, considered Colombian locations as a fixed factor or systematic part, while year a random factor or stochastic part and their relation to YIE. Generally, fixed factor includes classification variable such as region and are used to represent specific conditions assessing a contrast of interest in the study. In comparison with fixed factors, random factors do not represent conditions to meet the aims of the research [43]. Therefore, using the applied model, it was tested how regions and their variation in system management determine agricultural productivity, whereas changes each year are unpredictable. Otherwise, PCA is a useful methodology for conducting a data-driven classification and the biplot can be used to conclude based on a multivariate analysis [44]. In the present study, dimension 2 of the biplot (Figure 6) composed mainly of YIE, CPR, FPR, HPR and FUP was a determinant in the observed variation by locations, indicating such variables may be determinants for farmers in the agricultural management and productivity. Then, the Colombian government must improve agricultural information,

achieving data as shown in the database from 2018, where the correlation between crop yield and agricultural practices was tested (Figures 7 and S5).

The results obtained with the mixed regression model and the multivariate analysis indicate that cultivated regions determine productivity regardless of crop species and year (Table 1) for fruit and vegetable systems. The low variance displayed by time, indicates stability in crop productivity, even when the yields were low. Differences in agricultural practices among Colombia regions may explain such variability in yield, affecting national productivity. Otherwise, crops with the largest sowing area showed low productivity due to the use of marginal land that reduces crop yield [23,45]. A similar situation was observed in the present study with fruit and vegetable crops in Colombia. With the PCA, it was found that SAR, HAR and PRO are related to each other positively, and when one increases the others as well. However, YIE is more related to non-climatic variables, indicating that at higher prices of fertilizers and insecticides, yield is largest at the different locations. This situation is observed for the commodity prices and the efficiency of the agricultural system as well (Figure 5). Although PRO improves by increasing SAR and HAR, YIE is reduced, which may indicate agricultural management issues. This result has been previously observed in other investigations, especially when cereal crops are analyzed [46].

Cabas et al. [23], found that non-climatic factors like the units of applied agro-inputs increase the mean of the yield for maize, soybean and wheat. They utilized the "change in input use" that was calculated using the input price and the quantity of purchased input, finding that fluctuations in this variable can influence productivity and cultivated area [23]. Studies conducted in rice systems, using production data from 1992 to 2018 in China, found the expected rice price impacted yield [47]. Also, a study conducted in Canada, where fertilizer prices were evaluated, showed that the increases in this product reduce yield for both crops [48].

Usually, small farmers' agricultural management relies on increasing fertilizer use; however, research has shown that despite the increased use of inputs, low productivity is observed due to poor soil quality and erratic rainfalls [49]. Increases in agri-inputs prices may decrease the accessibility to these products reducing crop yield. In the present research, a direct relation between YIE and these product prices was observed (Figure 6). This could be explained considering two approaches: (i) a large offer of products and brands, can be found in the database, which differ in prices (data not shown). Then, smallholders have the possibility of buying less expensive products to manage the crop system. (ii) In the last few years, local Colombian authorities have led several subsidy programs for the agricultural sector, that are mainly focused on purchasing fertilizers and pesticides for farmers [50]. These programs allow agri-inputs accessibility, but do not assure adequate management of them.

In the present study crops like carrot, cabbage, tomato papaya, pineapple and passion fruit had the highest yields and low variability caused by the sowing year, this value increases especially in the regions where they are cultivated instead (Figure 4, Table 1). Therefore, a comprehensive understanding of such cropping systems may lead to the development of a reliable strategy to increase national agricultural and food production. Results obtained in the MLM analysis, showing resilient cropping systems such as tomato, papaya and pineapple, might be used to identify better agricultural practices that could be extended nationally, improving knowledge about crop production for the development of innovative, resilient, sustainable and high-nutrition quality fruit and vegetable growing systems.

Previous studies have determined that non-climatic factors such as poverty are related to environmental factors like soil erosion, and decreasing yield of coffee, forages and sugarcane in Colombia's rural areas [18]. On the other hand, in blackberry agricultural systems, it has been observed that productivity increases when appropriate management practices are applied, even at similar climatic conditions [16]. Also, agricultural management variables like planting and harvesting dates and cultivar choice may reduce yield losses [15]. Based on the results of the present research, Colombia's national authorities may develop management strategies that strengthen the fruits and vegetables agricultural systems, following the practices applied to regions with the highest yields. For instance,

since there is a relationship between the price of the fertilizers and the crop yield (Figure 6), it is crucial to apply plant nutrition handling addressed by crop requirements, optimizing the money investment and reducing soil erosion [8]. Furthermore, it is possible to understand the adaptation of these crops and the agricultural practices to the issues caused by climate change [12], improving the development of the agricultural sector. Therefore, it is important for Colombian authorities and researchers to identify agricultural solutions that may address low productivity in fruits and vegetable crops. Improving fruit and vegetable yields will increase food security that depends on the sustainable use and management of resources [51]. Improving fruit and vegetable cropping systems might be a good strategy to meet the food needs of rising populations and diet shifts [52]. Furthermore, understanding the impacts of climatic and non-climatic factors on fruit and vegetable quality may help to combat "hidden hunger" [53].

5. Conclusions

Based on the results shown by this research, it is concluded that for selecting those agricultural systems to be prioritized and promoted by national authorities, non-climate factors like agro-inputs prices and commodity prices might be considered when modeling agricultural activities. Government organizations like the Ministry of Agriculture and Rural Development should keep monitoring and evaluating crop productivity in Colombia. However, social, economic and cultural parameters should be assessed as well, for improving predictive models, increasing food security and promoting sustainable development goals. Future strategies, designed based on the understanding of resilient cropping systems that may lead to increased crop yields, farm income and input-use efficiency, should be transferred and adopted by smallholders, which is very low in farmers from developing countries [54]. As it is shown in this research, studies at the regional level are crucial, since the information can be used to develop strategies adapted to local communities. On the other hand, national authorities should promote greater crop diversity to reach year-to-year stability of the national yield [26] and improve food security. Agricultural subsidy programs of governments, that have paid around USD 600 billion per year worldwide [55], might be an approach to influence agricultural activities, supporting farmers' accession to fertilizers, pesticides and improved seeds. Nevertheless, the assistance should be focused on crop production research and development as well, especially on the local development of biologicals as an alternative to traditional products. Then, worldwide and Colombian authorities should minimize the agricultural yield gap and the environmental impact, adapting and elaborating on systems resilience to climate change risks, sustainability and high nutrition quality.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14091546/s1, Figure S1: data distribution and mean (crossed circle) per crop type, fruits and vegetables, of the variables cultivated area (CAR), harvest area (HAR), production (PRO) and yield (YIE) by Colombian farms. Figure S2: data distribution and mean (crossed circle) of commodity prices for fruits and vegetables. Figure S3: data distribution and mean (crossed circle) of agri-inputs prices in Colombia's national locations. Figure S4: biplots generated from PCA with the percentage of variance explained by the first two components for agricultural and non-climatic variables observed at different locations. Colors of the dots display the values grouped by analyzed fruits and vegetable crops. The analyzed variables were cultivated area (CAR), harvested area (HAR), production (PRO), yield (YIE), commodity price (CPR), fertilize price (FRP), herbicide price (HEP), insecticide price (INP) and fungicide price (FUP). Figure S5: heatmap showing correlation results among agri-input variables and yield of an agricultural database for the year 2018.

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

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Review

Agrivoltaics and Aquavoltaics: Potential of Solar Energy Use in Agriculture and Freshwater Aquaculture in Croatia

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Abstract: Agrivoltaics and aquavoltaics combine renewable energy production with agriculture and aquaculture. Agrivoltaics involves placing solar panels on farmland, while aquavoltaics integrates photovoltaic systems with water bodies and aquaculture. This paper examines the benefits and challenges of agrivoltaics and aquavoltaics, focusing on their potential for Croatian agriculture and freshwater aquaculture. Benefits include dual land use, which allows farmers to produce clean energy while maintaining agricultural practices. They diversify renewable energy sources and reduce dependence on fossil fuels and greenhouse gas emissions. Solar panels in agrivoltaics provide shade, protect crops, reduce water needs, and increase yields. Challenges include high initial costs and limited accessibility, especially for small farmers. Integration with existing systems requires careful planning, considering irrigation, soil moisture, and crop or fish production. Maintenance and cleaning present additional challenges due to dust, debris, and algae. Policy and regulatory frameworks must support implementation, including incentives, grid integration, land use regulations, and conservation. The location, resources, and crops grown in Croatia present an opportunity for agrivoltaics and aquavoltaics, considering cultivation methods, species, and regulatory requirements.

Keywords: agrivoltaics; aquavoltaics; Croatia; water evaporation; dual land use

1. Introduction

1.1. Agricultural Production and Climate Changes

Climate change poses a growing threat in the 21st century. It is a challenge to all humanity, affecting all aspects of the environment and the economy while threatening the sustainable development of society. Climate change affects the frequency and intensity of extreme weather events (extreme rainfall, floods and flash floods, erosion, storms, droughts, heat waves, and fires) and causes gradual climate change (increase in air, soil, and water surface temperatures, sea level rise, ocean acidification, and expansion of drylands) [1].

The agricultural sector is especially vulnerable to the profound impacts of climate change because of its dependence on weather [2]. Expected impacts on the agricultural sector include: (i) changes in growing seasons of arable crops, with a focus on crops and oilseeds (e.g., corn, sugar beets, soybeans, etc.); (ii) lower yields of all types of crops; and (iii) greater dependence on water. Extreme weather events such as droughts and hail led to average losses of 76 million euros per year in Croatia between 2000 and 2007, equivalent to 0.6% of national GDP [3]. Climate changes affect the duration/length of the vegetative period of agricultural crops and lead to lower yields. Frequent droughts will lead to a higher demand for irrigation water. A longer growing season will also allow for the

cultivation of some new crops and varieties. On the other hand, more frequent flooding and stagnation of surface water will reduce or eliminate yields.

Agriculture faces the challenge of producing sufficient food, feed, and fiber to meet increasing demand under conditions of a changing climate and the depletion of natural resources [4]. A rise in temperature beyond the optimum becomes a major concern since most agricultural crops are directly dependent on climatic conditions. Shifts in acreage, length of growing season, winter hardiness potential, frost and hail events, lower yields, and food quality are some of the most obvious consequences of global warming trends [5]. Observations show an increase in the frequency and duration of warm weather extremes [6]. Warming tends to result in lower yields as plants accelerate their annual development and yield less. In general, both winter and summer crops exhibit advanced growth, anthesis, and maturity stages in response to higher temperatures, and the duration of the crop growth cycle is predicted to decrease [7].

Agricultural intensification also suggests that agriculture will have higher energy demands. As part of the global energy transition, fossil fuels are being replaced by renewable energy. The installed capacity of PV power plants around the world and the amount of energy they generate continue to grow almost exponentially, and the cost of electricity for new projects has already reached minimum levels in many countries compared to other generation methods [8,9].

Renewables are expected to overtake coal in electricity generation in the second half of the 2020s, and by 2050, renewables will account for 50% of global electricity generation. In agriculture, solar energy can dry hay, heat water, build more efficient greenhouses, provide energy for buildings and equipment that are away from residential power lines, etc. Mandatory use of energy supply measures in all sectors will increase the role of RES [10,11].

Croatia is located in a sensitive area of Europe, as a transition zone between Central Europe and the Mediterranean, where the trend of increasing average annual air temperature is present throughout Croatia. In Croatia, extreme weather events such as droughts and hail have resulted in average losses of EUR 76 million per year from 2000 to 2007, or 0.6% of national GDP [3]. In the field of low-carbon development in the Republic of Croatia, major changes are planned in the near future. Power plants that run on fossil fuels will be replaced by renewable energy sources, and the development will move towards decentralization of electricity generation. Consumers (households and institutions) will also be energy producers, and energy exchange will take place at the local level. Energy producers and energy storage will be interconnected by advanced grids. In the Proposal for the Strategy of Low Carbon Development of the Republic of Croatia until 2030 with a view to 2050 [12], the Government of the Republic of Croatia has emphasized the need to build facilities that use renewable energy sources for electricity and/or heat production, such as solar power plants. The aim of the strategy is to initiate changes in Croatian society that will contribute to the reduction of greenhouse gas emissions and enable the decoupling of economic growth from greenhouse gas emissions.

The intensive use of solar energy (photovoltaics) in agriculture and freshwater aquaculture could make a significant contribution to avoiding or reducing potential damage from climate change. The combination of photovoltaics and agriculture or aquaculture, i.e., agrivoltaics (AgriPV) and aquavoltaics (AquaPV), creates a novel link between energy and food (land or water) that potentially benefits both parties. Agrivoltaics and aquavoltaics are emerging approaches that aim to combine agriculture/aquaculture and solar energy production in the same location on the land [13,14]. According to published statistics, the annual GHG emissions of all aquaculture operations worldwide (260 million t CO_2-eq/year) are rather small compared to those of cattle (3000 million t) or pig (800 million t) farming [15]. To meet the growing demand for aquatic food for a world population of 10 billion in 2050 [16], energy consumption and greenhouse gas emissions from the aquaculture industry are likely to increase significantly in the coming decades. In this regard, PV-integrated aquaculture systems with simultaneous production of food and electricity would be an important contribution to sustainable land use and climate

change mitigation. By promoting intensive synergies between solar energy projects and the agriculture and aquaculture sectors, multiplier effects such as physical protection of certain crops (e.g., vineyards, olive groves, and pastures) from certain extreme weather events (heat waves, extreme rainfall) can be achieved, which would have a positive impact on yield levels and product quality. In addition to the impact on crop and fish production, the implementation of AgriPV and AquaPV increases the profitability of agriculture and aquaculture by generating additional revenue through energy production [14,17].

1.2. Use of Solar Energy in the Agricultural Sector

Climate changes in turn triggered the development of projects based on renewable energy sources (RES), with particular interest in photovoltaic systems, including the use of photovoltaic systems in the agriculture sector (agrivoltaics) [18]. To reduce its greenhouse gas emissions, the EU has decreed that 40% of energy consumption must come from renewable resources by 2030. Photovoltaics are expected to reach 16% of global electricity generation in 2050, but given climate change, it should be 30 to 100 TW before 2050 [19]. There is no internationally unified definition of agrivoltaics as such. The term "agrivoltaic" was firstly proposed in 1982, which combines electricity generation and crop planting on the same farmland. The word agrivoltaics is a neologism based on "agri" for agriculture and "voltaics" for photovoltaics [20]. "Agricultural photovoltaics (agrivoltaics) is the combined use of one and the same area of land for agricultural production as the primary use, and for electricity production by means of a PV system as a secondary use. The dual use of the land not only leads to increased ecological and economic land use efficiency, but in practice can also lead to positive synergy effects between agricultural production and the agrivoltaic system" [20]. Agrivoltaics is also known as agrophotovoltaics, solar sharing, farming photovoltaics (PV), AgriPV, or solar farming.

Numerous studies have shown that it is possible to combine photovoltaics (PV) with agricultural production, enabling PV development on a larger scale while protecting agricultural crops and maintaining yield [21–24]. The first advantage of AgriPV is the area productivity in winter, when agricultural production is not possible in the fields. This land productivity refers to the generation of electricity. Many studies indicate that it is possible to increase crop yields under PV systems [25,26].

This is possible because agrivoltaics create a modified microclimate beneath modules by altering air temperature, relative humidity, wind speed, wind direction, and soil moisture [27]. Agrivoltaics protects crops from both excess solar energy and stormy weather, such as hail [1]. Agrivoltaics also offers more efficient use of water, which may help reduce water consumption [22] and stabilize yield in dry years [28]. This is of particular interest in drylands where unfavorable growing conditions such as excessive sunlight, high temperatures, and severe droughts (water shortages) are predominant.

When trying to describe the challenges associated with AgriPV, the term solar sharing is probably the most descriptive. Sharing solar resources to produce food and energy simultaneously means that the design of the PV system cannot always follow a standard approach of orienting panels to optimize energy production, and that system design may conflict with optimized food production [26,29]. Therefore, the system must be adapted to the local climate, crop type, or land shape [30].

AgriPV, as a concept or approach, includes a variety of different technologies defined by a specific way of combining agriculture and PV [20]. A closer look at the diversity of AgriPV solutions can be made using the framework recently proposed by some authors [31]. The first line of distinction is defined by whether the modules are installed in the open field or on the roof. Totally opaque roofs may be associated with agricultural buildings, even indoor agriculture, but there is no direct interaction between PV systems (other than electricity use) and agricultural activity. Aquaculture and horticulture can also be combined with ground-mounted PV or greenhouse systems. Open-space systems can be further differentiated by growing crops between rows of the modules (inter-space PV) or under modules that have a greater vertical distance (overhead PV). These systems can be

fixed tilt, single-axis tracking, or dual-axis tracking. Since compatibility with agricultural machinery is a key planning criterion for AgriPV, interspatial photovoltaics are expected to focus primarily on grassland farming, fodder production, and grazing, while ground-mounted systems can accommodate a wider variety of stable food crops on arable land as well as horticulture, including perennial crops, permanent crops, and specialty crops [20].

2. Agricultural Potentials of Croatia for Application of AgriPV

The Republic of Croatia is divided into the Adriatic region and Continental Croatia. The territory of Continental Croatia includes central Croatia, Slavonia, and Baranja. Central Croatia is a slightly hilly region covered with vineyards, meadows, and forests and crossed by river courses. Slavonia is located in the far east of Croatia and is characterized by vast plains and large amounts of arable crops, the so-called green treasury. In the Adriatic region, permanent grasslands prevail, and plant production includes mostly viticulture and olive growing as the most important branches of this area, but also the production of Mediterranean fruits and vegetables. The Republic of Croatia covers a surface of 56,594 km^2, which is divided into: forests and bushes cover about 35%, agricultural land about 27%, urban areas 9%, inland waters 1%, and others 29% (Figure 1). According to the Croatian Bureau of Statistics [32], total agricultural land used in the period from 2010 to 2019 on average was around 1,477,000 ha, and main field crops—cereals, industrial plants, and fodder crops—were sown on about 675,000 ha (46%).

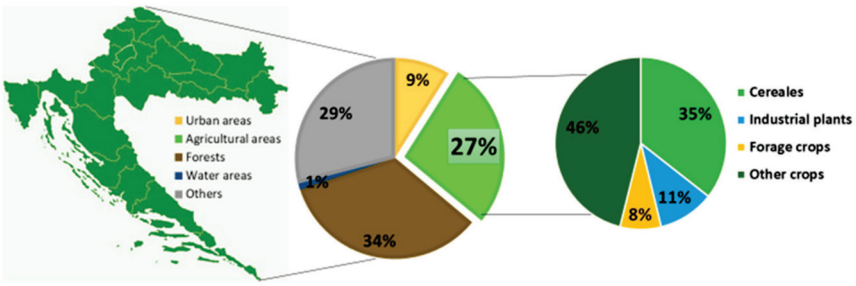

Figure 1. Land use in the Republic of Croatia Reproduced with permission from [32].

The agricultural farms of the Republic of Croatia are characterized by a large number of different production and economic entities. According to [32], the largest number of agricultural farms are small farms. Of the total number of farms, 14.1% have no agricultural land in use, while 59.7% use up to 3 ha of agricultural land. Of the total number of agricultural holdings, only 6% of holdings use more than 20 ha of agricultural land [33]. According to [34], of the total number of agricultural holdings (143,927), most of them (39%) have less than 2 ha, 30% have from 2 to 4.9 ha, and 15% have from 5 to 9.9 ha. The lowest number of agricultural holdings have over 100 ha (1%) (Figure 2).

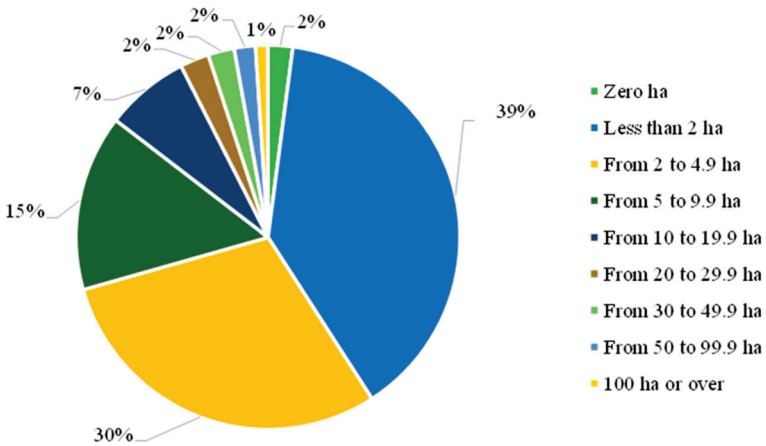

Figure 2. Agricultural land of family farms in Croatia in 2020 Reproduced with permission from [34].

This indicates that fragmentation of farms is still great in Croatia, where the average of commercial farms is about 8.5 ha and the average of all farms is only 2.9 ha, which can be a limiting factor in the wider application of AgriPV projects. About 55–60% of used agricultural land belongs to the category of arable land and gardens, which occupies more than 850,000 ha (Figure 3), followed by perennial grass areas (about 540,000 ha). Other crops—vegetables, orchards, olive groves, and vineyards—occupy about 6% of agricultural land (about 80,000 ha) [32].

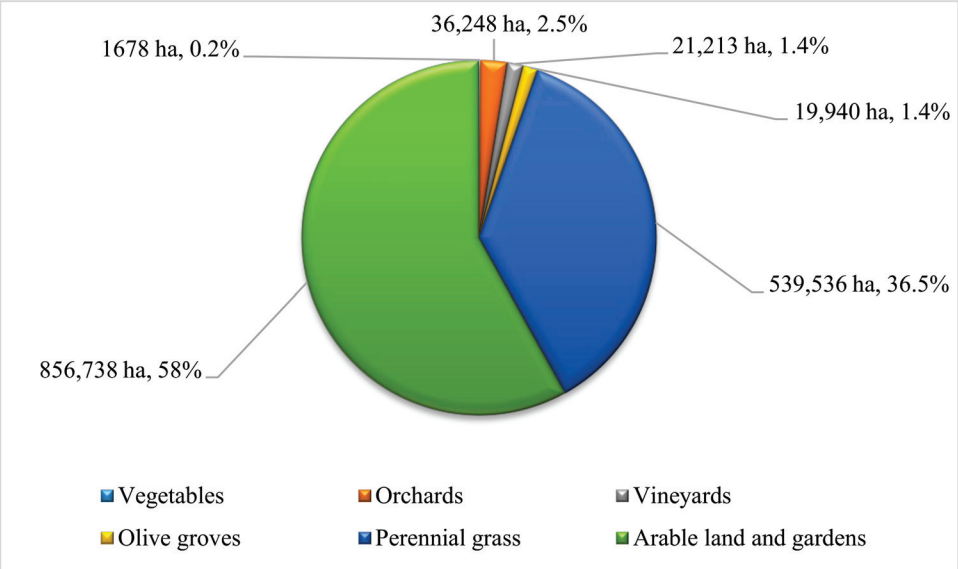

Figure 3. Area (ha) and share (%) of agricultural land by category in 2021, reproduced with permission from [32].

In the last decade, of the total agricultural area used, about 70% was located in the continental and about 30% in the Adriatic parts of Croatia (Figure 4).

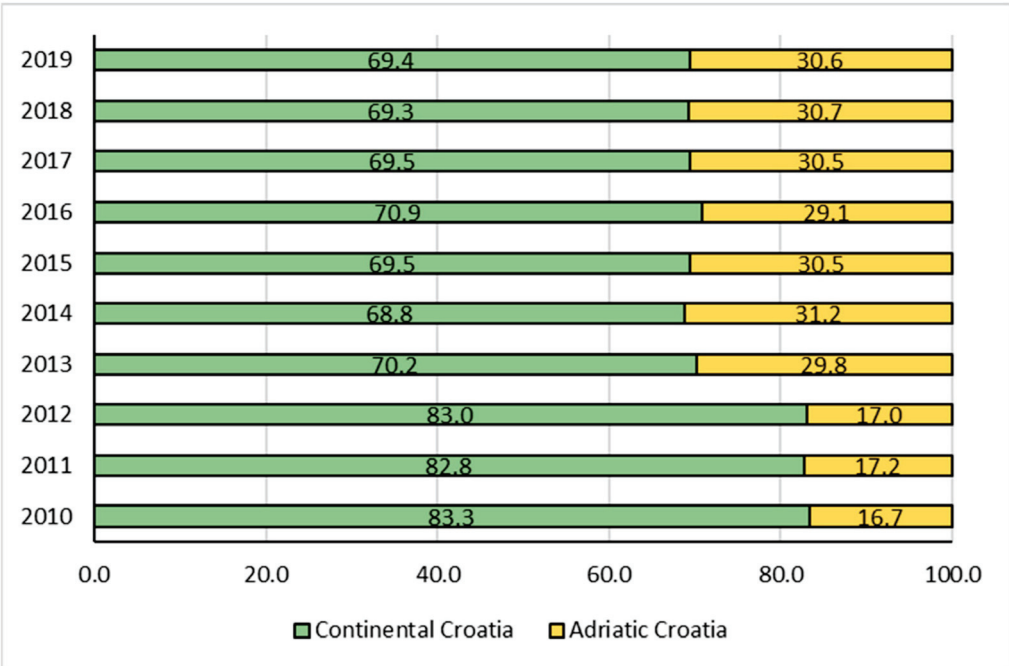

Figure 4. Share of used agricultural area for Continental and Adriatic Croatia from 2010 to 2019, reproduced with permission from [32].

The analysis of the advantages and limitations for the application of AgriPV projects for certain types of cultivated species considering different researches, the applicable case studies and examples of similar corresponding projects, and the conclusion about the applicability of AgriPV projects for certain types of crops in Croatia are given.

Unfortunately, there is still no legislation on AgriPV in Croatia. But, there is some slight movement in this area, as the Croatian government issued two legal documents on 28 June 2023: the Regulation on the Promotion of Electricity Production from Renewable Energy Sources and High-Efficiency Combined Heat and Power (OG 70/2023) and the Regulation on the Criteria for Conducting a Public Tender for the Granting of an Energy Permit and the Conditions for Granting an Energy Permit (OG 70/2023). In these documents, AgriPV (the term Agrosolar is used in the documents) is defined as a solar power plant located on an area designated as agricultural land by the land use plan of any level and on which the establishment of permanent agricultural plantations is registered in the Agricultural Land Use Records (ARKOD) or on which, in addition to the existing area, farms, greenhouses, or greenhouses with the installation of an agrosolar power plant achieve the objectives of the development of agricultural activity while maintaining the purpose of agricultural land, except in the National Park and Natural Park. These two documents are the only official legal documents that mention or define AgriPV in Croatia. Croatia has considerable solar energy potential due to its geographical location and climate. The country receives a considerable amount of sunlight throughout the year, which makes it suitable for solar energy production. The southern regions, especially Dalmatia, have the highest solar potential as they experience more direct sunlight. The use of photovoltaics is steadily increasing in Croatia. The government has also introduced various incentives and support programs to encourage the use of solar energy. However, the overall solar energy capacity in Croatia is still relatively modest compared to other European countries.

2.1. Viticulture

Vineyards could generally be considered for agrivoltaic farms. Firstly, one of the main reasons is the fact that grapevines are an agricultural crop of high economic value. Vineyards are usually established in areas with moderate temperatures and a significant sunlight duration. Grapevines are normally considered full-sun plants, but even in the absence of full sunlight all day, it is still possible to grow grapes in mostly shade [35]. Possible solutions should find the balance between energy production and tolerable shade that will not have a negative effect on grapevine growth and development. The main research questions still remain regarding the co-existence of crop vegetation and agrivoltaics, especially regarding soil characteristics, microclimate modifications, as well as agrivoltaics installation and maintenance costs and performance. Vineyards are generally planted in a row-based layout. The usual method to fully utilize the sunlight is to use fixed support systems with solar panels elevated above the crops. This allows vineyard machinery undisturbed access to the vines. Refs. [36,37] proposed PV panels in the interspace between vineyard rows. On the other hand, a vertical integration of photovoltaic surfaces over the vines is proposed using the same trellis structure, therefore minimizing cost and land building [30]. The authors have tried to avoid the negative impact of shading on grapevine yield and quality. They have established optimal trellis heights and distances between rows to minimize shading. The proposed symbiotic integration of photovoltaic modules into a vineyard trellis structure was termed Enovoltaics. APV modules placed above the vineyard can act not only as a sunlight barrier but also as protection against hail and/or intense rain showers. Vineyards with optimal surfaces for APV installations are usually larger than 1 hectare. In such large vineyards, grapevines are usually managed with mechanized equipment. Thus, APV architecture must adhere not only to regional climatic conditions and grapevine varieties, but also to canopy management in the vineyard. The elevation of APV modules, distance between modules, density, and sloping angle of solar panels are still the subject of much research [38]. The studies dealing with Agri PV systems have generally focused on very few crops, with almost no information for grapevine. Only in

recent years have some investigations into fruit trees such as grapevine [39] been started, but the data are very limited.

Structure of Vineyard Areas in Croatia

Climate is one of the main regionalization factors, along with soil and variety. The Republic of Croatia has a specific geographical position as it is a meeting point of two climate types: continental (eastern and central parts of the country) and Mediterranean (southern and coastal parts). According to the climate, temperature is one of the limiting factors for the cultivation of the grapevine. For grapevines, a mean daily temperature of 10 °C represents a biological zero, while all temperatures above that are regarded as active. As a rule, active temperatures last from April until the end of October (vegetative season). If biological zero is deducted from the active temperature, the result is the effective temperature. The Republic of Croatia is divided into four wine regions (OG 81/2022): the Croatian Uplands, Istria and Kvarner, Slavonia and Podunavlje, and Dalmatia. These regions are divided into 12 subregions: Hrvatsko Podunavlje, Slavonia, Moslavina, Prigorje-Bilogora, Zagorje-Međimurje, Plešivica, Pokuplje, Hrvatska Istra, Hrvatsko Primorje, Northern Dalmatia, Dalmatinska Zagora, and Central and Southern Dalmatia. According to the data in the viticulture database (OG 81/2022) from November 2022, the total winegrowing area in the Republic of Croatia was 17,715.31 ha [40].

The structure of vineyard areas in Croatia is characterized by small production plots and a small number of large viticulture producers (Table 1). In Table 1, it can be seen that 92.44% of producers have viticulture plots smaller than 1 ha, but, at the same time, their viticulture plots have a share of 32.12% in the total viticulture area in the Republic of Croatia. The chosen discriminating criterion for the construction of agrivoltaics was a plot size larger than 1 ha, which transpires to 67.88%, meaning that 12,026.17 ha of the total vineyard area is suitable for APV application. The average slope of vineyards is 6.38%, which does not represent an obstacle during the construction of agrivoltaics.

Table 1. Structure of vineyard plots in the Republic of Croatia.

Viticulture Plots (ha)	Area/No of Producers	Total	Share in Total Area (%)
<0.1	Area (ha) No. of producers	837.50 13,075.00	4.73 39.09
0.1–1	Area (ha) No. of producers	4851.63 17,848.00	27.39 53.35
1–5	Area (ha) No. of producers	4257.83 2191.00	24.03 6.55
5–10	Area (ha) No. of producers	1351.11 197.00	7.63 0.59
10–50	Area (ha) No. of producers	2143.14 117.00	12.10 0.35
50–100	Area (ha) No. of producers	700.68 11.00	3.96 0.03
100–200	Area (ha) No. of producers	973.91 7.00	5.50 0.02
>200	Area (ha) No. of producers	2599.50 6.00	14.67 0.02
Total Republic of Croatia	Area (ha) No. of producers	17,715.31 33,452.00	100 100
Avg. slope of the vineyard [%]		6.38	

Subregions with the most vineyards with an area larger than 1 ha are Croatian Danube, Slavonia, Croatian Istria (the regions with the most grid capacities available), Central and

South Dalmatia, and Dalmatian Interior. The fewest such vineyards are found in Pokuplje, Hrvatsko Primorje, Prigorje-Bilogora, and Norther Dalmatia subregions.

2.2. Fruit Growing

Agrivoltaics in orchards are an interesting but complex addition to farm production. Solar panels on top of the orchard will interfere with plant growth and fruit yielding, for sure. Whether this will have a positive or negative effect depends on various factors (fruit species, fruit varieties, location, weather conditions, etc.). In light of climate change, numerous problems are appearing in traditional combinations of fruit growing and location. That means either changing fruit species that are grown in certain locations, changing fruit growing region schemes, or adapting fruit growing technologies. Using agrivoltaics as part of fruit-growing technology seems to be a good idea. Photovoltaic panels on top of plants will definitely reduce sunlight that reaches the plant and thus reduce plant growth or fruit yield. That is important, as photosynthesis in plants produces nutrition for plant growth. But, on the other hand, vegetative and generative growth are in constant competition. If PV panels on top of the orchard reduce vegetative growth (at some certain level), there is a possibility that this will affect fruit production. This is confirmed by agrivoltaics in raspberry production (Babberich, The Netherlands, Figure 5), where the density of installed PV panels (60% coverage) reduces yield by only 5% in comparison to conventional technology (personal communication). Also, shading that is caused by installed PV in orchards has a positive effect on reducing some physiological disorders in plants and fruits, such as sunburn, heat stress, fruit overcoloration, etc. Installation of PV panels in orchards has its potential and benefits for fruit growing, but it needs to be carefully adjusted and applied. Considering the possibility of using agrivoltaics in plantations of Mediterranean fruit species, several aspects should be taken into consideration. First, it is about the influence of the system itself on cultivated crops. It is evident from the available foreign data that this influence can go in several directions. The ideal situation is when the use of an agrivoltaics system achieves a synergistic effect with fruit culture, i.e., agricultural production is improved qualitatively and/or quantitatively with the optimal effect of the agrivoltaics system. A situation is also possible when the impact on agricultural production is neutral or even slightly negative, but the overall effect of both sectors is positive. Of course, there is also the possibility of an extremely unfavorable impact of agrivoltaics on cultivated plants, in which case their connection to the same plots should be avoided.

Figure 5. Agrivoltaics in a raspberry orchard (Photo: Fruk, G.).

Structure of Fruit Growing in Croatia

Croatian fruit production is organized on an area of approximately 55,000 ha [32]. In Table 2, data on the total production area for different fruit crops are presented, while in Table 3, data about the number of orchards by county and by size are shown.

Table 2. Area of fruit production in Croatia in 2021.

Crop	Area Harvested (ha)
Apples	4390
Pears	750
Plums and sloes	3490
Sour cherries	2200
Cherries	1000
Peaches and nectarines	800
Apricots	310
Strawberries	270
Blueberries	380
Other berries and fruits of the genus vaccinium n.e.c.	1160
Raspberries	130
Tangerines, mandarins, clementines	2040
Oranges	40
Lemons and limes	60
Walnuts (in shell)	8420
Hazelnuts (in shell)	6710
Almonds (in shell)	810
Chestnuts (in shell)	280
Olives	19,940
Figs	570

Source: [41].

Table 3. Number of orchards by county by size (on 31 December 2022).

County	Orchard Size (ha)					
	0–1	1–5	5–20	20–100	>100	TOTAL
Continental part						
Bjelovarsko-bilogorska	3906	926	61	1	0	4894
Brodsko-posavska	5850	656	53	13	0	6572
Grad Zagreb	1612	30	0	0	0	1642
Karlovačka	4314	547	33	3	0	4897
Koprivničko-križevačka	3859	294	13	3	0	4169
Krapinsko-zagorska	8261	56	0	0	0	8317
Međimurska	1628	255	21	0	0	1904
Osječko-baranjska	4042	1381	136	20	0	5579
Požeško-slavonska	4415	607	26	5	0	5053
Sisačko-moslavačka	4572	589	52	6	0	5219
Varaždinska	4694	137	5	0	0	4836
Virovitičko-podravska	2608	479	29	9	1	3126
Vukovarsko-srijemska	1981	465	50	12	0	2508
Zagrebačka	5995	326	42	4	0	6367
	57,737	**6748**	**521**	**76**	**1**	**65,083**
Highlands/Coastal part *						
Ličko-senjska	4670	42	0	0	0	4712
Primorsko-goranska	805	15	1	0	0	821
Šibensko-kninska	1281	22	9	1	0	1313
	6756	**79**	**10**	**1**	**0**	**6846**
Coastal part						
Dubrovačko-neretvanska	7929	360	3	0	0	8292
Istarska	1931	68	5	1	0	2005
Splitsko-dalmatinska	3900	28	9	1	0	3938
Zadarska	4807	167	29	5	0	5008
	18,567	623	46	7	0	19,243
TOTAL	**83,060**	**7450**	**577**	**84**	**1**	**91,172**

* Three counties in this group are situated in both areas (highlands and coastal parts); Source: [42].

The main characteristic of all Mediterranean fruit crops, as can be seen from Table 4, is the small average land area (0.84 ha). Out of a total of 22,142 farms, only 292 (1.31%) have areas larger than 1 ha, while only 31 farms (0.14%) have slightly larger areas (>10 ha).

Table 4. Cultivation of Mediterranean fruit species in the Adriatic agricultural subregion (2021).

	Total Area (ha)	Agricultural Activity	Average Area (ha)	Agricultural Activity >1 ha	Agricultural Activity >10 ha
Olive	14,225.35	14,187	1.00	180	15
Mandarin	1589.87	1335	1.19	13	1
Lemon	31.92	201	0.16	1	0
Orange	14.96	92	0.16	0	0
Kumquat	0.60	10	0.06	0	0
Grapefruit	0.10	3	0.03	0	0
Almond	738.34	1041	0.71	33	5
Marasca sour cherry	347.09	236	1.47	8	4
Fig	303.96	813	0.37	31	1
Pomegranate	55.18	172	0.32	5	0
Carob	50.61	14	3.62	1	1
Kiwifruit	15.95	14	1.14	1	1
Jujube	3.01	12	0.25	0	0
Mixed fruit Cultivation	1273.31	3994	0.32	16	3
Fruit nurseries	17.28	18	0.96	3	0
TOTAL	**18,667.53**	**22,142**	**0.84**	**292**	**31**

Source: [43].

The most represented fruit among Mediterranean fruit species is the olive. The entire olive growing area in Croatia can be divided into six growing sub-regions with their own specificities based on various factors (Istria, Kvarner Islands, North Dalmatia, Central Dalmatia, South Dalmatia, and the hinterland of Dalmatia) (Table 5).

Table 5. Olive cultivation in the Adriatic agricultural subregion (2021).

	Total Area (ha)	Agricultural Activity	Average Area (ha)	Agricultural Activity >1 ha	Agricultural Activity >10 ha
Istria County	3171.84	2492	1.27	68	6
Primorje-Gorski Kotar County	562.05	495	1.14	19	0
Lika-Senj County	121.93	96	1.27	1	0
Zadar County	2625.96	3522	0.75	23	6
Šibenik-Knin County	2061.95	2082	0.99	28	0
Split-Dalmatia County	3511.11	2728	1.29	28	1
Dubrovnik-Neretva County	2170.51	2772	0.78	22	2
TOTAL	**14,225.34**	**14,187**	**1.00**	**180**	**15**

Source: [43].

2.3. Vegetable Growing

Conventional open fields face many challenges due to the pronounced effects of climate change, especially global warming, and the associated weather-related difficulties. The main concern is to produce adequate yields and high-quality, nutritious plant material. To protect vegetables from external influences, expensive protective structures such as hail nets or films are often used. In the agricultural sector, greenhouse technology, also known as closed agriculture, is strategic for increasing production and meeting global demand, as it provides plants with a suitable microclimate that enables optimal plant growth, extended production time, earlier harvest, and higher and better-quality yields [44]. Hydroponic systems in greenhouses are considered one of the most important technical approaches for sustainable food supply and reducing pressure on agricultural land by

moving food production to urban environments [45]. The advantage of this method of cultivation is easier management and control of a number of factors during cultivation (air temperature and relative humidity, balanced and rational fertilization, etc.), which ensures better conditions for the growth and development of vegetables according to their needs [46]. Although these systems ensure food production with efficient water use, they are not an energy-efficient solution and may cause additional costs and waste problems. The enormous energy consumption of the hydroponic system leads not only to an increase in operating costs, but also to environmental impacts [47], which are not in accordance with European environmental policy and the Green Deal. More recently, most hydroponic systems are increasingly using the natural power of the sun. To meet the high energy demand and make greenhouse agriculture more sustainable, there is a great interest in integrating photovoltaics [44]. Photovoltaic panels on greenhouse roofs may be opaque, semi-transparent, or transparent, allowing less solar radiation to pass through, which may or may not intentionally affect plant development [48]. As for cultivation in the open field, the risk of using solar panels lies especially in crop rotation, since these are usually annual species that alternate in space and time, i.e., during one year preceding crops are cultivated (usually a species in early spring or winter such as spinach, lettuce, radish, peas, early potatoes, and spring onions), then follows the main crop with the longest growing season (tomatoes, peppers, cabbage, and onions), and on the end the succeeding crop grown after the main crop (lettuce, spinach, spring onions). Such cultivation makes it possible to maximize the use of a specific growing plot throughout the year, as different vegetable species have different biological characteristics (mesophilic and thermophilic species) and different durations of vegetation. Due to different temperature, light, and water requirements, the use of solar panels could be a potential challenge, as well as adjusting the agrotechnical measures according to the installed AgriPV system when growing the different species.

The height of the steel structures and the spacing between PV rows must be suitable for standard agricultural equipment that can pass between the rows for harvesting without interfering with the PV modules. Generally, the distance between two rows of PV arrays in conventional PV systems is 6–12 m. The reason for this distance is to avoid shadows of PV modules on the next row, and it must be suitable for harvesting. The following parameters are important for plant growth between rows of PV plants: height of plant, diameter of plant, and number of plants [49]. All types of crops are generally suitable for cultivation under an AgriPV system, but different effects on yield can be expected due to shading effects. Highly shade-tolerant crops such as leafy vegetables (lettuce, chard, and spinach), field forage (grass/clover mix), various types of pome and stone fruits, berries, soft fruits, and other crops (such as wild garlic, peppers, carrots, asparagus, and hops) appear to be particularly suitable [50]. There is some concern about the impact solar panels may have on crop yields and fruit quality, as there is a direct correlation between solar radiation received by plants and lower crop yields and smaller fruit [48]. According to Edouard et al. [19], plants can become accustomed to the shading caused by the panels by increasing their efficiency in absorbing radiation. It has even been shown that a shade-tolerant plant, such as lettuce, grown under PV panels adapts its morphology (e.g., by producing larger leaves). In particular, lettuce, peppers, tomatoes, aloe vera, maize, and pasture grasses are successfully grown using this method. In one of the studies, it is mentioned that this method increased the product efficiency by 60–70% [49].

Structure of Vegetable Growing in Croatia

The Republic of Croatia has significant advantages for vegetable production, and thanks to climatic, pedological, and hydrological possibilities, the production of vegetables in the open field is possible almost all year round [51]. Intensive production (for the market) of vegetables in Croatia in 2021 amounted to 168,624 tons and took place on 8398 ha, while a smaller part of production is extensive production on family farms (kitchen gardens), where 45,750 tons of vegetables were produced on 1678 ha (Table 6). The most represented

vegetable is cabbage, whose share in the total vegetable production is about 15%. Cabbage is grown mainly in continental Croatia. It is followed by onions and garlic with 10%, peppers with 9%, watermelons with 8.5%, and green peas with 7%.

Table 6. Cultivation of vegetables in the Republic of Croatia (2021).

	Area (ha)	Production (t)	Yield (t/ha)
Total fresh vegetables (including kitchen gardens)	10,076	214,374	21.3
Total fresh vegetables	8398	168,624	20.1
Cauliflower and broccoli	195	3154	16.2
Cabbage (white and red)	1201	28,844	24
Other brassicas	146	2536	17.4
Leeks	97	1697	17.5
Lettuce	195	3586	18.4
Lettuce under glass	31	701	22.6
Other leafy or stalked vegetables	520	6419	12.3
Tomatoes	292	18,785	64.3
Tomatoes for fresh consumption	64	1316	20.6
Tomatoes under glass	88	11,902	135.3
Cucumbers and gherkins	98	8549	87.2
Cucumbers and gherkins under glass	43	7554	175.7
Melons	132	1852	14
Watermelons	720	21,476	29.8
Red peppers, capsicum	803	13,559	16.9
Red peppers and capsicum under glass	31	1778	57.4
Other vegetables cultivated for fruit	1327	17,938	13.5
Carrots	306	6403	20.9
Onions and garlic	914	19,044	20.8
Beetroot	126	3173	25.2
Other root and tuber vegetables	289	4107	14.2
Green peas	563	4600	8.2
Green beans	474	2902	6.1
Fresh vegetables (kitchen gardens)	1678	45,750	27.3

Source: [32].

Considering the areas under cultivation as well as the ecological conditions necessary for growth (thermophilic vegetable species), tomato, pepper, melon, watermelon, and cucumber could have been interesting in terms of AgriPV application. They are heat-loving vegetables with a long growing season, which makes them suitable and potentially profitable for an AgriPV system.

2.4. Aromatic and Medical Plants

It is estimated that 60,000 species are used worldwide for their medicinal, aromatic, and nutritional properties [41]. In the world, the need for medicinal plants is still mostly satisfied by collecting wild populations from nature, and a smaller part is cultivated. In Europe, around 20,000 to 30,000 tons of medicinal and aromatic plants are collected annually, and only 10% are from plantation cultivation. The Republic of Croatia has an extremely rich vascular flora and favorable conditions for the cultivation of medicinal and aromatic plants. The production of medicinal and aromatic plants in Croatia differs by region due to the diversity of climatic and agroecological conditions.

Structure of Medical Plant Production in Croatia

Chamomile is a mostly cultivated medicinal plant in Croatia. It is cultivated in continental Croatia, in the areas of Slavonia and Baranja. The second-largest production is of immortelle in Adriatic Croatia, as well as the third-largest of lavender. Fennel, milk thistle, mint, lemon balm, sage, wormwood, and common mallow also have more significant production.

Chamomile (Table 7) is the most cultivated medicinal plant in Croatia, covering a total area of over 6300 ha (more than 86% of all areas covered with medicinal and aromatic plants). It is grown in almost all counties, but mostly in Virovitica-Podravina County (about 65% of Croatian chamomile production) and Osijek-Baranja County (about 22% of Croatian chamomile production). Larger areas can still be found in the areas of Sisak-Moslavina County, Bjelovar-Bilogora County, and Koprivnica-Križevci County. The vast majority of chamomile is grown in plantations larger than 1 ha; there are 475 such plantations with a total production area of 6348 ha, while there are 178 plantations larger than 10 ha. Some plantations even reach a size of around 100 ha.

Table 7. Chamomile cultivation in Croatia (2021).

	Total Area (ha)	Agricultural Activity	Average Area (ha)	Agricultural Activity >1 ha	Agricultural Activity >10 ha
Zagreb County	41.64	13	3.20	8	1
Sisak-Moslavina County	346.37	17	20.37	14	7
Karlovac County	0.23	1	0.23	0	0
Koprivnica-Križevci County	115.30	18	6.41	17	2
Bjelovar-Bilogora County	219.61	10	21.97	10	7
Primorje-Gorski Kotar County	1.06	1	1.06	1	0
Virovitica-Podravina County	4137.89	361	11.46	351	123
Požega-Slavonia County	45.97	5	9.19	5	1
Brod-Posavina County	8.10	5	1.62	3	0
Osijek-Baranja County	1400.21	61	22.95	58	36
Vukovar-Syrmia County	22.38	3	7.46	3	1
Istria County	1.75	1	1.75	1	0
Dubrovnik-Neretva County	0.75	1	0.75	0	0
Međimurje County	2.02	2	1.01	1	0
City of Zagreb	16.54	4	4.14	3	0
TOTAL	**6359.92**	**503**	**12.64**	**475**	**178**

Source: [43].

2.5. Cereals, Industrial, and Fodder Plant Production

There is not much research dealing exclusively with the growing of most common field crops like cereals, industrial plants, and fodder plants in an agrivoltaics system. Cultivation under PV arrays is not identical to conventional farming on open fields. The main differences relate to methods of tilling, crop selection, and crop management. Regarding field management and arable crop growth, it is very important to adapt APV systems. It is essential to adjust the mounting structure of APV arrays to allow the passage of conventional agricultural machinery. For example, for cereal cultivation, a clearance of at least 4–5 m is necessary, especially because of large combine harvesters [14]. For Agri-PV systems combined with light-sensitive crops, alignment and spacing between the module rows must be designed to optimize light availability and homogeneity to avoid negative effects on plant growth [52,53]. Attention must be paid to ensure the PV system does not endanger workers or machinery [54]. In order to maintain crop yields in an agrivoltaic system and reduce the loss of quality arable land, mounting structures should be improved by adjusting the shading level of the system to the specific crops or growing shade-tolerant crops [55]. Generally, numerous studies have proved that agrivoltaics through combined crop and energy production can significantly increase land productivity [14,19], but also that crop performance and final yield are under great influence of weather conditions during the growing season, despite altered microclimatic conditions. Yield ranges of the crops cultivated under AV systems compared to the reference field were −19 to +3% for winter wheat, −20 to 11% for potato, and −8 to −5% for grass-clover in the common growing season, while in the hot and dry year, yields of wheat in AV were increased by 2.7% and of potato by 11% [56]. It is generally well known that the main effect of AgriPV systems is reduced solar radiation, which, especially for shade-intolerant crops (like maize or sunflower, for example), could lead to a considerable yield reduction. Information on the effects of shading on field crop yield and quality in real conditions is scarce. So far, the most research on shading impacts on maize growing under APV or in artificial shade confirms a negative effect on maize performance and yield [57–59]. In a meta-analysis

on the effects of shade on the yield of 38 different crop species, i.e., nine crop types, the greatest yield loss due to a reduction in solar radiation was determined for maize and grain legumes [60]. Under an AgriPV system, the average grain yield and the number of pods per plant for soybean were reduced by 8% and 13% [11]. Wheat grown in a shade condition in a Paulownia-wheat intercropping system in China showed a yield reduction of about 50% [61]. In an agroforestry system in France, durum wheat yield was decreased in all shading intensities, and by almost 50% in the most intense shade conditions (31% of light reduction). The greatest impact of shading was the reduction in grain number per spike and grain weight [62]. It can be assumed that other small-grain cereals would similarly respond.

Structure of Cereals, Industrial, and Forage Plant Production in Croatia

From all arable land areas with field crops, the most common are cereals, with about 60%. After cereals, about 20% are industrial plants and 13% are fodder crops (Figure 6).

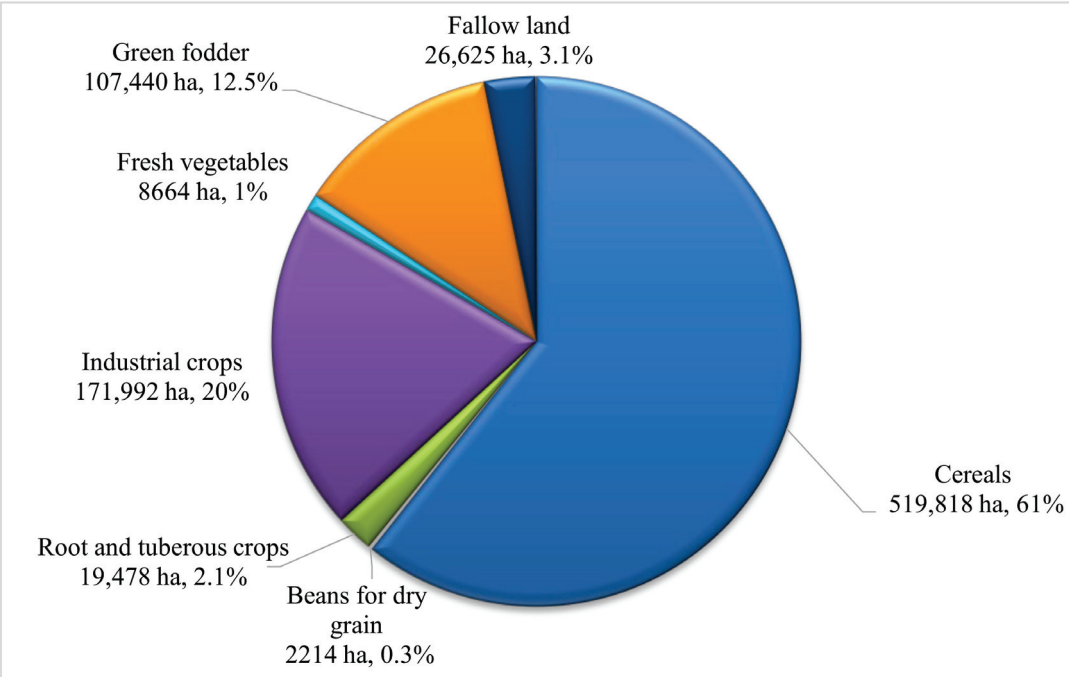

Figure 6. Area (ha) and share (%) of main field crops in 2021, reproduced with permission from [32].

In the Republic of Croatia, especially in the east, there are very favorable conditions for cereal production and also the tradition of growing them. Croatian agricultural production is dominated by cereal and oilseed production, and maize and wheat are the dominant crops in Croatia. Maize (for dry grain) occupies more than 30% of arable land, followed by winter wheat (spring and durum wheat are growing on a much smaller scale), then winter and spring barley, oats, triticale, rye, and other cereals like spelt, buckwheat, sorghum, etc.

The main industrial plants in Croatia are oilseeds (soybean, sunflower, and rapeseed, oilseed pumpkin), root crops (sugar beet and root chicory), potatoes, and tobacco, while fiber plants (industrial hemp and flax) are grown to a lesser extent. In the continental part of Croatia, the biggest share of total industrial plant production is located. Regarding fodder crops, alfalfa and green maize are the most represented (Table 8).

Table 8. Cultivation of some field crops in the Republic of Croatia (2021).

	Area (ha)	Production (t)	Yield (t/ha)
Cereals			
Grain maize	287,976	2,242,119	7.8
Wheat	143,535	961,940	6.7
Rye	511	2082	4.1
Barley	56,478	306,209	5.4
Oats	17,063	58,840	3.4
Triticale	9386	42,497	4.5
Other cereals	4869	15,463	3.2
Industrial plants			
Soybean	86,259	227,872	2.6
Sunflower seed	40,969	124,363	3.0
Rapeseed	30,281	73,423	2.4
Other oil seeds	4098	3548	0.9
Sugar beet	10,066	707,000	70.2
Potatoes	8786	127,826	14.5
Tobacco	3488	7384	2.1
Fodder crops			
Green maize	25,133	873,179	34.7
Other annual green fodder	5794	91,218	15.7
Alfalfa	28,128	179,680	6.4
Clover and mixtures	8425	46,986	5.6
Other leguminous plants harvested green	11,283	83,764	7.4
Fodder peas	792	2331	2.9

Source: [32].

2.6. Grassland and Animal Husbandry

The experiences of other countries [63,64] have shown that the use of AV systems on grasslands, in combination with animal husbandry (mostly sheep), can have different positive effects. By using sheep, it is ensured that grass and other plants at their photovoltaic arrays do not interfere with the functioning of the solar panels. This best practice also means less damage to the solar panels and lower operating costs. By keeping vegetation under control, the solar plant becomes a natural firebreak, helping prevent the spread of a fire should one break out in a neighboring area. It also leads to the saving of fuel that would be needed for mechanical cutting and avoids the use of chemical herbicides that can pollute both the soil and water resources [65]. Ref. [66] investigated the effect of grazing under solar panels on lamb live weight gains, pasture production, and land productivity. In solar pastures, the distance between solar panels was 6 m, giving a 3-m fully shaded and 3-m partially shaded sites. While the DM yield from open and partially shaded areas was similar, pastures under fully shaded sites were significantly lower. On average, pasture production was 9–33% less in agrivoltaic systems than open pastures. Live weight production of the lambs was similar as both open and solar pastures were grazed at the same stocking rates. Increased temperatures decrease the amount of time cattle are in zones of thermal comfort, and heat stress typically occurs above 25 °C for cows [67]. Heat stress has been estimated to cost the dairy industry in the United States more than $900 million annually due to production losses [68]. Ref. [69] investigated the effects on grazing cattle under shade from a solar photovoltaic system. They found no differences in fly prevalence, milk production, fat and protein production, or drinking bouts between cattle in shade and those not in shade. The authors concluded that agrivoltaics incorporated into pasture dairy systems may reduce the intensity of heat stress in dairy cows and increase their well-being and the efficiency of land use.

The Structure of Grasslands and Animal Husbandry in Croatia

According to [32], utilized agricultural area by categories, the total area of permanent grassland (meadows and pastures) in 2017 was 607,555 ha. According to data from the

ARKOD database [70], the total meadow area in the Republic of Croatia was 101,633 ha, the total area of pastures was 25,313 ha, and the total area of karst pastures was 91.499 ha (Table 9). Therefore, the total number of grasslands registered in the ARKOD system is 218,444.6 ha.

Table 9. Type of agricultural land use.

Meadow		Pasture		Karst Pasture	
Total Surface (ha)	**Number of Parcels**	**Total Surface (ha)**	**Number of Parcels**	**Total Surface (ha)**	**Number of Parcels**
101,632.95	242,376	25,313.13	16,479	91,498.52	56,051

Source: [70]

In the AGRONET system from 2022, there are a total of 24,602.68 ha of pastures (continental grasslands-pastures), karst pastures of 91,933.64 ha, and meadows of 93,825.45 ha (Table 10). The total area of grasslands in 2022 was 210,361.77 ha. The majority of grasslands of all types were reported by family farms (82% of continental grasslands and pastures, 85% of karst pastures, and 81% of meadows).

Table 10. Pastures by type of agricultural holding.

Type of Agricultural Holding	Continental Pasture (ha)	Karst Pasture (ha)	Meadows (ha)
Family farm	20,244.76	78,388.62	76,266.18
Craft	863.71	913.10	2259.69
Other legal entities (church, army, educational institutions)	134.01	272.47	244.13
Self-sufficient agricultural holding	401.6	1581.86	12,100.29
Company	2656.62	7447.78	2698.5
Cooperative	301.98	3329.81	256.66
TOTAL	**24,602.68**	**91,933.64**	**93,825.45**

Source: [40].

3. Aquavoltaics

Considering the title of the review article, this subsection provides a somewhat more detailed overview of the definition of aquavoltaics, its uses, benefits, and challenges, with an addition on the structure of freshwater aquaculture (cyprinids) in Croatia.

Aquavoltaics, or AquaPV, is a concept combining electricity production with aquaculture. The goal of AquaPV is the efficient use of water for both food and energy generation. While solar panels above the water or on its surface provide electrical energy, the aquatic organisms living within the water below provide a sustainable food source. AquaPVs floating on the water body can lessen water losses by preventing evaporation by up to 70–85% due to covering the water [71]. Aquavoltaics technology enables electricity to be generated and aquaculture to be carried out in the same area, significantly improving overall productivity per unit area compared to conventional land use [17]. These systems withstand fluctuating water levels; however, they are not commonly designed to operate while resting on the bottom if the body of water is drained [72]. The AquaPV approach aims to maintain parameters such as water and air temperature, light availability, water pH, dissolved oxygen (DO), feeding system, and predator pressure and improve the system by exploiting synergies between the aquaculture and PV systems. Cultured species have different requirements, confirming the need for variation in essential parameters as a function of species type and farming systems. The integration of photovoltaic technology with aquaculture creates synergies as aquatic farming can benefit from module shading effects when temperatures are high, while modules' efficiency values are enhanced at the same time due to the proximity to cool water environments [73]. Aquaculture systems are characterized by a very high energy input, mainly due to their need for an artificial oxygen supply.

Electric power generation using floating, elevated, or other forms of PV module integration offers the possibility to substitute fossil-based energy sources without the occupation of additional land. To maximize the productivity of aquavoltaic systems, the coverage of PV modules and the mounting of the whole system require careful consideration [73]. Common benefits from these installations were a reduction in water evaporation from the reservoir/pond [74,75] and decreased algal growth (due to the reduction in sunlight penetration within the water body) [76]. Also, electrical yields were slightly improved in most reported cases, probably because of the cooling benefit offered by the underlying water surface, as illustrated in some papers [77] while testing a PV panel that was in direct contact with water (Figure 7). According to [67], the high humidity conditions under aquavoltaics operation can reduce the lifespan of photovoltaic modules. Additionally, advancements in photovoltaic technology, such as longer lifespans and higher power output rates, can improve the economic and environmental efficiency of the system.

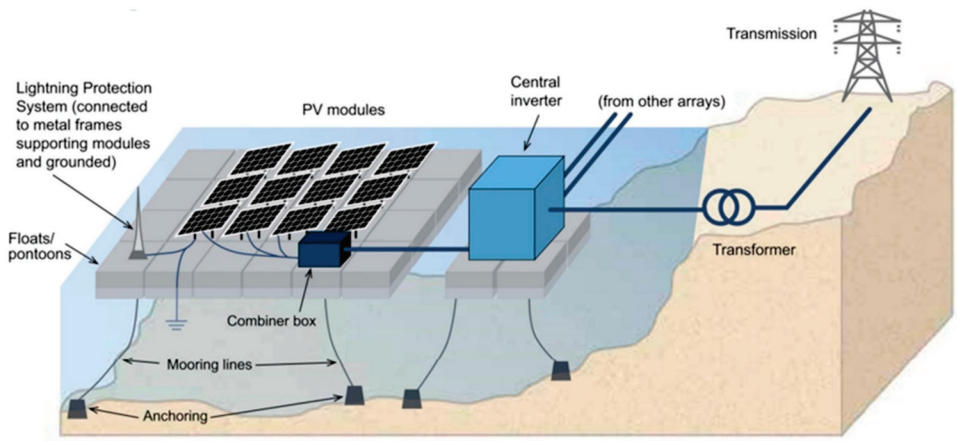

Figure 7. Schematic representation of a typical large-scale FPV (Reproduced with permission from source: Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore).

Several projects and studies are carried out to verify positive and negative aspects in terms of ecosystems and the technical and economic feasibility of dual use in aquavoltaics:

Cooling

Regardless of the system design, several aspects must be considered when integrating PV modules into aquaculture systems. It is well known that the efficiency of PV modules decreases with increasing temperatures. In the AquaPV approach, a positive cooling effect can be achieved by both water and increased wind speeds. Thanks to the cooling effect, increases of ~10–15% in PV output can be achieved compared to fixed ground-mounted solar systems [78]. The cooling effect of water on solar cells, which favors higher energy conversion efficiency, is considered one of the main advantages of FPVs [79]. The magnitude of this effect depends on the orientation and the amount of contact of the module with the water. The greatest improvement was found for floating, tracking, cooling, and concentrating (FTCC) systems [17].

Light

In waters exposed to the sun, photosynthesis allows the growth of organic matter, including algae. These algae are generally not desirable in water reservoirs because they can obstruct pumping and filtration systems and require costly chemical treatment to control the problem. Installing FPVs shades the water and reduces photosynthesis. This reduces the formation of algal blooms and reduces chemical and operational costs. Aquavoltaic systems provide shade on the water surface of the pond, and the blocked light is absorbed by solar cells and converted into usable energy. If uncontrolled, an increase in shading decreases, and general plant life and microbial density are reduced, affecting the entire food chain down to the fish intended for breeding [80]. Typically, fish are either more active in

light and less active in darkness or vice versa [81], and this can be altered by daily changes in factors such as temperature or oxygen [82]. The growth of aquatic organisms is linked to light, but it is not unique because species vary in their growth conditions. Fish and larvae, for example, must be reared in specific light ranges depending on the species and stage of development [81]. Light-emitting diodes (LEDs) can be installed on the underside of the pontoon structures in the aquavoltaic system, powered by the PV portion of the system, to affect the photoperiod of aquatic life. This design provides the "aquaculturist" with a powerful tool to increase and further optimize production for specific aquatic species [17]. This needs to be tested further, and the effects of energy conversion need to be considered. Another alternative is to rotate or move the plant around the water body in which it is located. This action would limit the amount of natural light shading that a given water area experiences [80]. A change to the pontoon structure itself could increase the distance between the modules that make up a facility. This change would allow a controlled amount of light to penetrate the water below. This approach does reduce the efficiency per unit area of the array because the density of the solar modules is lower, but if the area is not a constraint, this is an insignificant drawback [83].

Land use and evaporation

PV systems floating on water do not occupy habitable land and can be deployed in degraded environments and reduce land-use conflicts [84–86], as can dual-use infrastructure, such as reservoirs, where evaporation can also be reduced [87,88]. One of the most important synergistic effects resulting from coupling PV systems with aquaculture is saving water. In aquaculture systems where high water flow rates are observed, the prevention of water loss is a great benefit from both economic and ecological points of view. FPVs save water by reducing evaporation and improving water security in arid areas while being flexible for use in various water bodies such as fishponds, drinking water reservoirs, etc. Because the system acts like a protective blanket over the water, FPVs can reduce water evaporation by up to 33% for natural lakes and ponds and up to 50% for man-made facilities [89]. Some authors noted that water loss from reservoirs could be reduced by as much as 70–85% with FPV [17,71]. Especially in the context of climate change, where dry periods are becoming more frequent, reducing evaporation is a major achievement [75].

Maintenance

Another advantage related to proximity to water emerges when considering pollution effects. First, particles are washed off the module surface more regularly. Soiling of the surface of PV modules can also occur from other sources, such as bird droppings or biofouling [17]. Biofouling describes the colonization of organisms such as algae on PV surfaces, which can affect not only the modules but also mounting systems and cables. According to some of the authors [17], one of the biggest unknowns is the interaction of FPVs with aquatic organisms and the potential for biofouling to occur. Mechanical stress would also be high due to increased wind speeds and waves, especially during stormy conditions [73]. Stable anchoring is essential to compensate for lateral forces [74], while flexible mounting of PV modules offers the advantage of floating with the waves and protecting the system from external forces. Depending on the location, maintenance of the system may be more difficult, as work must be performed from boats or from the movable pontoons. However, because accessibility is difficult, vandalism and theft can be expected to decrease [3]. On the other hand, floating systems do not require thousands of metal frames to be attached to the ground, which means that a panel array can be constructed more quickly. In addition, decommissioning a floating system is much easier and less expensive.

Material availability

Material requirements for PV are likely to increase substantially to limit warming to well below 2 °C, but PV materials are widely available, have possible substitutes, and can be recycled [18,90]. The main materials for PV are silicon, copper, glass, aluminum, and silver, with silicon being the most expensive and glass the most important by mass

at 70%. None of these materials are considered critical or potentially in short supply [91]. FPVs are compatible with the existing hydropower and electric infrastructure, which supports diversifying the energy supply and its resilience. The lack of supporting policies and development roadmaps by governments could hinder FPVs' sustainable growth [85]. There is scarce research on the socio-environmental impacts of FPV farms. [92] reflected on three key socio-environmental impacts of FPVs: job creation, non-occupation of habitable land, and improving water security in water-scarce regions. The addition of floating modules will most likely increase the difficulty of tending the aquaculture system, and the aquatic life may slow or disrupt the maintenance of the PV modules. After a typical useful life of 30 years, PV modules can be recycled to prevent environmental pollution from the toxic materials they contain, reuse valuable materials, and avoid the accumulation of waste (Figure 8).

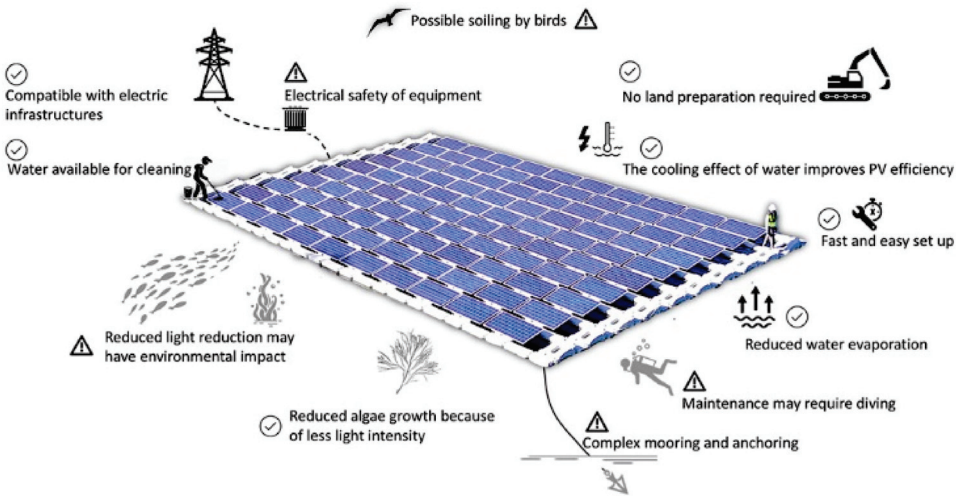

Figure 8. Benefits and challenges of floating solar panels Reproduced with permission from [85].

Structure of Freshwater (Cyprinid) Aquaculture in Croatia

In Croatia, cyprinid species are traditionally farmed in carp ponds, which usually cover several hundred hectares, with five carp ponds having an area of over 1000 ha. The total area of carp ponds in Croatia is currently 14,081.49 ha, while the production area in 2021 was 12,539 ha [93], preliminary data) (Table 11).

Table 11. Register of aquaculture permits for inland waters (warmwater species only).

County	Area (ha)
Bjelovar-Bilogora	3267.04
City of Zagreb *	1273.69
Požega-Slavonia/Bjelovar-Bilogora	1274.659
Osijek-Baranja	2920.31
Karlovac	391.78
Virovitica-Podravina	981.22
Sisak-Moslavina	742.15
Brod-Posavina	3069.95
Zagreb/Bjelovar-Bilogora	117.99
Varaždin	4.72
Međimurje	5.75
Požega-Slavonia	0.44

Source: [92]; * permit for cold and warmwater aquaculture.

Most carp ponds are located along larger river basins in the lowlands and the continental area of the Republic of Croatia, where the continental climate prevails. Continental Croatia has a temperate continental climate, and throughout the whole year it is in a circulation zone of mid-latitudes, where the atmospheric conditions are very variable. They are characterized by a diversity of weather situations with frequent and intense exchanges during the year. These are caused by moving systems of low or high air pressure, often resembling vortices hundreds and thousands of kilometers in diameter. The climate of continental Croatia is modified by the maritime influence of the Mediterranean, which is stronger in the area south of the Sava River than in the north and weakens towards the east. Cultivation of cyprinids in Croatia mostly involves controlled rearing of common carp (*Cyprinus carpio*) in monoculture or polyculture with other species, the most common of which are Grass carp (*Ctenopharyngodon idella*), bighead carp (*Hypophthalmichthys nobilis*), silver carp (*Hypophthalmichthys molitrix*), catfish (*Silurus glanis*), perch (*Sander lucioperca*), pike (*Esox lucius*), and tench (*Tinca tinca*). The production is mostly semi-intensive, where, in addition to the natural food produced in the pond by biological processes and whose production is stimulated by agrotechnical measures (fertilization, etc.), the fish are also fed additional feed, usually cereals (corn, wheat, rye, and barley). The production cycle in carp farming usually lasts three years [93], preliminary data (Table 12).

Table 12. Freshwater aquaculture production in Croatia (t) (2017–2021).

Species	2017	2018	2019	2020	2021
Common carp	2039	1959	2037	1691	2738
Grass carp	169	141	122	133	266
Silver carp	73	36	141	161	212
Big-head carp	477	301	344	326	414
Catfish	31	23	20	32	32
Sander	9	7	7	6	4
Pike	12	7	9	2	3
Rainbow trout	395	336	364.5	379	335.6
Brown trout		34	7.5	12.4	15
Other	67	55	48	37	22
TOTAL (t)	**3272**	**2899**	**3100**	**2779**	**4040**

Source: [92].

According to [94] the analysis of spatial capacities and conditions for the use of the potential of renewable energy sources in the Republic of Croatia, as well as the considered criteria for determining the vulnerability of an area to the energy potential of the sun, encourages the development of the possibility of establishing hybrid photovoltaic systems and aquaculture. Mainly because of their symbiotic relationships, which include increasing the efficiency of energy conversion due to cooling and cleaning the surfaces of the PV modules, reducing the evaporation rate of the water surface, improving the growth rate of fish through integrated designs with PV-powered pumps to control oxygen levels, etc. [17].

4. Conclusions

Viticulture

In Croatia, 92.44% of producers have vineyard plots smaller than 1 ha, but, at the same time, their plots have a share of 32.12% in the total viticulture area in Croatia. Thus, 67.88%, or 12,026 ha, of the total vineyard area seems suitable for APV technology application. It is highly recommended to apply APV only in vineyards with a large area, precisely greater than 1 ha (1 ha is taken as the profitable limit for installing APV systems). The vast majority of recommended vineyard surfaces are located in five viticultural subregions (Croatian Danube, Slavonia, Croatian Istria, Middle and Southern Dalmatia, and Dalmatian Zagora), with a total surface of 10.402 ha. An average slope of 6.38% is not an obstacle for agrivoltaic construction. It was also not possible to obtain the exposure data of vineyards,

but considering the grapevine as a long-day plant, it is assumed that all vineyards are on exposures suitable for setting up APV systems.

Fruit growing

Agrivoltaics in orchards has great potential in Croatia, especially in small- to medium-sized orchards (5–15 ha), such as family farms. Photovoltaic panels above fruit crops can reduce physiological disorders in plants and fruits (sunburn, heat stress, overcolor, etc.). At the same time, panels can be used as hail protection with no need for removal during the offseason (time- and labor-consuming). Panels are changing microclimate conditions (lower air temperatures during the day, higher temperatures during the night, diffusing sunlight, and changing the solar spectra that reach the plants) in orchards, but they also reduce damage and could even improve fruit quality. It is estimated that for at least 2/3 of plantations larger than 1 ha (some 200 plantations–950 ha), there could be a potential for installing agrivoltaics systems, either in the existing cultivation form or with a slight adjustment of agrotechnical measures in the plantation.

Aromatic plants

It is estimated that for at least three-fourths of plantations larger than 1 ha (about 500 plantations in CRO), there are assumptions about the potential for installing agrivoltaic systems, either in the existing cropping pattern or with a slight adaptation of agrotechnical measures in the plantation. Of course, apart from the production conditions of cultivation, not all medicinal and aromatic plants are of the same degree of convenience for setting up agrivoltaic systems. The possibilities for the current successful implementation of agrivoltaic systems in plantations of medicinal and aromatic plants are relatively small due to numerous circumstances, but one should not abandon their installation, even in small quantities.

Vegetable growing

In the Republic of Croatia, despite favorable agro-ecological conditions (pedological and hydrological), existing production is insufficient for the production of most vegetables and is often price uncompetitive with imported vegetables, and the export of domestic fresh and processed vegetables is low in terms of quantity and value. Insufficient production to meet the needs of the Croatian market is a result of fragmented cultivation areas, disorganized production infrastructure, a lack of heating, irrigation, hail and frost protection systems, and inadequate storage areas. All of this indicates that additional investment in modernization, such as agrivoltaic systems, is needed, to make vegetable production competitive and profitable. The use of solar panels in the construction of greenhouses or in open fields is considered the most environmentally friendly solution. Agrivoltaic offers advantages such as protection against hail, frost, and drought damage and eliminates the need for protective films and other materials. In Croatia, the chances for successful implementation of AgriPV systems in vegetable production are currently relatively low due to numerous limiting circumstances (fragmented cultivation areas, unorganized production infrastructure). In addition, growing vegetables with solar panels requires certain adjustments in cultivation practices focused on mitigation of light reduction (especially when growing melons, watermelons, and peppers) and selection and combination of crops with maximum radiation efficiency. Despite the limiting factors, it is recommended to start research projects in the form of "pilot projects" with the most commonly grown vegetables in the Republic of Croatia in order to analyze the possible impact of PV systems in terms of production, growth, yield, resistance to microclimatic changes both in the field and in greenhouses, etc.

Cereals industrial and fodder plants production

About 45% of the total utilized agricultural land in Croatia is used to grow cereals, industrial crops, and fodder crops, which include morphologically and physiologically very diverse plant species with different demands on agroecological conditions, agrotechniques, and agricultural management. Also, most of them, except some fodder crops like alfalfa

or clovers, are annual plants with various growing seasons (winter and spring crops). Concerning necessary crop rotation practices and different cultivation requirements, the implementation of common field crops in AgriPV could be very challenging. Shade tolerance of the crop is one of the most important factors determining the economic result of AgriPV. From that point of view, maize and sunflower are probably the most unsuitable for cultivation in AgriPV.

Grassland and animal husbandry

One of the top three land covers associated with greatest agrivoltaics potential are grasslands. The highest potential of agrivoltaic systems is anticipated in semi-arid and arid regions. Here, grasslands often suffer from the adverse effects of high solar radiation and accompanying water losses. Grassland production under solar panels may benefit from increased water savings by a reduction in evapotranspiration and the adverse effects of excessive radiation, while economic viability is increased and rural electrification is made possible. The main disadvantage of photovoltaics is the shadows cast by the panels, which can affect plant productivity to varying degrees, requiring the selection of hardier plants and limiting those that rely more heavily on sunlight. This also limits the latitudes where agrivoltaics work best, as profitability can suffer in cooler areas where the intensity of sunlight varies throughout the year.

Aquavoltaics

To avoid increasing land use, the approach of aquavoltaics offers a solution in the dual use of land. Especially in countries with long periods of drought, the concept of aquavoltaics offers many synergies. The strong reduction in water loss due to lower evaporation rates is especially interesting. With a suitable system approach, aquavoltaics can contribute to sustainable water use and fulfill the concept of the food-water-energy nexus. The technical feasibility of integrating PV modules into water surfaces has been demonstrated, but solid studies on fish farming are still lacking. More research is needed to understand the effects of direct contact with pontoon structures and solar arrays on aquatic life. The total area of carp ponds in Croatia is currently 14,081.49 ha, while the production area in 2021 was 12,539 ha. Based on this value, it is difficult to estimate how much area is available for the installation of floating solar panels due to several variables. This is mainly due to the undefined extent and intensity of vegetation (sedges, woody vegetation, and copses) in certain places of the registered water area and the classification of production intensity (RAS systems, rearing cages, etc.). Large carp farms are located in the continental part of the Republic of Croatia, mainly in the area of major river courses, and are therefore important for the conservation of biodiversity. Warm freshwater farms (carp farms) represent areas of great natural value in Croatia and are designated as part of the ecological network EU-Natura 2000. Consequently, many different rules and laws apply in these places for the preservation and protection of nature. Maybe this consideration should also be taken into account as a kind of limiting factor for the installation of floating photovoltaics.

Overall conclusions

Agrivoltaics involves the integration of solar panels within agricultural fields, allowing for simultaneous land use for crop cultivation and solar power generation in Croatia. This approach provides numerous benefits, including increased land productivity, reduced water evaporation, and enhanced energy generation. Similarly, aquavoltaics explores the integration of solar panels in freshwater aquaculture systems, offering advantages such as improved water quality, reduced algae growth, and efficient renewable energy production. Through this research, Croatia can harness the synergy between renewable energy production and sustainable agriculture and aquaculture practices, promoting a greener and more resilient future. Further research can focus on optimizing the design and implementation of integrated systems, considering factors such as crop and fish species selection, panel orientation, and system efficiency. In addition, studying the economic via-

bility and long-term sustainability of these approaches will be crucial for their widespread adoption. Collaboration between researchers, farmers, and policymakers can help develop tailored solutions for the Croatian context that maximize the benefits of renewable energy production while ensuring food and water security. Overall, future research in agrivoltaics and aquavoltaics has the potential to revolutionize the energy landscape and contribute to the sustainable development of the Croatian agricultural and aquaculture sectors.

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Article

Accumulation of Stinging Nettle Bioactive Compounds as a Response to Controlled Drought Stress

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Abstract: As the impact of global warming intensifies drought effects, plants need to adapt to drought and other climate change-induced stresses through various defense mechanisms. One of them is the increased synthesis of bioactive compounds (BCs), which helps plants overcome adverse environmental conditions. This effect can be used in sustainable controlled cultivation as a tool for the nutritional improvement of crops, so this study focused on growing stinging nettle (*Urtica dioica* L.) for human consumption in a controlled environment. Since nettle can be consumed as a green leafy vegetable due to its nutritional value, the aim of this study was to determine the content of BCs (ascorbic acid, phenolic compounds, and pigments) and antioxidant capacity of nettle leaves grown under different drought stress conditions in an ebb and flow hydroponic system. During the experiment, plants were treated with a nutrient solution adjusted for nettle cultivation for 1 hour and then exposed to three different drought intervals: 24, 48, and 96 h. During the 48 h drought interval, the plants accumulated the highest amounts of total phenolic content and total non-flavonoid content (400.21 and 237.33 mg GAE/100 g, respectively), and during the 96 h drought interval, the nettle accumulated the highest amount of ascorbic acid (96.80 mg/100 g fw). The highest antioxidant capacity was recorded during the 24 and 48 h treatments (2435.07 and 2444.83 μmol/TE, respectively) according to the ABTS and during the 48 h treatment (3773.49 μmol/TE) according to the FRAP assay. The obtained results show that different drought stress durations caused by the absence of nutrient solutions can have a positive effect on the accumulation of nettle BCs.

Keywords: *Urtica dioica* L.; climate change; drought stress; phenolic compounds; ascorbic acid; antioxidant capacity; sustainable cultivation; ebb and flow hydroponic system

1. Introduction

Global warming and climate change are increasing the risk of droughts, making them longer, more frequent, and more severe, which has a significant influence on plants [1]. Drought stress is a form of abiotic stress that occurs when plants experience a prolonged period of water deficit and is one of the main factors limiting plant productivity in agriculture [2,3]. One of the major challenges for modern agriculture is to deal with the negative effects of climate change, such as drought. To cope with these problems, food production systems are turning to sustainable controlled cultivation that does not have harmful effects on the planet [4].

Drought can have different impacts on plants, affecting their growth, development, morphology, physiology, and biochemical composition, including altering the content of bioactive compounds (BCs) [5,6]. Since drought stress limits the availability of water, which is essential for plant growth and development, it can have several effects: lower yields, reduced cell turgidity, decreased nutrient uptake, reduced photosynthetic activity, altered hormonal balance, induction of oxidative stress, and others [7–11]. To maintain normal

physiological functions, molecular adaptation mechanisms occur at the metabolic and gene levels [12,13]. Such mechanisms can significantly change the nutritional value as well as the biological effects of plants. These responses aim to minimize water loss and maintain cellular functions under limited water availability. One of the most common responses to drought is the production of reactive oxygen species (ROS), such as hydrogen peroxide and superoxide radicals, which are highly reactive molecules that can cause oxidative damage to plant cells [7,14]. Antioxidant defense systems can overcome or mitigate these negative effects and are often accompanied by alterations in the production and accumulation of BCs. Thus, drought stress can significantly affect the content and profile of BCs [15,16]. In favor of the above, studies have shown that plants grown under stressful conditions are often richer in nutrients than the same plants grown under optimal conditions [17,18].

Drought is one of the major challenges of global open-field crop production. Since agriculture significantly contributes to climate change [19], in order to reduce the negative consequences on the environment, it is necessary to turn to sustainable agricultural practices such as hydroponic ebb and flow cultivation. The ability to use less fertilizer, water, and energy makes this agricultural system environmentally friendly [20]. It involves periodic flooding and draining of the nutrient solution, which allows the application of controlled drought stress [21]. It is also important to emphasize that this technique eliminates contamination with heavy metals, nitrates, and pesticides that normally accumulate in the soil and ensures uniform plant material thanks to the possibility of controlling abiotic factors [22]. Choosing the appropriate cultivation method can contribute to the improvement of nutritional quality and the accumulation of bioactive substances in the plant material [22].

BCs are products of different metabolic pathways of plants, and their synthesis is influenced by abiotic and biotic factors. It has been found that different stress factors can intensify and enhance the synthesis of BCs [23]. Numerous studies show that plants subjected to deliberately induced stress and growth environment modifications such as drought, salinity, and temperature stress can increase the accumulation of some BCs (carotenoids, AsA, phenolics, anthocyanins, and glucosinolates) [24–29]. Some plant responses to the application of controlled stress also showed that water stress increased the levels of phenolic compounds in *Hypericum brasiliense* Choisy [24]; drought increased the glucosinolate concentration of *Tropaeolum majus* L. [26]; hot and cold water treatment increased the concentration of vitamin C, chlorophyll b, lycopene, *p*-coumaric and ferulic acid, and glucosinolates of young broccoli [30]; total phenols, carotenoids, ferulic and *p*-coumaric acid of broccoli seedlings were induced by high temperature [31]; induced mechanical stress resulted in a significantly higher content of major antioxidants in lettuce and green chicory [32]; and controlled nutrient solution management had a positive effect on total phenolic and flavonoid content, AsA, and pigment content of nettle grown in a floating hydroponic system [33].

The nutritional value of stinging nettle (*Urtica dioica* L.) derives from numerous BCs that possess antioxidant activity, such as ascorbic acid (AsA), polyphenols, pigments, and minerals [34]. These compounds have great health importance for the human organism because they can pair electrons from free radicals, activate antioxidant enzymes, and inhibit oxidases and carcinogenic compounds [35–37]. For its BCs, fresh stinging nettle leaves can be consumed as a green leafy vegetable, in cooked dishes, and as a source of medicinal substances. Despite its rich nutritional composition, nettle is rarely cultivated, and information on the effects of drought stress on nettle leaf phytochemistry is lacking.

Most research on nettle focuses on wild-collected plant material [38–40], but hydroponic cultivation offers many advantages and can be a great tool for producing nettle leaves of known origin, rich in BCs, and safe for consumption [22]. Since nettle is rarely cultivated, it is important to emphasize that there is no detailed information on the ebb and flow cultivation conditions and the influence of different drought intervals on BC composition. Most research studies on drought stress mainly provide data on the influence of longer water deficit periods (6 to 18 days) on various crops [5,41,42]. This type of experi-

ment tends to show whether shorter dry periods, which do not disturb the morphological characteristics and do not cause wilting or irreversible damage to the plant tissue of nettle, can have a significant effect on the BC content, thus improving the nutritional quality of nettle leaves. Since nettle naturally grows in moist habitats, it is important to determine how it can withstand moderate drought stress that may occur as a result of climate change. Therefore, the aim of this study was to define adaptation to moderate drought conditions and to determine the direct influence of 3 different irrigation regimes, i.e., drought stresses for 24, 48, and 96 h (1, 2, and 4 days, respectively), on the content of selected BCs in nettle leaves. The interval of 24 h was set as a control irrigation interval, while 48 h and 96 h each represented moderate droughts, with different durations. This research is the first step in defining the conditions for controlled nettle cultivation in the ebb and flow system.

Using sustainable techniques with low environmental impact helps to preserve the environment and reduce the damage of climate change. Understanding the influences of drought on plants is crucial for devising strategies to enhance their resilience, improve quality, and mitigate the negative impacts of water scarcity on ecosystems and agriculture.

2. Materials and Methods

2.1. Plant Material

The experiment was conducted in a heated greenhouse at the Department of Vegetable Crops, University of Zagreb Faculty of Agriculture, in Croatia in 2022. Plants were cultivated on three tables (6 m^2 each) using the hydroponic ebb and flow technique. Nettle seeds were sown on January 20 in polystyrene containers with 40 potsfilled with a commercial substrate (Klasman Potgrond H). Approximately 5 seeds were sown per pot, placed on the tables, and regularly irrigated. The beginning of sprouting was noted on February 6. When the plants reached the appropriate size and density, on April 11, they were subjected to different drought and irrigation intervals. Plants were treated with a nutrient solution for 1 h and then exposed to 3 different drought treatments lasting 24, 48, and 96 h. Mature plants were manually mowed on May 10 at the pre-flowering stage. After the yield was measured, leaves were cleaned, separated from the stems, and chemically analyzed at the Laboratory for Quality Analysis of Agricultural Products of Plant Origin at the University of Zagreb Faculty of Agriculture.

2.2. Cultivating Conditions

From April 11, plants were irrigated with a nutrient solution and subjected to different drought treatments. The nutrient solution according to the Johnson recipe was used and prepared with the following salts: KNO_3—250.99, KH_2PO_4—142.7, $Ca(NO_3)_2 \times 4H_2O$—501.5, $MgSO_4 \times 7H_2O$—256.25, FeEDTA 13%—12.8, H_3BO_3—1.32, $CuSO_4 \times 5H_2O$—0.026, $MnSO_4 \times 4H_2O$—0.79, $ZnSO_4 \times 7H_2O$—0.11, and $Na_2MO_4 \times 2H_2O$—0.018 mg/L (EC 1.5 mS/cm, pH 5.8—6.2). The pH of the solution was regulated by adding 56% HNO_3.

Throughout the entire plant growth and development process, the abiotic factors of the greenhouse air (from February 6 to May 10) and the nutrient solution (from April 11 to May 10) were regularly monitored. Figure 1 shows the values of temperature and relative air humidity measured during nettle cultivation. Air temperature and RH were measured using a tabletop thermohygrometer (Agrologistika d.o.o., Čakovec, Croatia). Air temperature values ranged from 4.5 to 40.6 °C with an average value of 22.3 °C, while relative humidity ranged from 32 to 53% with an average value of 41.4%. A multiparameter instrument (Hanna instruments HI98194, Nușfalău, Romania) was used to measure the pH, EC values (mS/cm), and DO (mg/L) of the nutrient solution. The pH averaged 6.7, the EC value averaged 1.5 mS/cm, and the average value of DO in the nutrient solution was 4.6 mg/L, as shown in Figure 2.

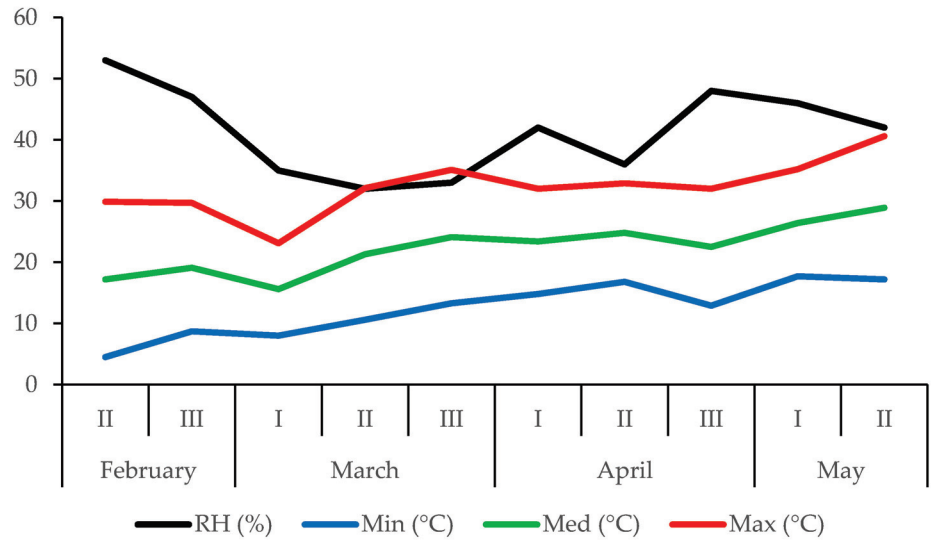

Figure 1. Abiotic factors of the greenhouse during the cultivation period; RH—relative humidity, Min—minimum temperature, Med—medium temperature, Max—maximum temperature. I, II, and III—first, second, and third 10 days of the month, respectively.

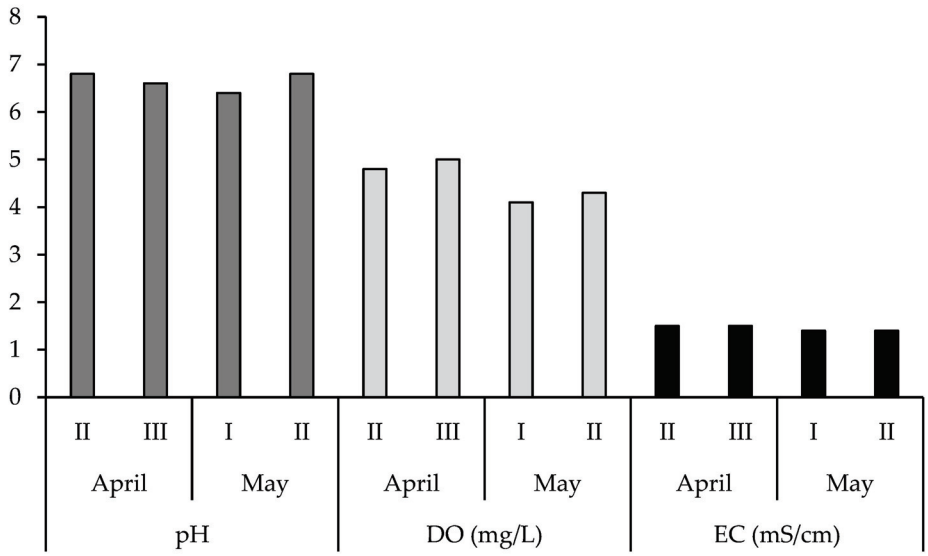

Figure 2. Abiotic factors of the nutrient solution during the cultivation period; DO—dissolved oxygen, EC—electrical conductivity.

2.3. Determination of Physico-Chemical Properties

Chromaticity parameters (L*, a*, b*, C, and h°) were determined according to the CIELab method using a colorimeter (ColorTec PCM+, PCE Instruments, Southampton, UK), where the L* value represents the lightness (0–50 indicates dark and 51–100 indicates light) and a* and b* values represent chromaticity (red to green and blue to yellow, respectively) [43]. The total dry matter content (DM, %) of stinging nettle leaves was determined by drying in an oven at 105 °C to constant mass, and the total acid content (TA, %) was determined by potentiometric titration with sodium hydroxide solution (c = 0.1 mol/L) according to the Association of Officiating Analytical Chemists (AOAC) [44].

2.4. Determination of the Ascorbic Acid Content

According to the standard AOAC method [45], titration with 2,6-dichloroindophenol (DCPIP) was used for the determination of the ascorbic acid (AsA) content. Approximately

4 g of the samples were homogenized with 100 mL of 2% (*v/v*) oxalic acid and then filtered through Whatman filter paper, and 10 mL of obtained filtrate was titrated with freshly prepared DCPIP until the appearance of pink stable coloration. The final quantitative measure of AsA content was expressed as mg/100 g fresh weight and calculated according to Equation (1):

$$\text{AsA (mg/100 g fw)} = (V \times F/D) \times 100 \quad (1)$$

where V is the DCPIP volume (mL), F is the DCPIP factor, and D is the sample mass in the filtrate (g).

2.5. Determination of Total Phenolic and Individual Phenolic Compounds

The spectrophotometric method with the Folin–Ciocalteu (FC) reagent was used for the determination of phenolic compounds, as described by Ough and Amerine [46]. Extracts were prepared by heating 10 g ± 0.01 of finely chopped leaves and 40 mL of 80% EtOH (*v/v*), to a boiling point with reflux, for 10 min. The process was repeated with another 50 mL of 80% EtOH (*v/v*). The solutions were filtered through Whatman filter paper into a 100 mL volumetric flask and made up with 80% EtOH (*v/v*), and obtained extracts were used for the determination of total phenolic (TPC), total flavonoid (TFC), and total non-flavonoid (TNFC) content and for the ABTS and DPPH assays as well.

The chemical reaction for TPC determination was prepared by mixing 0.5 mL ethanolic sample extract, 30 mL distilled water, 2.5 mL previously diluted FC reagent (1:2, *v/v*), and 7.5 mL saturated sodium carbonate solution in a 50 mL volumetric flask. The mixture was shaken well and made up to the mark with distilled water. After incubation for 2 h at ambient temperature, absorbances were determined at 750 nm with a spectrophotometer (Shimadzu, 1900i, Kyoto, Japan). Distilled water was used as a blank, and gallic acid was used as an external standard (concentrations 0–500 mg/L). The final TPC was expressed as milligrams of gallic acid equivalents per 100 g fresh weight (mg GAE/100 g fw) based on the equation of the gallic acid standard curve.

To determine the TNFC (phenolic acids, tannins, stilbenes, lignans, etc.), reaction mixtures were prepared by mixing 10 mL of the sample extract, 5 mL of HCl in EtOH (1:4, *v/v*), and 5 mL of formaldehyde (p.a.) and were blown with nitrogen. After incubation for 24 h in a dark place at ambient temperature, the solutions were filtered through Whatman filter paper, and the same aforementioned reaction with FC reagent and spectrophotometrically measurements were conducted. As an external standard, gallic acid was used, so TNFC was expressed as milligrams of gallic acid and equivalents per 100 g fresh weight (mg GAE/100 g fw). TFC was mathematically calculated as the difference between TPC and TNFC and expressed as milligrams of catechol equivalents per 100 g fresh weight (mg CTH/100 g fw).

Besides total phenolic compounds, some selected individual phenols were determined by liquid chromatography. For this purpose, the HPLC method (high-performance liquid chromatography) defined by Otles and Yalcin [47] was used to analyze caffeic acid, coumaric acid, ellagic acid, ferulic acid, and naringin. The extraction process was set up as follows: 1 g ± 0.01 of finely chopped leaves was mixed with 10 mL of 80% MeOH (*v/v*), homogenized with a laboratory homogenizer (IKA, UltraTurax T-18, Staufencity, Germany), and left for 30 min at 50 °C in an ultrasonic bath (Bandelin RK 103H, Berlin, Germany) to complete the extraction process. Before injection into the vials, the obtained extracts were filtered through Whatman paper and Chromafil PA filter. As an external standard for calibration of the method, a mixture of commercial standards of caffeic acid, coumaric acid, ellagic acid, ferulic acid, and naringin (Sigma Aldrich, Steinheim, Germany) was used. The solutions were prepared by dissolving the standards in HPLC-grade methanol to make stock solutions of 500 μg/mL, which were then used to prepare solutions (2–100 μg/mL) for the standard curve. Analysis of the phenolic compounds was conducted on a NUCLEOSIL 100-5 C18 column (5 μm, 250 × 4.6 mm i.d., Macherey-Nagel, GmbH, Düren, Germany) using an LC Nexera (Shimadzu, Kyoto, Japan) equipped with a photodiode array and fluorescence detector (PDA-RF). The phenolic standard solution mixtures and

methanolic extracts were injected in duplicates using an autoinjector with an injection volume of 20 μL. Operation conditions were the same as those set up by Repajić et al. [40] with minor modifications. A gradient elution of two solvents was used: solvent A (3% formic acid in HPLC-grade water (*v/v*)) and solvent B (3% formic acid in HPLC-grade acetonitrile (*v/v*)). The gradient elution program started with 90% of solvent A and was reduced to 60% at 25 min. This was followed by a solvent A concentration of 30% at 30 min and 90% for the next 35 to 45 min. During a total run time of 45 min, a constant flow rate of 0.9 mL/min and a temperature of 23 °C were used. Qualitative identification was performed by comparing obtained retention times with the retention times of purchased commercial standards, and quantitative analyses were performed by calculating the calibration curves from the mixture of standards (Table 1). The final concentrations of individual phenols were expressed as mg/L. Phenolic compounds present in each sample during the different drought stress intervals are shown in chromatograms (Figure 3).

Table 1. Calibration curves equations of the individual phenolic standards mixtures.

Standard	Calibration Curve Equation	R^2 Value
Caffeic acid	y = 13159.9x + 12112.7	0.9998
Coumaric acid	y = 2551.11x + 2349.01	0.9999
Ellagic acid	y = 33829.1x − 6862.97	1.0000
Ferulic acid	y = 27461.5x − 90059.3	0.9870
Naringin	y = 3941.28x − 30329.7	0.9914

2.6. Determination of Pigment Compounds

Pigment compounds were determined by following the Holm [48] and Wettstein [49] method. Total chlorophylls (TCh), chlorophyll a (Chl_a), chlorophyll b (Chl_b), and total carotenoids (TCa) were measured spectrophotometrically (Shimadzu, 1900i, Kyoto, Japan) at wavelengths of 662 (Chl_a), 644 (Chl_b), and 440 nm (TCa), using acetone (p.a.) as blank. For extract preparation, the amount of 0.3 ± 0.01 g of fresh leaves was homogenized (laboratory homogenizer IKA, UltraTurax T-18, Staufencity, Germany) with a total volume of 15 mL of acetone (p.a.), which was added in 3 repetitions. The obtained acetone extracts were filtered through Whatman filter paper, and measured absorbances were used to quantify the pigment compounds by using Holm–Wettstein Equations (2)–(5). The final contents were expressed in mg/g.

$$\text{Chl_a} = 9.784 \times \text{A662} - 0.990 \times \text{A644 (mg/L)} \quad (2)$$

$$\text{Chl_b} = 21.426 \times \text{A644} - 4.65 \times \text{A662 (mg/L)} \quad (3)$$

$$\text{TCh} = 5.134 \times \text{A662} + 20.436 \times \text{A644 (mg/L)} \quad (4)$$

$$\text{TCa} = 4.695 \times \text{A440} - 0.268 \times \text{TCh (mg/L)} \quad (5)$$

2.7. Determination of Antioxidant Capacity

The same ethanolic extract used for phenolic compound determination was also used for antioxidant capacity determination through two spectrophotometric methods, ABTS (2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) and FRAP (ferric reducing antioxidant power).

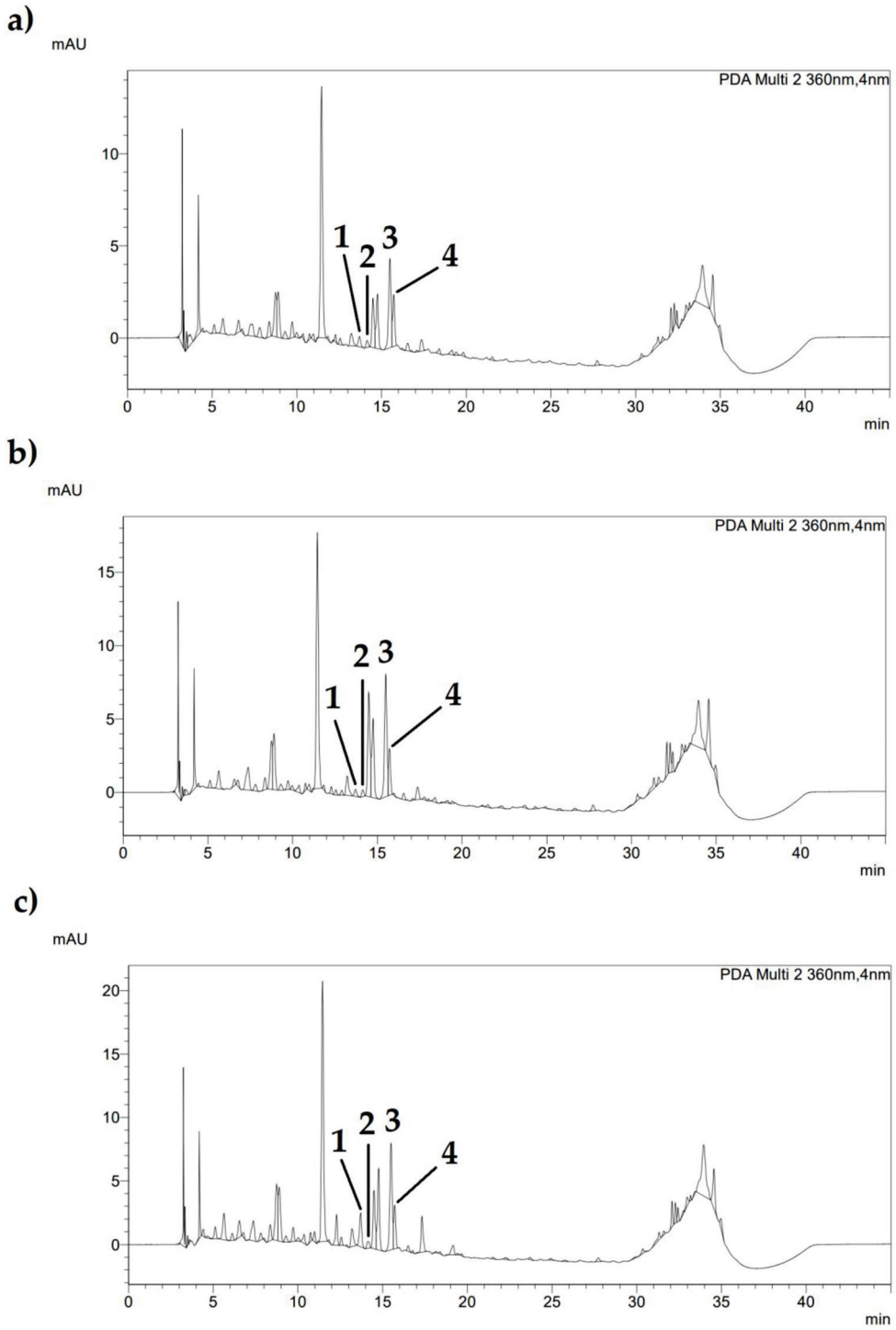

Figure 3. HPLC chromatogram of the individual phenolic compounds of fresh stinging nettle leaves recorded at 360 nm, cultivated under different drought stress intervals of (**a**) 24, (**b**) 48, and (**c**) 96 h drought treatment; 1—coumaric acid, 2—ellagic acid, 3—naringin, 4—ferulic acid.

The free radical scavenging capacity of the plant samples was determined by ABTS assay according to Miller et al. [50]. The method is based on the capacity of antioxidants to scavenge $ABTS^{\bullet+}$ radical cations, which is manifested as solution decolorization. For preparing an $ABTS^{\bullet+}$ radical cation solution, 88 µL of a 140 mM $K_2S_2O_8$ and 5 mL of a 7 mM ABTS solution were mixed and left to stand for 16 h in the dark at ambient temperature. From this reaction solution, a 1% working solution in 96% ethanol (*v*/*v*) was prepared. The absorbance was set up to 0.70 ± 0.02 at 734 nm. The amount of 2 mL

of 1% $ABTS^{\bullet+}$ radical cation solution and 160 μL of ethanolic extract were pipetted into a cuvette and left to incubate for 5 min at ambient temperature. Trolox was used as a standard and 96% ethanol as a blank control. Absorbances were measured at 734 nm with a spectrophotometer (Shimadzu, 1900i, Kyoto, Japan), and the final results were expressed as μmol TE/L (Trolox equivalents).

The ferric reducing antioxidant power (FRAP) of the ethanolic extracts was determined according to the method of Benzie and Strain [51]. In the presence of the sample antioxidant, Fe^{3+}–TPTZ (2,4,6-tri(2-pyridyl)-1,3,5-triazine) is reduced to Fe^{2+}–TPTZ, and reduced iron is correlated with the amount of antioxidants and measured at 593 nm on a spectrophotometer (Shimadzu, 1900i, Kyoto, Japan). The FRAP reagent contained 75 mL of 300 mM acetate buffer (pH 3.6), 7.5 mL of 10 mM TPTZ reagent, and 7.5 mL of 20 mM $FeCl_3 \times 6H_2O$. It was freshly prepared, and 6240 μL of the FRAP reagent was mixed with 720 μL of water and 80 μL of ethanolic extract samples. The reaction mixtures were incubated in a water bath at 37 °C for 5 min. For the blank, a similar reaction was prepared, but instead of extracts, 80% EtOH (*v*/*v*) was used. To draw a calibration curve, Trolox was used as a standard, and antioxidant activity was expressed in μmol TE/L.

2.8. Statistical Analysis

The greenhouse experiment was laid out according to the randomized block design in three repetitions, and all laboratory analyses were performed in triplicate. All results were analyzed with one-way analysis of variance (ANOVA) using a general linear model procedure (PROC GLM) in SAS 9.4. software [52]. Mean values were compared using the *t*-test (LSD) and considered different at $p \leq 0.05$., while different superscript letters in the tables indicate significant statistical differences between the different drought treatment intervals.

3. Results

The values obtained for aboveground nettle yield (kg/m^2) during treatments of 24, 48, and 96 h of drought are presented in Figure 4. There were significant differences among the tested treatments. The highest yield was obtained under the most frequent nutrient solution irrigation period (24 h of drought).

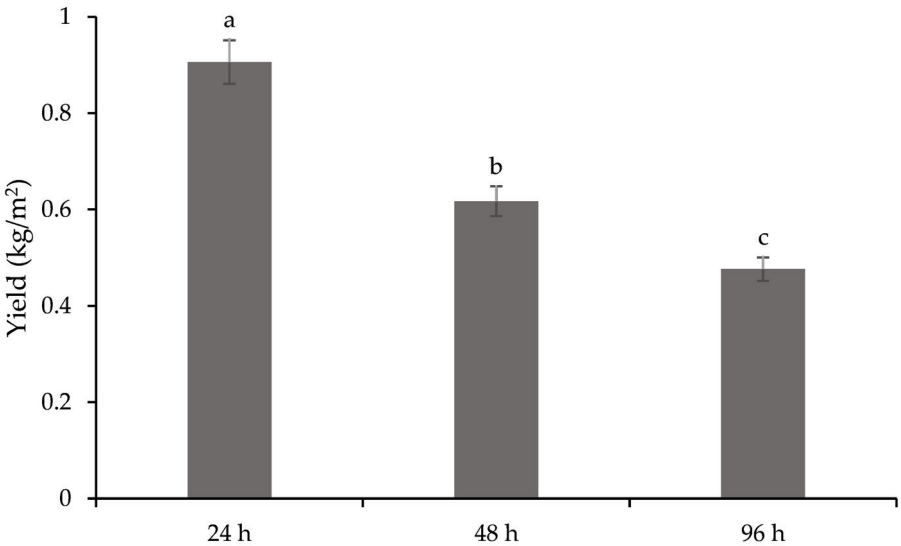

Figure 4. Yield of fresh aboveground stinging nettle cultivated under different drought intervals. Different letters indicate significant differences between mean values.

Table 2 shows the effects of drought on chromaticity parameters. All L* values below 50 indicate darker leaves, with the measured average being 42.44. Negative a* values show the presence of green color, with no change in green color among treatments. The average a* value was 14.73. Positive b* values show the presence of a yellow color. During the

treatment of 96 h, the highest b* value was recorded, which was higher by around 22% than in the other treatments. Analysis of variance showed that drought treatments had no significant effects on L* and a* values but strongly affected the b* value.

Table 2. Chromaticity parameters of fresh stinging nettle leaves cultivated under different drought intervals.

Treatments	L*	a*	b*	C*	h°
24 h	41.34 ± 1.45	−14.65 ± 0.56	23.17 ^{b} ± 1.85	27.41 ^{b} ± 1.85	122.35 ^{a} ± 1.13
48 h	41.77 ± 1.68	−13.91 ± 1.00	22.29 ^{b} ± 2.07	26.28 ^{b} ± 2.26	121.99 ^{a} ± 0.99
96 h	44.22 ± 0.98	−15.62 ± 0.32	27.69 ^{a} ± 0.44	31.79 ^{a} ± 0.49	119.44 ^{b} ± 0.44
ANOVA	NS	NS	0.0137	0.0169	0.0148
LSD	2.8008	1.3804	3.2414	3.4151	1.8092

L*—lightness; a*—green–red color; b*—blue–yellow color; C*—chroma; h°—hue; NS—non-significant. Results are expressed as mean ± standard deviation. Different letters indicate significant differences between mean values.

The results of the total dry matter content (DM) and total acid content (TA) of nettle leaves grown under different irrigation intervals are presented in Table 3. The different intervals had a significant influence on DM. The highest DM was recorded under intervals of 48 (21.5%) and 96 h (21.28%), which was about 13.5% higher than during the shortest (24 h) interval. On the other hand, the treatments did not affect the TA content, and values ranged from 0.24 to 0.29% of TA.

Table 3. Total dry matter content (DM %) and total acid content (TA %) of fresh stinging nettle leaves cultivated under different drought intervals.

Treatments	DM (%)	TA (%)
24 h	18.85 ^{b} ± 0.43	0.29 ± 0.03
48 h	21.50 ^{a} ± 0.56	0.24 ± 0.01
96 h	21.28 ^{a} ± 0.64	0.26 ± 0.06
ANOVA	0.0018	NS
LSD	1.0957	0.0769

Results are expressed as mean ± standard deviation. Different letters indicate significant differences between mean values.

The results of the analyzed bioactive compounds are shown in Tables 4–6. Statistical analysis of variance showed significant differences in AsA content between all varied treatments (Table 4). The highest content of AsA, 96.8 mg/100 g fw, was recorded during the longest (96 h) irrigation regime, while the lowest value was noted during the shortest interval (24 h treatment). The content of analyzed phenolic compounds (total phenolics—TPC, non-flavonoids—TNFC, and flavonoids—TFC) also differed significantly depending on the irrigation regime, as shown in Table 4. During the 48 h treatment, the highest TPC (400.21 mg GAE/100 g fw) and TNFC (237.33 mg GAE/100 g fw) were recorded, while the highest values for TFC were observed during both 24 h and 48 h irrigation intervals. Variance analysis showed that the controlled drought intervals had a significant effect on all phenolic compound contents.

As for individual phenols, values of the identified compounds are noted in Table 5. Naringin was dominant among the tested compounds, with an average value of 7.91 mg/L. The values obtained for ferulic and ellagic acid did not statistically differ and were present with an average amount of 4.21 mg/L and 1.18 mg/L, respectively. Coumaric acid was predominant in the longest dry period (6.81 mg/L), which was around 8 times higher than during the other two regimes, while caffeic acid was not detected in any sample. The results suggest that the different treatments had a significant influence only on coumaric acid.

Table 4. Ascorbic acid and phenolics compound content of fresh stinging nettle leaves cultivated under different drought intervals.

Treatments	AsA (mg/100 g fw)	TPC (mg GAE/100 g fw)	TNFC (mg GAE/100 g fw)	TFC (mg CTH/100 g fw)
24 h	73.01 ^{c} ± 2.63	328.06 ^{b} ± 0.51	166.01 ^{c} ± 0.90	162.05 ^{a} ± 0.40
48 h	79.52 ^{b} ± 3.60	400.21 ^{a} ± 1.41	237.33 ^{a} ± 1.35	162.88 ^{a} ± 2.76
96 h	96.80 ^{a} ± 2.48	308.45 ^{c} ± 0.52	173.61 ^{b} ± 0.56	134.84 ^{b} ± 0.63
ANOVA	0.0002	≤0.0001	≤0.0001	≤0.0001
LSD	5.8844	1.8354	1.9781	3.2987

AsA—ascorbic acid; TPC—total phenolic content; TNFC—total non-flavonoid content; TFC—total flavonoid content. Results are expressed as mean ± standard deviation. Different letters indicate significant differences between mean values.

Table 5. Individual phenolic compound content of fresh stinging nettle leaves cultivated under different drought intervals.

Treatments	Caffeic Acid (mg/L)	Coumaric Acid (mg/L)	Ellagic Acid (mg/L)	Ferulic Acid (mg/L)	Naringin (mg/L)
24 h	nd	1.15 ^{b} ± 0.10	0.79 ± 0.18	4.19 ± 0.05	7.88 ± 0.01
48 h	nd	0.61 ^{b} ± 0.32	1.23 ± 0.47	4.22 ± 0.03	7.89 ± 0.07
96 h	nd	6.81 ^{a} ± 1.94	1.52 ± 0.22	4.23 ± 0.07	7.96 ± 0.01
ANOVA	-	0.0010	NS	NS	NS
LSD	-	2.2702	0.6293	0.102	0.0793

nd—not determined; NS—non-significant. Results are expressed as mean ± standard deviation. Different letters indicate significant differences between mean values.

Table 6. Pigment compound content of fresh stinging nettle leaves cultivated under different drought intervals.

Treatments	Chl_a (mg/g)	Chl_b (mg/g)	TCh (mg/g)	TCa (mg/g)
24 h	0.85 ^{a} ± 0.01	0.50 ^{a} ± 0.02	1.34 ^{a} ± 0.03	0.23 ^{a} ± 0.01
48 h	0.64 ^{c} ± 0.01	0.26 ^{c} ± 0.01	0.90 ^{c} ± 0.01	0.23 ^{b} ± 0.01
96 h	0.71 ^{b} ± 0.01	0.42 ^{b} ± 0.01	1.13 ^{b} ± 0.01	0.22 ^{c} ± 0.01
ANOVA	≤0.0001	≤0.0001	≤0.0001	0.0004
LSD	0.0143	0.0242	0.0387	0.0036

Chl_a—chlorophyll a; Chl_b—chlorophyll b; TCh—total chlorophylls; TCa—total carotenoids. Results are expressed as mean ± standard deviation. Different letters indicate significant differences between mean values.

The content of chlorophyll a (Chl_a), chlorophyll b (Chl_b), total chlorophylls (TCh), and total carotenoids (TCa) was determined from a group of pigment compounds, and the results are presented in Table 6. Analysis of variance showed that the tested factor had a significant effect on pigment content. Additionally, according to the statistical analysis, significant differences were observed in the content of all pigments in the leaves during all treatments. The levels of Chl_a, Chl_b, TCh, and TCa were significantly higher in nettle leaves grown under the shortest irrigation interval (24 h) with the amounts of 0.85, 0.50, 1.34, and 0.23 mg/g, respectively.

The results of the antioxidant capacity of the studied samples exposed to different drought regimes are presented in Table 7. The values ranged from 2410.72 to 2435.07 µmol TE/L according to the ABTS and from 3114.24 to 3773.49 µmol TE/L according to the FRAP assay. Considering the results of the antioxidant capacity, it can be noticed that there was no statistical difference between 24 h and 48 h when using the ABTS assay. Using the FRAP assay, the highest antioxidant capacity was obtained under the influence of the intermediate irrigation interval of 48 h (3773.49 µmol TE/L), which was 21% higher than during the shortest drought period. A significant influence of controlled irrigation on the antioxidant capacity of nettle leaves was recorded.

Table 7. Antioxidant capacity of fresh stinging nettle leaves cultivated under different drought intervals.

Treatments	ABTS (μmol TE/L)	FRAP (μmol TE/L)
24 h	2435.07 [a] ± 4.23	3114.24 [c] ± 51.31
48 h	2444.83 [a] ± 4.57	3773.49 [a] ± 39.22
96 h	2410.72 [b] ± 12.78	3220.97 [b] ± 40.84
ANOVA	0.0058	≤0.0001
LSD	16.4	88.134

Results are expressed as mean ± standard deviation. Different letters indicate significant differences between mean values.

4. Discussion

One of the major agricultural tasks is to provide enough food through sufficient crop yields. Yield can be affected by many abiotic and biotic factors, but water availability is one of the critical conditions that can cause various challenges to agricultural production [53]. The results of this study show that the highest yield (0.91 kg/m^2) was accomplished when the plant received the most water (Figure 4). During the shortest drought period (24 h), the yield was 47% higher than during 48 h of drought and even 90% higher than during 96 h of drought. Based on obtained data, it can be concluded that prolonged unavailability of a nutrient solution leads to greater yield reduction. Droughts, with their complex patterns, are consistently related to negative impacts on crop yield on a global scale [54], and many studies recorded the same effect of reducing crop yield under drought stress [55–58]. Since water is essential for plants, physiological processes are disrupted when water supply is insufficient, resulting in reduced plant growth and development. Drought conditions decrease yield through reduced photosynthesis, nutrient deficiency, inhibition of cell division, and elongation [59,60]. Some of these effects may be responsible for yield reduction in nettle leaves. Under drought conditions, yield reduction is expected, so it is necessary to optimize and control drought stress in order to avoid large losses in agricultural production.

Visual perception plays a key role in the selection of nutritious and healthy foods, and color can serve as an indicator of food quality or defects. Customers associate different fruits and vegetables with their specific colors, which provide information about the condition of the plant material. The color of leaves can also be specific to different plant species and is related to pigment composition, mainly chlorophylls [61]. A change in the specific color and appearance of multi-colored spots may indicate disease [62], nutrient deficiency [63], or stress effects. In addition to various morphological changes, typical drought stress symptoms in plants include leaf yellowing [6], as was also observed in this research, where the leaves under the influence of the longest drought period (96 h) were the yellowest. To measure and define the color and color differences of nettle leaves, the CIELAB scale was used, and the results indicated darker leaves with the presence of green and yellow color, while drought treatments affected only the intensity of the yellow color (Table 2).

Total dry matter content (DM) represents the basic chemical composition of the raw material, i.e., the content of all components, such as proteins, carbohydrates, minerals, and BCs, except water [64]. Thus, plant materials with higher DM values possess higher nutritional quality. The obtained DM values in the nettle leaves ranged from 18.85 to 21.50% (Table 3), and plants irrigated for 48 and 96 h were more prone to DM accumulation than those with more frequent irrigation (every 24 h). Thus, longer dry periods positively affected DM accumulation, showing about 14% higher DM content than during the shortest dry period. This confirmed the expectation of the lowest DM content during the most frequent irrigation period due to the highest water availability. The increased accumulation of DM content may be due to several reasons. In general, the DM of plant tissues can be affected by various factors, including ecological and agronomic conditions and cultivation systems [65–67]. Water stress can have a positive or negative effect on the content of total DM in plant material, which depends on the length of the stress periods as suggested by the

results of this study. The trend of longer dry periods significantly increasing the DM content in leafy vegetables was confirmed by Mogren et al. [68]. Additionally, Soltys-Kalina et al. [5] confirmed that prolonged dry periods can lead to a decrease in the water content of leaves, i.e., an increase in DM content. Since drought results in temporary salt accumulation in the root zone as a consequence of the drying of the substrate [69,70], it is likely that under the influence of drought, an accumulation of nutrients occurred in the substrate. These nutrients are used for the production of DM, so it can be assumed that salt accumulation could result in an increase in DM during both 48 and 96 h periods. DM can also be affected by abiotic factors, and its accumulation is strongly correlated with water transpiration [71]. An average RH of 41.4% in the greenhouse during the cultivation period may have slowed down transpiration, causing high DM values during all treatments. This is one reason why cultivation in controlled conditions might take precedence over open-field-produced or collected plant material. Regardless of the influence of the investigated treatments, the obtained DM values are very close to those obtained for floating hydroponically cultivated nettle [72,73] and can be considered high compared to other leafy vegetables [74,75].

Organic acids naturally occur in vegetables as products of cellular metabolism and contribute to the sensory properties and durability of fresh raw materials [76]. The results of the present study showed that different absences of water had no effect on TA content in fresh nettle leaves (Table 3). Usually, the presence of TA in plant material can depend on environmental conditions, the type of plant tissue, and plant maturity [77]. Organic acids are key components in mechanisms that some plants use to better adapt to environmental stress [78]. Thus, it can be assumed that due to the stress caused by the deficiency of water, nettle synthesized an equal amount of organic acids during all treatments in order to preserve the plant metabolism.

AsA is an important compound with antioxidant properties found in various plant tissues including fruits and leaves [79,80], where it plays a crucial role in plant defense mechanisms against oxidative stress caused by various environmental factors, including drought [81]. On the other hand, AsA is an essential nutrient with numerous beneficial health properties required for the normal functioning of the human organism [82,83]. As previously shown in some other studies [14,55,84–87], the results of this research also confirm that drought can have a significant influence on the AsA content in plants. In this study, AsA content increased with the prolongation of dry periods, with the lowest value recorded during the shortest and the highest value during the longest dry period (Table 4). During the 96 h treatment, nettle leaves accumulated even 33% more AsA than during the 24 h regime. Regardless of the highest measured value, all nettle samples grown in the hydroponic ebb and flow system under drought treatments of 24 to 48 h can be considered a rich source of AsA, especially when compared to other studies on wild collected nettle leaves [88,89], other leafy vegetables [90–92], and the recommended daily intake (RDI) of vitamin C (according to the Institute of Medicine) [93]. Drought can both decrease [14,86] or increase AsA content in different agricultural crops, but most studies have shown that drought stress generally leads to an accumulation of AsA in plants. Accordingly, the enhancement of AsA levels affected by drought was established in several studies [55,84,85, 87]. Drought stress triggers various adaptive responses in plants, including the activation of antioxidant defense mechanisms [94]. Drought can cause increased ROS (reactive oxygen species) production, which leads to oxidative stress [7,95]. AsA plays a crucial role as an antioxidant by scavenging ROS, neutralizing its harmful effects, and protecting plant cells by maintaining cellular redox homeostasis and protecting various cellular components (proteins, lipids, and DNA) from oxidative damage [79,96]. Therefore, under drought conditions, plants may allocate more AsA towards antioxidant defense, which was the case in the present study. Oxidative stress induced by adverse environmental conditions (drought and salinity) leads to lipid peroxidation with free radicals attacking and damaging cell membranes [15,97]. This, in turn, increases AsA production in order to overcome the negative effects. Another way to deal with environmental inconveniences and oxidative stress is to stimulate the biosynthesis of antioxidant enzymes, such as superoxide dismutase,

catalase, or glutathione peroxidase, whose activity can be affected by AsA [96,98]. On the other hand, drought can also disrupt normal AsA (nonenzymatic antioxidant) metabolism and affect the activity of other enzymes responsible for AsA biosynthesis, leading to changes in its content [98], as in the present study. Apart from the fact that the specific effect of drought on AsA content can vary depending on plant species, nutrient availability, duration, and severity of drought, different plant tissues may respond differently to drought stress. The results of this study show that nettle leaves grown under stress caused by 24 to 96 h of the absence of nutrient solution are a valuable source of AsA.

Phenolics are a diverse group of compounds found in plants that play various roles in their growth and development and are crucial in secondary metabolism as defense molecules [99]. In addition to plant protection, phenolic compounds have great application potential in human health, acting as antimicrobial, anti-inflammatory, and antitumor agents [100]. Drought stress can affect the concentration of phenolic compounds in plant tissues as suggested by some other studies [41,42,101–106] but also confirmed by the results of this research (Table 4). The results show that the irrigation interval of 48 h caused the highest levels of TPC and TNFC, with the TPC content being 22% higher than during the shortest treatment (irrigation interval of 24 h). Results for TNFC show that during the same 48 h treatment, non-flavonoid compounds were around 37% more abundant than during the longest drought treatment (96 h) and even 43% higher than during the shortest drought period (24 h). As for TFC, the 24 and 48 h treatments had the same effect on flavonoid accumulation, which was around 21% higher than during the longest irrigation interval (96 h). Drought can stimulate the biosynthesis of phenolic compounds in plants as a response to stressful conditions. Increased phenolic production is considered to be a protective mechanism against oxidative stress that enhances plant defenses [94]. In some cases, total phenolic content may increase as a result of drought-induced stress responses [42,87,101,102,105,106]. However, in other cases, prolonged drought stress may lead to a decrease in phenolic content due to various physiological and metabolic changes in the plant [41,103,104]. Moreover, different plant tissues, such as leaves, stems, and roots, may respond differently to drought stress in terms of phenolic production and accumulation [6,15,56,85,100]. The obtained results of the present study suggest that a moderate disruption of nutrient solution supply for 48 h is optimal to increase the accumulation of total phenolic compounds in nettle leaves.

Various individual phenolic compounds were recorded in nettle, depending on plant origin [107,108]. The presence of caffeic, coumaric, ellagic, and ferulic acid and naringin has been previously noted in nettle [38,47,107–110], other leafy vegetables such as spinach, lettuce, basil, Pakchoi, and Chinese cabbage [111,112], and leaves of other plant species as well [111–115]. These compounds play important roles in plant organisms: caffeic acid is involved in stress tolerance [116], coumaric acid modulates plant growth and metabolism [112], ellagic acid has a protective role [115], ferulic acid is found widespread in plant cell walls [117], and naringin is involved in leaf development [118]. Apart from the fact that all selected individual phenols have a role in plant development, they also show positive effects on human health and many pharmacological activities [100,111,112,115,118]. Of the individual phenolic compounds investigated, coumaric acid was the most dominant in the irrigation interval of 96 h. The increase in the content of coumaric acid was almost 8-fold higher compared to the other treatments. Drought-induced treatments had no influence on other individual phenolic compounds (ellagic and ferulic acid and naringin), and caffeic acid was not detected at all. This goes in favor of different phenolic compounds responding differently to drought stress. Moreover, depending on the plant species and their specific stress response mechanisms, different individual phenolic compounds may be synthesized or accumulated. For example, levels of caffeic, coumaric, and ferulic acids in *Vitis vinifera* L. leaves decreased significantly under drought stress [41], while the levels of coumaric and caffeic acids were greater in water-stressed leaves of *Ctenanthe setosa* (Rosc.) [101]. This, as well as the results of the present study, confirms that some plants may increase the production of certain phenolics, while others may decrease or

maintain their levels. Apart from the fact that the specific effects of drought on phenolic content can depend on plant species and organs, it is important to note that they can vary among plant developmental stages, genotypes, environmental conditions, and durations of drought [103,104,119]. In addition, due to the complexity of plant phenolic metabolism and interaction with other stress factors, it is challenging to generalize the precise influence of drought on the phenolic content of plants [100,120].

Photosynthetic pigments are molecules that play a crucial role in photosynthesis and are vital for the proper development and growth of plants. The two primary pigment groups involved in photosynthesis are chlorophylls and carotenoids [121]. They also manifest numerous beneficial biological functions and health benefits for the human organism [61,122]. In nettle leaves grown under different irrigation intervals, all pigments were most abundant in the 24 h interval (Table 6). The lowest Chl_a, Chl_b, and TCh contents were found during the 48 h treatment, and the values were about 25, 48, and 33% lower than during the 24 h treatment, respectively. The lower leaf chlorophyll content in treatments with reduced irrigation was also confirmed in experiments by other authors [55,123–125]. In general, drought stress inhibits the photosynthetic rate. When water becomes limited, plants may close their stomata to reduce water loss through transpiration. This also reduces the availability of CO_2 for photosynthesis. As a result, plants may reduce the synthesis of chlorophyll molecules because they are not needed in large quantities under reduced photosynthetic activity [9,126–128]. This reduction in chlorophyll content can also result in a visible symptom known as chlorosis, in which the leaves appear yellow or pale green due to lower chlorophyll levels. This can be correlated with the chromaticity parameter b*, where leaves under a 96 h irrigation interval were the yellowest (Table 2). Drought stress can also alter the ratio of different chlorophyll molecules (a and b) within the plant, increasing the ratio of chlorophyll a to chlorophyll b. This adjustment helps to maintain a more efficient energy transfer process and optimize the limited available light energy [129,130]. In the present study, this trend was recorded between the first and second treatments, where the Chl_a to Chl_b ratio increased by 1.5-fold as drought prolongated from 24 to 48 h. Carotenoids are accessory pigments that cooperate with chlorophylls and help protect chlorophyll molecules from excessive light energy [131,132]. During drought stress, plants may increase the production of carotenoids as a defense mechanism against oxidative stress caused by high light intensity and limited water availability as shown by some studies [85]. However, the results of the present study showed a different trend, with the highest carotenoid content detected during the shortest treatment, which was then slightly increased by prolonging irrigation regimes (Table 6). Although reductions in chlorophyll content can decrease photosynthetic rates and thus limit plant energy production and growth [133], the increased production of other BCs can help protect the plant from excessive light and oxidative damage, which could improve its survival chances under drought conditions. The specific responses of plant pigments to drought can vary depending on plant species, the severity and duration of the drought, and other environmental factors [6]. This study confirmed, as other experiments had previously shown, that drought conditions can have significant effects on plant pigment composition, with drought stress often leading to a decrease in total chlorophyll content in plants.

Antioxidants are any compounds that help protect cells from damage caused by free radicals [36,134]. All chemical compounds analyzed in this study (AsA, pigments, and phenols) are considered to have antioxidant properties. As previously confirmed, under drought stress, plants often respond by increasing the production of antioxidants because a drought-induced water deficit can lead to an imbalance between the production of ROS and the plant's ability to scavenge and neutralize them [7,105,135]. Compounds with antioxidant activity also protect lipids from peroxidation, preventing cell membrane damage caused by drought-induced oxidative stress [134]. Drought stress also triggers the activation of various antioxidant enzymes in plants, as previously mentioned, which scavenge and convert harmful ROS into less reactive or non-toxic forms [135]. In this study, two different assays for the determination of antioxidant capacity were used because antioxidant

systems can be both hydrophilic and lipophilic. Considering the values determined for nettle leaves under different irrigation intervals, it can be noted that the highest values were recorded during the 24 and 48 h treatments according to the ABTS assay, but these values were only about 1.2% higher than during the 96 h treatment. Higher antioxidant capacity values detected by the FRAP assay during longer irrigation intervals (48 and 96 h) are most likely due to the accumulation of antioxidant compounds in response to oxidative stress conditions. These results are in agreement with those of AsA and TNFC, for which the highest values were also determined during longer dry periods (48 and 96 h). It is necessary to emphasize that regardless of the statistical differences between irrigation intervals, high antioxidant capacity values were detected during all treatments, highlighting that nettle leaves are a potent antioxidant source, even under moderate drought conditions.

5. Conclusions

The conducted research provides additional data on the production of nettle in a sustainable ebb and flow hydroponic system under controlled drought stresses. The results show that drought encouraged the increased production of some BCs, especially AsA. The highest AsA and coumaric acid contents were recorded during the longest drought period (96 h), while the highest DM, TPC, and TNFC were determined during either 48 or 96 h of nutrient solution absence. The shortest treatment (24 h) was suitable for achieving the highest yield and the best accumulation of pigments. In general, the results suggest that at the expense of yield, the nutritional quality of nettle leaves can be significantly improved under the influence of moderate drought. Apart from the fact that the task of agriculture is to produce a sufficient amount of food, it is very important that this food is nutritionally rich, so it is necessary to find a balance in the application of controlled drought in order to meet the needs of yield and quality. The ebb and flow system with the possibility of controlled irrigation intervals and abiotic factors can be used as an efficient and sustainable practice for the production of nettle leaves rich in BCs. Further studies on the effects of longer drought on nettle phytochemistry, simulating severe climatic stress, are recommended. Understanding the influence of drought on BC levels in plant tissues is important for both plant physiology research and agricultural practices, as it can provide insights into the mechanisms of plant responses to water stress and help in the development of drought-tolerant crop varieties, which is also important in the context of climate change.

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Technological Capabilities for the Adoption of New Technologies in the Agri-Food Sector of Mexico

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Abstract: Agriculture 4.0 and 5.0 generate good expectations of satisfying the growing demand for food in a sustainable way. However, in order to make effective use of scientific and technological developments, infrastructure, knowledge, experience and skills are required. In this sense, the objective of this research was to analyze the technological capacity of the Mexican agri-food sector for the adoption of new technologies. The documentary research method was used, and the information was obtained from the Encuesta Nacional Agropecuaria, the Instituto Nacional de Estadística y Geografía and the Instituto Mexicano para la Competitividad. A cluster analysis was performed to generate a typology of states, in addition to an analysis of variance with the Kruskal–Wallis H Test for independent samples, for which the IBM® SPSS Statistics program was used. The variables analyzed presented very low values, indicating low technological capabilities. Three clusters of states with different technological capabilities were identified. The first was formed of four states in the north of the country with high technological capabilities, for which it was expected that they would have higher adoption rates. Next, there was a group made up of ten states in the north and center of the country with intermediate technological capabilities. Finally, there was a group of 18 states of the country made up of states from the center and south of the country, which present the lowest levels. The results indicate that the technological capacities for the adoption of new technologies in the Mexican agri-food sector are low in general, and are concentrated in some highly specialized regions linked to international markets.

Keywords: smart agriculture; technological change; science and technology; innovation; sustainability

1. Introduction

At present, society faces very complex problems derived mainly from the dominant economic development model, which affect us more and more and are more frequent [1]. This situation has its origins in the 20th century, which was characterized as a period of unprecedented economic expansion and was seen as the natural state of things, in which population growth was not conceived as a problem [2]. Global demographic trends such as population growth and aging, poverty, migration and urbanization have important implications for economic development and for the environment [3]. Consequently, it is estimated that the demand for food will increase by more than 60% by 2050, and this will exert great pressure on agri-food systems [4].

Gradually, a greater awareness of the constant crises caused by environmental, economic, social and health problems has developed. Currently, there is a certain consensus among the world scientific community that the current development model could lead to an environmental catastrophe in the long term [5]. Faced with these global problems, it is necessary to develop new forms of organization and economic integration. That is to say, a profound reconfiguration of all our economic, technological, political, social and environmental relations is required, especially of the productive systems and specifically the agri-food system.

The agri-food sector has historically experienced a series of scientific and technological revolutions that have allowed it to increase productivity, efficiency, performance, and profitability to levels never before imagined [6]. Currently, it is proposed that a digital agricultural revolution will be the change that could help ensure that agriculture meets the needs of the world population [7]. In the agri-food sector, science and technology have been adopted, adapted and developed very successfully and have managed to minimize, and in some cases eliminate, the effect of factors related to environmental conditions and resource endowment [8]. New technologies have recently emerged that have been developed in other sectors and have adapted very well to the agri-food sector; for example, the use of sensors to monitor crops, drones to carry out some monitoring activities and the application of agrochemicals, and robots to carry out activities that put the health of man at risk [9–11].

The use of digital technologies is transforming all the processes, products, and services of the agri-food systems. Their use improves efficiency and facilitates agri-food management, which increases productivity, effectiveness, profitability and the conservation of natural resources [12–14]. The positive and negative effects of new technologies have been discussed, although not enough; however, there is no doubt that the benefits are much greater in all segments of the value chain [15,16]. Consequently, digital agriculture has received considerable attention for policies in recent years, mainly aimed at complying with the principles of sustainable development, such as biodiversity conservation, waste management, soil protection and human health [17]. In addition, it is believed that the further development of the application and data transfer infrastructures and their integration into all sectors will play a crucial role in the future [18].

It is important to mention that not all countries and sectors innovate in the same way, nor do they have the infrastructures and social consensus to generate trust and information for people and organizations to manage digital technologies [19]. For example, the northern region of Mexico from its origin emerged as a highly technical agriculture and this has allowed a greater and better integration of agri-food chains. In the case of the central western region of the country, the production systems have also been modernized. The center of the country has maintained less dynamism, and in the case of the south, until a few years ago it was not characterized as an agri-food producer. In addition, from the research, no information has been generated on the consequences of heterogeneity and asymmetries between countries, sectors, regions and actors, and there is a lack of adequate measurement and evaluation instruments [20]. The foregoing is relevant because business strategies, processes, technologies, final products, relationships with suppliers and customers are conditioned by the new technological complexity [19] and the diffusion and adoption of digital technologies in society and in production systems introduce a disruptive change to the entire economic system.

Despite the benefits, the adoption rates of technologies such as smart agriculture are not uniform across countries [12]. However, the reality indicates that all countries, companies and markets are being affected by the digital transformation and more so as a result of the health emergency created by COVID-19, which forced the entire world into confinement and to adopt the use of digital tools [6]. In addition, it originated the emergence of four trends in the food sector: food innocuousness, food production with bioactive compounds, food safety and sustainability [21]. The production of functional foods enriched with bioactive compounds and antioxidants that promote health and support the immune system is necessary [22,23]. The foregoing generated changes in the usual forms of organization of production, distribution and consumption and transformed the generation, transmission and use of knowledge, the forms of recreation and leisure and, on a personal level, the ways of relating to each other and even the perception of reality [24]. Consequently, all agri-food systems are undergoing transformation to respond to the new demands of consumers.

This new dynamic is characterized by the application of digital technologies in all phases of the production process. They are not reduced only to the field of production, but rather have implications in all aspects of life, since their use enables a more complex

economy based on the massive use of data and information [19]. The Mexican agri-food sector has experienced, since before the green revolution, good scientific and technological development [8]. The Mexican agricultural, livestock and fishing activity in 2020 and 2021, despite the social distancing measures, has maintained a constant growth [25]. Undoubtedly, agriculture 4.0 and 5.0 have generated good expectations about the possibilities of satisfying the demand for food. However, in order to make effective use of scientific and technological developments, infrastructure, knowledge, experience and skills are required. In other words, it is necessary to have a certain technological capacity and the necessary resources to generate and manage this dynamism [26]. In this sense, promoting the knowledge and skills necessary for companies to choose, install, operate, maintain, adapt, improve and develop technologies is a vital strategy [27].

Technological capacity is generally considered as an essential catalyst to improve the innovation, competitiveness, and performance of enterprises [28]. It is convenient to mention that the term capacities has been defined as the strengths or resources available to a community, which allow it to lay the foundations for its development as well as face a disaster [29]. Another approach to its conceptualization is the so-called freedom approach, which presents freedom understood as capacity as a basic value. The concept of capacity expresses the real freedom that a person must have to achieve what he intends to obtain [30]. The previous definitions are very general, and in the case of technological capacities they focus specifically on acquiring, using, absorbing, adapting, improving and generating new technologies [26].

The concept of technological capabilities has been in constant change, transformation and evolution since its origin. It was transformed from a phenomenon of static to dynamic analysis by incorporating different concepts. Added to the natural evolution of the concept, various ways of measuring technological capabilities have been proposed and it has been emphasized that the processes of technological accumulation come fundamentally from scientific and technological development [31]. To achieve continuous growth and competitiveness, countries, sectors and companies must accumulate knowledge to develop technological capabilities [32]. In this case, and with the vision of this investigation, technological capabilities are understood as the knowledge, experience, skills and infrastructure available to make effective use of science and technology and to generate innovation [1]. In various fields of scientific literature, emphasis has been placed on the role of productive and technological capacities as important drivers of exports, growth and development [33].

Currently, the technological capacities of a company, sector, region, or country are essential to adapt to the increasingly constant changes and transformations in the world economy. Studies on technological capabilities began in the early 1980s, and since then an extensive literature has flourished that recognizes their importance for technological and economic development [34,35]. However, there is an insufficient number of studies on the mediating role of technological capacity in this relationship [36]. In addition, it is believed that an oligopolistic concentration of infrastructure, information and knowledge about new technologies has naturally occurred [37].

The Mexican agri-food sector is divided into five regions, according to their productive vocation, in order to take advantage of the potential of their land, water and labor force (Figure 1) [38]. However, Jalisco, Veracruz, Oaxaca, Chihuahua and Sinaloa concentrate the largest agricultural production. These entities together produce one hundred and fourteen million, twenty-four thousand, nine hundred and fifty-four tons of agricultural products in a total of six million, five hundred and twelve thousand, six hundred and twenty-six hectares that are planted and harvested in the different crop cycles [39]. This suggests that the development of the Mexican agri-food sector is very heterogeneous, agricultural production is concentrated in specific areas, and there is no clarity about the technological capabilities of each region.

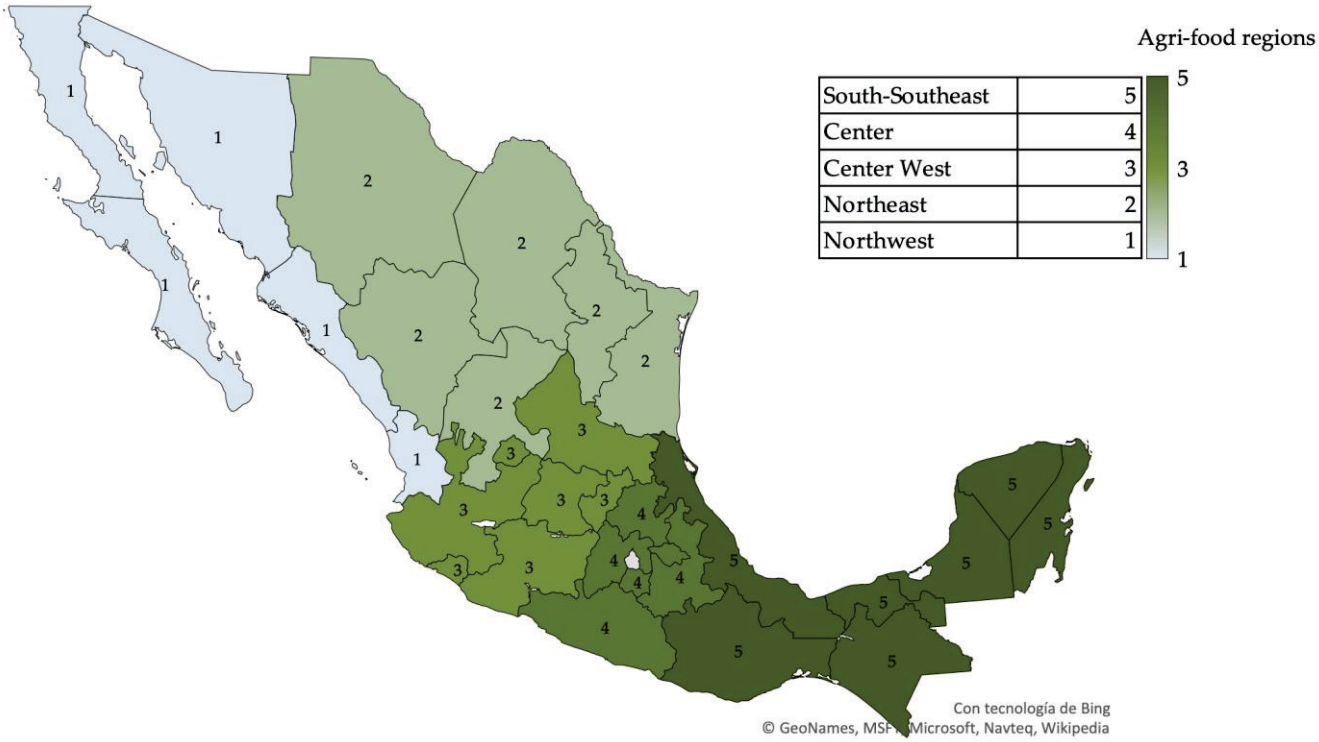

Figure 1. Agri-food regions of Mexico.

In the Mexican agri-food sector, studies of this type are very few and are oriented to variables that are far from the behavior of the sector. In this sense, the research question that guided this work was: what are the technological capacities that Mexico has in order to massively implement new technologies in the agri-food sector? That is, technologies related to agriculture 4.0, which refers to precision agriculture, the use of drones and sensors, automation, robotic machines and smart agriculture (farms and greenhouses) [9,11] and agriculture 5.0, which is a second phase of mastery, and is based on the emerging technologies of artificial intelligence, machine learning and big data analytics [40]. As a hypothesis, it was proposed that the technological capacities in Mexico for the adoption of new technologies in agribusiness are limited, and are concentrated in certain regions that have specialized over time. In this sense, the aim of the research was to analyze the technological capacity that Mexico has for the adoption of new technologies, in order to predict the dynamics of their adoption. With this information, innovation and technological-change policies could be designed that allow a more balanced development, for example, through regional innovation systems.

2. Materials and Methods

2.1. Analysis Method

The documentary research method was used, which basically consists of the search, analysis and interpretation of data obtained through secondary sources. The focus of this research is mixed, with a predominance of the quantitative type. However, it contains a small qualitative component, and its integration occurs in the interpretation and discussion of the results obtained and the evidence of other investigations. This approach offers significant opportunities to gain a deeper understanding of the phenomena. Their integration can occur at any point in the research process [41]. We worked with a non-experimental design of a transversal and descriptive type to delve into the current situation of the object and subject of study.

In this analysis, the 32 states of the Mexican Republic were considered as the fundamental geographical units to analyze the behavior of technological capabilities at the national level. It is a question of identifying the behavior of the states that present greater

technological capacities, states with intermediate levels, and those that present the lowest. To define the variables to be used for the analysis of the technological capacities of the agri-food sector, the conditions that most affect or determine the adoption of agriculture 4.0 and 5.0 were identified. In this sense, the conditions that determine the digital transformation were investigated and it was determined to analyze said variables or, in the case of not having the exact variables, the ones that are closest to those found in the existing literature were analyzed [1].

Derived from the above, according to Trendov et al. (2019) [7], there are several conditions that will determine the adoption of digital technologies in agriculture, and the most important are the following: (1) information and communication technologies, (2) enablers such as the internet, cell phone, and social networks, (3) instruction, literacy, and/or knowledge about the use and management of digital technologies, (4) the agribusiness culture and digital innovations, (5) the availability of credits to promote the adoption of digital technologies and (6) policies and programs to facilitate digital agriculture. In this sense, for the present investigation we sought to obtain information related to the variables previously raised.

2.2. Information Collection and Treatment

The information on the variables related to the adoption of digital technologies was obtained from the Encuesta Nacional Agropecuaria (ENA) 2019 [42]. The survey presents a very clear and explicit methodology for obtaining information. It was designed to obtain information at the national level of each of the federal entities. Regarding the sampling units, they were defined as the economic units that carry out agri-food activities, under the control of the same administration. The sampling frame was integrated from two sources, one for agricultural products and the other for livestock products. In addition, a stratification was carried out, based on the planted area in hectares and the number of cattle heads (large, medium and small). The sampling scheme was stratified probability sampling, with simple random selection within each study domain. The sample size was calculated independently for each study domain, taking a confidence level of 95%, a relative error of 9%, and an expected non-response rate of 30%. The sample size obtained was 19,320 economic units nationwide. The results are expressed as a percentage of economic units where the variables were analyzed.

The first analysis variable was the use of computer and communication technologies in agricultural activities by state in an aggregated manner. That is, it includes all information and communication technologies used in agri-food systems. In this sense, information and communication technologies are understood as the set of equipment, systems, means and procedures used for the communication, processing and storage of information, and is made up of computers, the internet and smartphones, among other devices [42]. Subsequently, a separate analysis of the use of the computer, the use of the internet and the use of the cell phone was carried out in order to identify independent relationships of these variables and their influence on technological capabilities. In addition, the use of satellite navigation systems was analyzed, and understood as the technologies used by global positioning systems to identify the exact location of an object or person. In this case, it is being used to carry out soil sampling, monitor crops and generate yield maps, as well as for tractor orientation and topographic mapping, among other uses [42].

With respect to instruction and/or literacy, the closest available variable was used and was obtained from the level of undergraduate studies of the person who administers and manages the production units in the Mexican agri-food sector. It is convenient to mention that it corresponds to the last grade of studies within the formal academic education system. In relation to the availability of credits, the percentage of production units that requested credit or a loan to carry out agricultural activities and those that obtained it was considered. The foregoing are understood as the economic resources received by the production units for the financing of agricultural, livestock or forestry production [42].

The three variables identified in the literature that are most related to technological capabilities were analyzed: competitiveness, the capacity to produce goods and services, and successful internationalization (participation in international markets) [43,44]. For the above, the Competitiveness Index that measures the capacity of the states to generate, attract and retain the talent and investment which detonate the productivity and well-being of its inhabitants was analyzed, and was obtained from the federal entity of the Instituto Mexicano para la Competitividad for the 2019 [45].

Regarding the production capacity of goods and services, the Agricultural Gross Domestic Product for 2019 was analyzed by state, with values at constant prices for the year 2013, which is an important indicator of the economic value of the production of the sector and therefore of the productive capacity [46]. Finally, for the exports understood as the total of goods and services sold by a country in foreign territory, in this case by the federal entity, the information was obtained in thousands of dollars for 2019, specifically from the agri-food sector that includes agriculture, breeding and the exploitation of animals, forest use, fishing and hunting [46].

2.3. Statistic Analysis

Most of the statistical analyses make specific assumptions derived from the data we have and which are based on them; the decision must be made about what type of analysis is most convenient to carry out. In this sense, it was verified if the study variables complied with the assumptions to perform a parametric statistical analysis, the normality, homoscedasticity and independence of errors were analyzed [47]; the results obtained indicated that the data did not comply with these principles. Because of this, it was decided to use non-parametric statistics. The next step was to carry out the analysis of the descriptive statistics of the variables analyzed in order to obtain an overview of the data.

Subsequently, a cluster analysis was carried out in the IBM® SPSS statistical program in order to generate a typology of states with different technological capabilities, for which cumulative hierarchical algorithms were used as a classification method. For the above, the "classify" option was used, and later "hierarchical cluster analysis" was selected. The "farthest neighbor method" was used as the clustering method, and the "squared Euclidean distance" as the distance measure. This technique avoids inconsistencies and uncertainties in the formation of clusters [48]. Standardized exports were used as the discriminant variable in order to be able to compare elements of different variables and different units of measurement. The export variable was used because participation in international markets is one of the variables that, according to the existing literature, is one of the best ways to express technological capabilities [31,34,43,44] and the results obtained are consistent and coherent. It is convenient to mention that tests were carried out with the agri-food GDP and the Competitiveness Index; however, no significance was obtained. Finally, a one-way analysis of variance (ANOVA) was performed for non-parametric tests, for which the Kruskal–Wallis H Test was used for independent samples with a significance level of 0.10, which is considered the most appropriate non-parametric test according to the characteristics of the data [49]. The IBM® SPSS Statistics program was used to perform the statistical analyses.

3. Results

In general, the variables analyzed for information and communication technologies that are related to the technological capacities of the agri-food sector at the national level present very low levels (Table A1 in Appendix A). It is possible to perceive that some states of the Mexican Republic have higher levels of use, for example, Baja California, Baja California Sur, Sonora, and Chihuahua, among others. Some states, such as Chiapas, Tlaxcala, Tabasco, present the lowest levels. The use of cell phones stands out, as one in which a different behavior is presented, and there are several states that are close to 100% use in the production units; a few states present a lower level of behavior, as in the case of Tlaxcala, Mexico City and Guerrero.

Regarding the educational level of a bachelor's degree, it is important to mention that it is very low in the agri-food sector, despite the fact that in recent years there has been a significant increase. In none of the states do more than 20% of the agribusinesses have an administrator with a bachelor's degree, and it is possible to identify that there are several cases with values of 2% (Table A2 in Appendix A). In relation to the availability of credits, it is possible to observe that it is highly variable, which could suggest that it is concentrated in some states. The variables related to the measurement of technological capabilities present a similar behavior to the previous variable, with much variation among states. This suggests a geographical concentration that is the origin of a very uneven historical development (Table A2 in Appendix A).

The descriptive statistics of those related to the technological capacities of the agri-food sector in Mexico, in general, allow the identification of their behavior to be carried out more clearly (Table 1). The average indicates a very low behavior, with the exception of cell phone use. The indicators of dispersion or variation of the data suggest that there is a high variability of data with respect to the average in all the variables analyzed (Table 1). This corroborates the fact that the behavior of the states in relation to the variables analyzed is very heterogeneous. The foregoing is closely related to the origin, evolution, and orientation of the agri-food sector of each state.

Table 1. Descriptive statistics of the variables related to the technological capacities of the agri-food sector in Mexico.

Variables	N	Minimum	Maximum	Mean	Standard Error	Standard Deviation	Variance
Information and communication technologies	32	17.86	92.17	48.11	3.89	22.01	484.52
Computer use	32	0.95	20.00	6.93	0.88	5.02	25.21
Internet use	32	0.81	40.59	10.20	1.50	8.53	72.85
Cell phone use	32	70.55	97.28	89.29	1.25	7.11	50.61
Use of satellite navigation systems	32	0.01	4.28	1.25	0.19	1.09	1.19
Education level, Bachelor's degree	32	1.62	17.45	7.07	0.81	4.61	21.20
Credit availability	32	0.63	44.03	11.58	2.01	11.32	128.19
Agri-food Gross Domestic Product	32	1245.77	71,043.77	18,510.10	2949.06	16,682.44	278,303,879.80
Competitiveness Index	32	32.63	85.14	58.09	2.45	13.88	192.83
Exportations	32	80,908	57,434,140	13,049,369.81	2,754,923.82	15,584,202.56	242,867,369,300,000.00

The cluster analysis allowed the construction of a taxonomy of Mexican Republic states with different technological capacities, based on their export dynamics (Figure 2). Cluster 1, made up of the majority of the states, is the one with the lowest technological capacities and, in general, is made up of states from the south and center of the country. It is characterized by presenting the lowest levels in the use of computers, Internet use and cell phone use, presents the lowest educational levels and maintains lower export dynamics (Table 2).

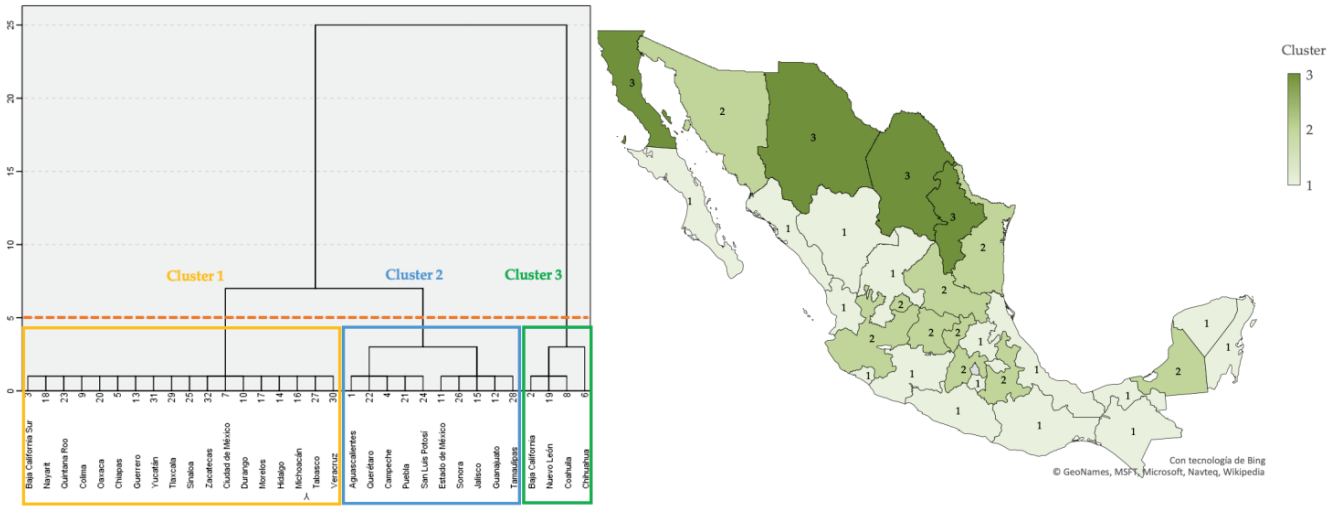

Figure 2. Typology of the technological capabilities of the states, according to the cluster analysis.

Table 2. Typology of the technological capabilities of the states, according to the cluster analysis.

Variables	General	Cluster 1	Cluster 2	Cluster 3
No. of states	32	18	10	4
Information and communication technologies	43.25	39.72 a	40.72 a	63.36 a
Computer use	5.9	4.13 b	6.25 ab	8.44 a
Internet use	7.29	5.91 b	8.88 ab	16.48 a
Cell phone use	90.44	87.34 b	90.50 ab	96.22 a
Use of satellite navigation systems	0.86	0.59 a	1.08 a	2.12 a
Education level, Bachelor's degree	6.11	6.36 ab	3.81 b	9.73 a
Credit availability	8.28	6.78 a	9.04 a	11.71 a
Agri-food Gross Domestic Product	13,345.07	9945.27 a	17,400.72 a	14,755.88 a
Competitiveness Index	58.73	56.23 a	60.61 a	63.80 a
Exportations	5,299,648.00	1,880,104.50 c	18,694,252.50 b	45,028,206.00 a

Note: Medians with different letters in rows indicate significant differences ($p \leq 0.10$), according to the Kruskal–Wallis H test.

Cluster 2 is made up of 10 states in the center and north of the country and, according to the results, presents medium technological capabilities (Table 2). It is characterized by presenting intermediate levels in the use of computers, the Internet and cell phones, and intermediate behaviors in educational levels and in its export dynamics. Cluster 3 is the smallest, and is made up of four states belonging to the north of the country, and these are the ones with the greatest technological capabilities (Table 2). It is characterized by presenting the highest levels of computer, internet, and cell phone use, the highest educational levels and higher export dynamics. Regarding the use of information technology and communications analyzed in aggregate form, there are no differences. A similar situation occurs with the availability of credit and the agri-food Gross Domestic Product (Table 2).

4. Discussion

The variables analyzed present very low levels, with the exception of the use of cell phones, for which the majority have this technology and use it for agri-food activities. Internet access, computer use, and the use of satellite navigation systems is very low, and educational levels are very low. This greatly limits the implementation of new technologies. The results obtained show that the states with the greatest technological capabilities are in the north of the country. It is the region of the country that has developed an agricultural business since its origins, which is highly technical and closely linked to international markets [1]. These results are close to those found by Pérez Hernández et al. (2017) [50],

who carry out an analysis of the technological capacities of Mexico and identify the fact that they are concentrated in five entities. It is worth mentioning that their results coincide on several points with respect to the technological capabilities of the agri-food sector. The development of the different scientific and technological revolutions in the agri-food sector show very heterogeneous rates of transformation and technological adoption by country and by region [51].

To better understand the results obtained, it is necessary to highlight the fact that Mexico is a country that stands out for the heterogeneous and specialized nature of its agricultural regions. The most frequent and important barriers to the adoption of new technologies are the lack of infrastructure and the lack of accessible solutions for farmers [52], situations that have worsened over time. The regions present very different profiles in terms of innovation capacity, specialization of the economic fabric and composition of the regional innovation systems [53]. Consequently, activities with very unequal levels of productivity and remuneration are carried out [54]. In recent years, this situation has intensified in such a way that globalization has unevenly transformed the country's economic structure. The interactions that have been generated from the above are not stable; they change over time, and generate very dissimilar technological trajectories and productive results in the regions [55,56].

Currently, the Mexican agri-food sector presents a series of adjustments and technological changes that have affected its basic productivity structure. This has transformed all production systems by replacing crops or livestock breeds, and integrating plasticulture and new agricultural constructions, which further amplify economic asymmetries. This situation is becoming evident with the rapid technological and productive specialization of agricultural regions [57]. This has naturally generated a concentration of infrastructure, information and knowledge about new technologies [37]. It is worth mentioning that technological capabilities are gradually generated through learning mechanisms and incremental improvements until reaching the level of the international technological frontier [58]. It is important to accurately identify factors that favor the adoption of new technologies, especially in emerging economies [59], as well as the technical and socioeconomic obstacles to the implementation of agriculture 4.0 and the transition to agriculture 5.0 [60]. Derived from the above, the technological trajectories of the Mexican agri-food sector, understood as the coevolution of products, processes, rationalities, and the social, economic, political and technological events that have occurred at the local, regional and national level have generated very different technological capacities, and they are concentrated in some regions.

In this sense, it is possible to identify hyper-specialized regions in crop production. For example, tomato production is concentrated in Baja California, Sinaloa and San Luis Potosí [8]. Avocado production is concentrated in Michoacán, Colima and the State of Mexico [61]. In the case of strawberries, production is centered in Michoacán and Jalisco [62]. Chili production is concentrated in San Luis Potosí and Zacatecas [63] and lemon production in Colima and Veracruz [64]. However, it is worth mentioning that production is located in a few municipalities that have become hyper-specialized and have a good command of their production systems. In other words, technological capacities have accumulated in these areas over time, and are even part of the international technological frontier. New technologies are being adopted in regions and companies that are linked to global value chains and international markets [65]. These regions make up agri-food systems that focus on crops of high commercial value, respond to international demands and in some cases are companies with foreign capital. Hence, the need to decentralize scientific and technological capacities to contribute to the economic development and well-being of all regions of the country is clear, taking into account their productive vocation [50]. In addition, it is essential to continue improving technological and management capacities throughout all the value chains of the agri-food sector [66].

The agri-food sector in general has basic technological capabilities that do not meet the needs of the current competitive environment [67]. This coincides with what happens in

other countries where it is observed that most of the cases of use of digital technologies are in the initial development or prototype phases [60]. However, the health crisis has accelerated the digitization process of society, and advances that were expected to take years have occurred in a few months [68]. Currently, and as a consequence of the confinement caused by COVID-19, which forced society to remain in isolation, there has been a significant increase in the use of information and communication technologies in all sectors [6]. In other words, it is certain that the data related to the analysis variables are greater today [1].

In the current knowledge society, the new challenges of the agri-food sector are faced from the perspective of the exchange of tacit and explicit knowledge and the accumulation of capacities within the organizations, which are the actors of the change and innovation [69]. In this sense, it is relevant to think about the infrastructure to increase the efficiency of the processes. This infrastructure has a human part and a strictly material part; however, both refer to the generation, development and dissemination of new scientific–technological knowledge [70]. A crucial point is having a research and development structure and facilities, and access to networks and financing [71]. In addition, it has been shown that maintaining a link and interaction with the institutions that carry out research has important benefits [72].

It is clear that great scientific and technological developments are not enough to achieve economic progress without governments creating education and training programs necessary to absorb new technologies and innovations [73]. In addition, there is a strong dependence on the exterior, with high costs in the transfer and import of technological goods and services and a late incorporation into the advancement of world changes [74]. In addition, human capital must be valued more, as the most precious resource of a nation, and its recruitment, training and development must be among the nation's priorities [75].

Digital technologies are valued by most companies; however, there is still no clear recognition of their potential in the specific field of planning, management and control of production processes [76]. In addition, some social, ethical, political, cultural and environmental concerns associated with digitization arise [14,15], and even digital technological sovereignty is questioned in relation to each country [37]. Simultaneously, other findings show that digital technologies can cause negative effects on food security, mainly due to existing asymmetries among farmers [13]. In addition, it is necessary to identify the key problems of the new technologies based on solid evidence to guide the formulation of policies and achieve greater effectiveness, efficiency and sustainability [16,77,78].

The use of mobile applications to monitor and control all processes seems to be the most viable option for starting the digital transformation in the agri-food sector [79]. In general, the integration of monitoring technologies, support for decision-making and improved administration is needed throughout the entire agri-food chain [17]. This will make it possible to manage territories as common goods and empower farmers and consumers [80]. Hence, the basis for the adoption and adaptation of new technologies in the agri-food sector will be the access and use of 5G technology that will allow the massive use of data and information for analysis and decision-making [6]. Access to information and data through platforms is used to support the knowledge and decision making of producers. With this, the interactions of all the links of the agri-food chains and the exchange of information are increased [81,82].

With these results, it is possible to start with the design of a proposal for the adoption of technologies associated with agriculture 4.0 and 5.0 in the Mexican agri-food sector. This is important for public policies in terms of avoiding excessive power asymmetries in agrifood value chains [83]. In this sense, Buenrostro Mercado (2022) [84], for example, proposes four phases, determined by the complexity of digital technologies and the possibilities of use that the incorporation of each of them makes possible. That is, with the results obtained it is possible to develop proposals according to the phases of technological development that are more balanced. However, they are changes that generate great uncertainty and complexity [20]. Obviously, it is necessary to carry out more research that serves as an

input to be able to propose agri-food policies in accordance with the new realities and future needs.

The technology adoption process is uneven among industries, countries, regions, and companies, which is generating a new source of polarization among advanced countries, emerging economies, and developing countries [65]. In addition, it is important to promote public understanding of science and the greater participation of other actors in the processes of knowledge production and the appropriate interactions of institutions, organizations and economic agents for the design of public science and technology policies [85], in order to identify the capabilities and potential of the regions to make the innovation process more efficient and to generate smart specialization processes [86].

Improving agri-food systems to make them more sustainable and resilient is, more than ever, an urgent priority [87]. In Mexico, public policies are required to stimulate a broader adoption of new technologies in all sectors, in order not to allow regional asymmetries to worsen [65]. The logic of smart specialization is useful for the design of regional policies; however, it must take into account the characteristics of the territories and the existing vulnerabilities [53]. Regional innovation systems are a fundamental tool for the design and implementation of smart specialization strategies [88]. In this sense, strategies must be designed for each region, in order to adapt more quickly to changes in the world economy and maintain their competitive position [89]. In this way, it would be possible to promote regions with the capacity to maintain an adequate dynamic in their innovative processes with identity and sustainability [61,72].

In addition, education and training in emerging technologies has proven to be a good strategy, and at the same time the design of initiatives that encourage change in consumer behavior will be increasingly important [21,71,81], especially for small producers who find it more difficult to access this type of technology, and this could cause greater asymmetries in the different agri-food regions. Lastly, it is important to directly link financial and non-financial instruments such as supply and demand incentives, fiscal incentives, economic incentives and subsidies [71,90], facilitate policy making, and provide public services such as the Internet [81].

5. Conclusions

The variables analyzed generally present very low values, except for the use of cell phones. This indicates that the Mexican agri-food sector has a low technological capacity for the adoption of new technologies. Three groups of states with a different behavior regarding their technological capabilities were identified. Four states in the north of the country stand out as having the greatest technological capabilities, as a result of which they are expected to have higher rates of adoption of new technologies, followed by a group made up of ten states in the north and center of the country. Finally, there is a broader group of 18 entities in the country made up of the states in the center and south of the country with the lowest levels. This suggests that most of the country will present low rates of adoption of new technologies in the agri-food sector.

The results suggest that the technological capacities of the agri-food sector in Mexico are concentrated in regions with very specific trajectories and characteristics. It is possible to infer that these are hyper-specialized regions in the production of high-value crops, aimed at satisfying the demand for food in international markets and, in some cases, they are companies with foreign capital. The foregoing has a historical origin; that is, the technological trajectories of the Mexican agri-food sector have developed gradually. These are regions that concentrate a greater knowledge of production systems, are more closely linked to educational and research institutions, and that have managed the development of the necessary infrastructure for the success of their production and marketing systems.

The current behavior of the technological capacities of the agri-food sector suggests that if the same dynamics continue, the regional asymmetries will worsen. In this sense, it is convenient to design agri-food policies that make it possible to stimulate the adoption and diffusion of new technologies, especially with small producers. In addition, it is

important to better coordinate all the agents of the sector's innovation systems, manage the infrastructure that supports agricultural technologies 4.0 and 5.0, and redesign science and technology agendas for the agri-food sector oriented towards smart specialization. Finally, it is worth mentioning that there is still a lack of research, and more needs to be carried out on the real impacts of new technologies and on how to measure technological capacities and their promotion.

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Appendix A

Table A1. Variables analyzed related to the technological capabilities of the agri-food sector in Mexico.

Federal Entities	Information and Communication Technologies	Computer Use	Internet Use	Cell Phone Use	Use of Satellite Navigation Systems
	%				
Aguascalientes	61	9	12	91	1
Baja California	91	20	22	97	3
Baja California Sur	92	19	12	96	2
Campeche	28	4	4	86	0
Chiapas	18	4	5	97	2
Chihuahua	77	7	11	97	0
Mexico City	22	16	23	73	0
Coahuila	44	10	41	96	2
Colima	69	7	7	85	4
Durango	76	4	4	90	1
Mexico State	26	5	10	91	1
Guanajuato	46	7	9	90	0
Guerrero	27	3	5	71	0
Hidalgo	27	1	6	97	1
Jalisco	69	7	10	87	3
Michoacan	43	4	6	88	2
Morelos	50	8	10	83	1
Nayarit	62	3	4	87	1
Nuevo Leon	50	7	7	94	3
Oaxaca	34	4	7	82	2
Puebla	36	6	7	90	1
Queretaro	22	9	9	91	1
Quintana Roo	37	3	31	90	1
San Luis Potosi	27	3	4	84	1
Sinaloa	70	8	8	96	1
Sonora	86	18	20	95	3
Tabasco	45	3	3	94	0
Tamaulipas	71	6	7	97	1
Tlaxcala	24	1	1	79	0
Veracruz	37	8	10	80	1
Yucatan	33	5	6	97	0
Zacatecas	42	3	5	85	1

Table A2. Variables analyzed related to the technological capabilities of the agri-food sector in Mexico.

Federal Entities	Education Level Bachelor's Degree	Credit Availability	Competitiveness Index	Agri-Food Gross Domestic Product	Exportations
		%		Millions of MXN	Thousands of USD
Aguascalientes	6	6	67	9076	11,794,073
Baja California	17	40	38	15,458	42,396,951
Baja California Sur	12	9	56	5368	291,812
Campeche	5	11	83	5751	16,579,076
Chiapas	10	2	73	19,522	820,170
Chihuahua	7	12	57	33,904	57,434,140
Mexico City	3	4	37	1246	2,667,127
Coahuila	6	11	78	14,054	47,659,461
Colima	15	1	43	5061	684,838
Durango	7	14	78	19,263	2,737,229
Mexico State	3	15	48	19,881	20,010,001
Guanajuato	4	11	59	26,645	25,065,798
Guerrero	3	1	34	12,636	966,475
Hidalgo	6	19	64	9902	2,299,343
Jalisco	2	1	58	71,044	21,659,641
Michoacan	5	11	55	55,622	5,586,480
Morelos	7	19	37	6595	3,086,705
Nayarit	8	37	66	8679	266,760
Nuevo Leon	12	3	70	6325	39,857,053
Oaxaca	3	6	59	15,255	712,575
Puebla	2	3	58	24,433	17,547,974
Querétaro	2	4	62	9844	12,868,797
Quintana Roo	5	6	54	2099	80,908
San Luis Potosi	3	7	63	14,367	15,531,677
Sinaloa	17	44	66	47,074	2,840,002
Sonora	15	29	63	40,736	19,840,531
Tabasco	7	4	33	8641	5,012,816
Tamaulipas	12	18	59	14,920	29,130,161
Tlaxcala	6	3	59	3427	1,460,866
Veracruz	6	8	57	42,870	6,697,248
Yucatan	3	3	85	9989	1,119,624
Zacatecas	4	9	41	12,636	2,873,522

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The Impact of Socialized Agricultural Machinery Services on the Labor Transfer of Maize Growers

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Abstract: Socialized agricultural machinery services, effectively cracking the "who to plant, how to plant" dilemma, are an important grasp of the development of modern agriculture. Based on the specialization division of labor theory, using the 2019 national survey data of maize growers in 13 provinces, the instrumental variable method and systematic generalized moment estimation (GMM) were used to overcome the endogeneity problem of mutual causality between socialized agricultural machinery services and labor transfer, analyze the impact of socialized agricultural machinery services on the labor transfer of maize growers and its link to heterogeneity, and explore the impact effect in different terrain conditions, part-time. We also explored the cohort differences in the effect in different terrain conditions and degree of part-time work. The endogenous switching regression model (ESR) was also applied to construct a counterfactual framework to further analyze the impact effect of socialized agricultural machinery services on labor transfer. The results showed that socialized agricultural machinery services could effectively promote labor transfer among maize farmers. Compared with maize farmers in other terrain conditions and part-time degree, the impact effect of agricultural machinery socialization services on labor transfer of flatland and pure farming households was more significant. Socialized agricultural machinery services play an important role in driving traditional farming households to labor transfer and realizing their organic connection with modern agriculture.

Keywords: socialized agricultural machinery services; maize growers; labor transfer; farm household differentiation

1. Introduction

Against the background of accelerated urbanization, China's agricultural transformation faces difficulties with inconsistent decline in the share of agricultural employment and value-added, low agricultural returns and lower agricultural labor productivity than in other countries [1]. China's agricultural industrial structure is too homogeneous, agricultural production lacks integration of different industries, and the cost of agricultural products continues to rise. Relatedly, the root cause lies in the restricted restructuring and upgrading of production factors. Zhang Peigang first proposed the industrialization of agriculture, the core of which is the dynamic combination and continuous upgrading of production factors. The continuous promotion of urbanization and industrialization has induced a gradual "merit-based transfer" of rural labor [2], which has led to a decrease in the proportion of agricultural labor among Chinese maize-producing farmers and has promoted the adoption of socialized agricultural machinery services by farmers after considering the rational allocation of labor and capital factors. World maize production in major producing countries is shown in Table A1.

Accelerating rural labor force transfer is an important way to improve agricultural labor productivity in China, which is conducive to rural economic development, farmers' income growth, and promoting the upgrading and adjustment of industrial structures. China's rural labor force transfer increased from 19.12 million in 1978 to 288.36 million

in 2018 [3], an increase of 15.08 times. At the same time, various socialized service organizations, including agricultural mechanized operations, have developed rapidly, filling the gap of labor shortage and increasing the level of agricultural mechanization [4]. The socialized service of agricultural machinery evolved from the "socialized service" proposed in the First Document of the Central Government in 1983 for the first time, emphasizing the need for a social division of labor that is difficult for farm families to provide to achieve the needs of agricultural production development [5–7].

In the past, farmers would obtain agricultural technology by buying agricultural machinery. However, things have changed in China since 2000. The cost of agricultural labor has gone up, and most people working in rural areas are older or women. Plus, farming households are small-scale. Even though subsidies have made buying machinery cheaper, it is still too expensive for small-scale farmers who do not make much money. As a result, farmers are choosing to use shared farm machinery services instead of buying their own machinery.

Agricultural services are becoming increasingly popular in various countries, including China, Indonesia in Asia, and Africa. In Indonesia, more and more farmers are renting land and using agricultural services to expand their farming operations [8], leading to the replacement of labor with machinery. Similarly, in Africa, farmers are adopting agricultural services due to rising labor costs and the inability to afford agricultural machinery [9]. Subsidized agricultural services have been implemented in Ghana and Nigeria, with Ghana focusing on land preparation and farming services [10], and Nigeria investing in machinery to reduce costs and promote the adoption of agricultural services by small-scale farmers [11].

Starting in 2004, the state issued ten consecutive "No. 1 documents" to actively develop the socialization of agricultural machinery services. The 19th Party Congress report even pointed out: "improve the socialized agricultural service system, to achieve organic linkage between small farmers and modern agricultural development". In 2019, China's agricultural socialized service area reached 13.33 million hm^2, the future market size can reach trillions of yuan (CNY) or even trillions of yuan. The most direct effect of socialized agricultural machinery services is to reduce labor intensity, improve labor productivity, form a direct alternative to agricultural labor, and have a certain impact on the transfer of farm labor. So, does the socialized agricultural machinery service promote the transfer of farm labor by improving the mechanization level of farm households? This is a question worth exploring and has very important practical significance.

Agricultural mechanization is the way to modernize agriculture while achieving agricultural modernization requires a continuous increase in agricultural labor productivity, so that agricultural labor productivity and non-agricultural labor productivity are equal at a high level. The increase in agricultural labor productivity comes from two sources [12]: first, the increase in land productivity, i.e., the increase in yields; and second, the expansion of arable land per capita. The increase in land yields depends more on factor inputs and total factor productivity, while the expansion of arable land area per capita needs to be achieved by expanding the scale of operation or reducing the number of laborers per unit area. China has many people and little land, and there is little room for agricultural labor productivity growth by expanding land size. It measured that the moderate operation size of farm households is about 8–13.3 hm^2 [13,14]. Therefore, expanding the arable land area per capita needs to rely more on the transfer of agricultural labor. The current official statistics of the share of agricultural labor in China is 28% [15], and if the share of agricultural labor is calculated at 15% when agricultural modernization is achieved, 12% of agricultural labor still needs to be transferred to the non-agricultural sector, which shows the necessity of promoting the transfer of farm labor.

The accelerated transfer of China's rural labor force to the non-farm sector has been accompanied by rapid growth in agricultural mechanization during the same period. Many domestic scholars have analyzed and confirmed the existence of a significant relationship between agricultural mechanization and farm labor transfer [16–18], and in fact, the driving effect of agricultural mechanization on farm labor transfer is widely taken

for granted [19–21]. Along with the massive outflow of agricultural labor in China, the opportunity cost of agricultural labor continues to increase, and under the constraint of small-scale farming based on family contracting [22], Chinese agriculture, under the condition that neither the per capita nor the scale of individual farming households' arable land has been substantially expanded, has adopted socialized agricultural machinery services to ensure national food security and come out with a distinctive road of agricultural mechanization to make up for the serious deficiency of operation fragmentation [23,24], which facilitates the realization of a higher level of mechanization for small-scale farmers [25]. To address the high demand for agricultural machinery and the low purchasing power of small-scale farmers at the current stage in China, land transfer can be used in the long term to change the status quo of small-scale farming; however, a large number of farmers will be separated from agriculture after the land transfer, and it may be difficult for the secondary and tertiary industries in China to provide sufficient employment opportunities in the short term. Therefore, in the short term, agricultural labor can be released from the land through socialized services of agricultural machinery under the social division of labor, which can promote the transfer of farm labor to a certain extent and introduce small-scale farmers into the development track of modern agriculture and share the division of labor economy [26].

The role played by socialized agricultural machinery services has always been the focus of academic circles, one of which is the promotion of labor transfer for farmers. On the one hand, the socialized services of agricultural machinery emerged from the deepening of the professional division of labor, the strengthening of technological innovation, and the increasing shortage of agricultural labor [27]. Due to the constraints of farmers' own time, technology, and machinery, outsourcing the links of food production to socialized service organizations through the socialized services of agricultural machinery replaces the own labor and promotes the continuous deepening of farmers' labor transfer. On the other hand, the adoption of socialized agricultural machinery services by farmers facilitates the reallocation of resources (labor, land, and capital) and can weaken the constraints on labor.

In this study, the instrumental variables approach, systematic generalized moments estimation (GMM), and endogenous switching regression model were used to assess the impact effect of socialized agricultural machinery services on labor migration.

2. Materials and Methods

2.1. Data

The data used in this study were obtained from a rural survey conducted by the China Agricultural University in 2019 among maize growers. Data were collected by a combination of stratified and random sampling, and the main maize-producing provinces in the country, namely Hebei Province, Shandong Province, Anhui Province, Hunan Province, Hubei Province, Henan Province, Jiangsu Province, Sichuan Province, Gansu Province, Jilin Province, Liaoning Province, Heilongjiang Province, and Inner Mongolia Autonomous Region, were selected based on the principles of high production and many farmers involved. The research team consisted of teachers and undergraduate, master, and doctoral students from China Agricultural University and took the form of one-on-one interviews with farmers. The questionnaires were filled out by the researchers, and their contents were reviewed by experts after the questionnaires were collected. Researchers who completed the questionnaires with high quality were given certain rewards, and those who completed them with poor quality were eliminated to fully ensure the authenticity of each questionnaire. After removing invalid questionnaires, such as logical errors, lack of key information, and missing variables, a total of 1048 valid maize grower questionnaires were collected.

2.2. Empirical Model Setting

2.2.1. IV-Tobit Model

The study examined how socialized agricultural machinery services impact labor transfer among maize growers. This study focused on the core explanatory variable of socialized agricultural machinery services. To measure labor transfer, the group used the percentage of farm households with members working outside of the home as a proxy indicator. The labor shift of maize farmers is a restricted variable, ranging from 0 to 1 with a right-handed truncated distribution. The study utilized an IV-Tobit model with a restricted dependent variable to test the effect of socialized agricultural machinery services on labor shift. The estimated model is as follows:

$$\begin{aligned}\text{Migrantratio}_i = \alpha + \beta_1 \text{service}_i + \beta_2 Ln(age_i) + \beta_3 edu_i + \beta_4 health_i + \beta_5 train_i + \beta_6 staff_i + \beta_7 Ln(asset_i) \\ + \beta_8 Ln(area_i) + \beta_9 quality_i + \beta_{10} Ln(block_i) + \varepsilon_i\end{aligned} \tag{1}$$

The subscript *i* denotes the *i*th farm household, the Migrantratio is the labor transfer of the maize grower, and service is whether or not socialized agricultural machinery services are used. In order to ensure the accuracy and reliability of the estimation results, and also confined to the availability of data, this study used per capita maize sown area (AREA), land quality (QUALITY), land fineness (BLOCK), age of household head (AGE), education of household head (EDU), health of household head (HEALTH), household agricultural training (TRAIN), household cadre status (staff), and average agricultural machinery assets per mu (asset) as control variables. The constant term was α, and β was the parameter to be estimated, where β_2 was the parameter of interest for this study, and was the random disturbance term. In order to attenuate the heteroskedasticity problem of the model, the variables were scaled down by taking the natural logarithm of the age of the household head, the average agricultural machinery asset per mu, the degree of land fragmentation, and the maize sown area per capita. In addition, to control for factors that cannot be observed and measured in different survey areas, such as differences in crop production characteristics, natural environment, and different agricultural industrial policies, this study also controlled for regional differences in the model.

The development of socialized agricultural machinery services and labor shifts of maize farmers may have a causal endogeneity problem, in that the development of socialized agricultural machinery services promotes labor shifts, and in turn, the shifts of rural labor promote the development of socialized agricultural machinery services. In addition, farmers' labor shifts decisions may be influenced by observable (e.g., age of household head, education level, sowing area, etc.) and unobservable factors (e.g., farmers' innate ability, motivation, risk preference, etc.), thus causing bias due to omitted variables.

In order to minimize the impact of the endogeneity problem on the model, the instrumental variable method was used for estimation in this study. Referring to the discussion of the endogeneity problem by Xinyan Hu et al. [28], the average level of adoption of agricultural machinery socialized services in the village was chosen as the instrumental variable, i.e., the percentage of farmers in the village who adopted agricultural machinery socialized services other than that farmer [29].

$$\text{service}_i = \theta_0 + \delta_i V_i + \sum \omega_i Z_i + \mu_i \tag{2}$$

In the above equation, V is the instrumental variable for this study, Z is the control variable, service is the endogenous variable, μ_i is the random error term, and the instrumental variable is selected as the average level of adoption of socialized agricultural machinery services in villages. Obtaining instrumental variables from aggregated data at the district level to deal with endogeneity has been widely accepted and its validity has been verified in many pieces of the literature [30].

2.2.2. GMM Model

Generalized moment estimation (GMM) model is a semi-parametric estimation method under loose assumptions, and Hansen won the 2013 Nobel Prize in Economics for inventing this method. It allows for the presence of serial correlation and heteroskedasticity in the random error term when the exact distribution of the random error term is not yet clear, and its estimated parameters are accurate and valid compared to other methods.

For the IV estimator in a linear or nonlinear regression model, the equation is as follows:

$$E[\overline{m_n}(\beta)] = E\{\frac{1}{n}\sum_{i=1}^{n} z_i[y_i - h(x_i, \beta)]\} = 0 \tag{3}$$

where there are L instrumental variables in Z_i and K parameters in β.

2.2.3. Endogenous Switching Regression Model

While the PSM method is usually applied to deal with situations where selectivity bias exists, the PSM method suffers from the drawback of controlling only the heterogeneity of the observable variables, when the endogenous switching regression model is applied. Unlike the Heckman two-step method that focuses only on the observable equation, the endogenous switching regression model (ESR) proposed by Maddala (1983) can treat the unobservable variables as missing values by first estimating the decision selection equation followed by the outcome decision equation.

The specific steps are shown below:

Behavioral equation (adoption of socialized agricultural machinery services or not):

$$A_i = \delta' Z_i + k' I_i + \mu_i \tag{4}$$

Resulting in Equation (1) (treatment group, i.e., labor transfer equation for the socialized agricultural machinery service adopter group):

$$Y_{ia} = \beta_a' X_{ia} + \varepsilon_{ia} \tag{5}$$

Resulting in Equation (2) (control group, i.e., labor transfer equation for the group of non-adopting households of socialized agricultural machinery services):

$$Y_{in} = \beta_n' X_{in} + \varepsilon_{in} \tag{6}$$

A is a binary choice variable indicating whether farmers adopt socialized agricultural machinery services; Z is the influencing factor of whether farmers adopt socialized agricultural machinery services; μ_i is the error term; and I is the instrumental variable. It was incorporated into the decision model of agricultural machinery socialization services of farm households. Y_{ia} and Y_{in} denote the labor transfer of the two sample groups of agricultural machinery socialization service adopter households and agricultural machinery socialization service non-adopter households, respectively; X_{ia} and X_{in} are the factors influencing the labor transfer of farm households; and ε_{ia} and ε_{in} are the corresponding error terms.

The expectation of labor transfer of households adopting socialized agricultural machinery services (treatment group) is as follows:

$$E[Y_{ia}|A_i = 1] = \beta_a' X_{ia} + \sigma_{\mu a}\lambda_{ia} \tag{7}$$

Labor transfer expectations of non-adopting households of socialized agricultural machinery services (control group) are expressed as follows:

$$E[Y_{in}|A_i = 0] = \beta_n' X_{in} + \sigma_{\mu n}\lambda_{in} \tag{8}$$

The expectation of labor transfer in the case of non-adoption of services by adoptive households of socialized agricultural machinery services is expressed as follows:

$$E[Y_{in}|A_i = 1] = \beta'_n X_{ia} + \sigma_{\mu n}\lambda_{ia} \tag{9}$$

The expectation of labor transfer in the case of non-adopted household adoption of socialized agricultural machinery services is expressed as follows:

$$E[Y_{ia}|A_i = 0] = \beta'_a X_{in} + \sigma_{\mu a}\lambda_{in} \tag{10}$$

$$ATT_i = E[Y_{ia}|A_i = 1] - E[Y_{in}|A_i = 1] = (\beta'_a - \beta'_n)X_{ia} + (\sigma_{\mu a} - \sigma_{\mu n})\lambda_{ia} \tag{11}$$

$$ATU_i = E[Y_{in}|A_i = 0] - E[Y_{ia}|A_i = 0] = (\beta'_n - \beta'_a)X_{in} + (\sigma_{\mu n} - \sigma_{\mu a})\lambda_{in} \tag{12}$$

In summary, this paper will examine the average treatment effect of socialized agricultural machinery services on labor transfer of farm households using the average values of ATT_i and ATU_i.

2.3. Variable Selection

1. Explanatory variables. The proportion of labor shifted by maize farmers as the explanatory variable was based on the method defined by Mullan [31], the proportion of labor shifted by maize farmers = number of workers outside the household/(number of agricultural laborers in the household + number of workers outside the household).

2. Core explanatory variables. As the core explanatory variables, most previous studies used "whether or not to adopt socialized agricultural machinery services" or "whether or not to adopt socialized agricultural machinery services in a production chain" to define the socialized agricultural machinery services variable [32,33]. In this study, we first defined the variables based on whether the farmers adopted the socialized agricultural machinery services and conducted the baseline regression. Then, in order to further improve the accuracy of the measure of the socialized agricultural machinery service variables, we referred to the construction of the socialized agricultural machinery service indicators by Hu Xinyan [28] and used the data information of farmers' adoption of socialized agricultural machinery services (mu) and maize sowing area in the five segments of maize planting in the questionnaire to construct the following measures:

$$service = \frac{\sum_{i=1}^{n} w_i}{m},\ n = 5$$

where service is the degree of adoption of socialized agricultural machinery services by farmers; w_i (i = 1, 2, 3, . . . , 5) denotes the area of socialized agricultural machinery services in tillage, seeding, plant protection, irrigation and drainage, and harvesting, respectively; and m denotes the area of maize sown. That is, the degree of adoption of socialized agricultural machinery services is defined as the ratio of the area of adopted socialized agricultural machinery services in each segment of maize production to the sown area, and a substitution indicator is used for robustness testing.

In addition, the control variables of this study were based on three levels: farm household, land, and region. At the farm household level, the age and health status of the household head were selected to control for the household life cycle effect acting on the labor transfer behavior of farm households; the education level of the household head, the agricultural training status of the household, and the cadre status of the household were selected to control for the differences in household resource endowment; and the average agricultural machinery assets per mu of the household were selected to control for the stock of agricultural machinery in the household and the possible opportunity cost of abandoning agricultural production. At the level of the land situation, per capita maize

sowing area, land quality, and land fragmentation were selected and introduced into the model to control for differences in farm households' land endowment.

At the regional level, this study divided China into four major regions—eastern (Shandong Province, Jiangsu Province, and Hebei Province), western (Sichuan Province, Gansu Province, and Inner Mongolia Autonomous Region), central (Anhui Province, Hunan Province, Hubei Province, and Henan Province), and northeastern (Liaoning Province, Jilin Province, and Heilongjiang Province)—to control for unobserved fixed effects. Similarity, it was divided to control for differences in unobservable factors, such as geographic location, hydrological conditions, climatic factors, and agricultural production habits in different regions, and to eliminate the influence of regional factors on the labor transfer of farmers (Table 1).

Table 1. Definition of variables and descriptive statistics.

Type	Variables and Codes	Variable Code	Variable Definition	Mean	Standard Deviation
Explained variable	Maize Growers Labor Transfer	Migrantratio	The proportion of the number of people working outside the household to the number of people in the household labor force	0.218	0.209
Core explanatory variables	socialized agricultural machinery service	Service	Used in any of the 5 segments of maize production = 1, not used = 0	0.569	0.495
	The degree of adoption of socialized agricultural machinery services	Service degree	Ratio of the area of socialized agricultural machinery services to the sown area adopted in each segment of maize production	1.151	1.629
	Tillage link socialized service of agricultural machinery	Service1	Adopted = 1, not adopted = 0	0.324	0.468
	Sowing link socialized service of agricultural machinery	Service2	Adopted = 1, not adopted = 0	0.309	0.462
	Plant protection link agricultural machinery socialized service	Service3	Adopted = 1, not adopted = 0	0.094	0.292
	Irrigation and drainage link agricultural machinery socialization service	Service4	Adopted = 1, not adopted = 0	0.135	0.342
	Harvesting link agricultural machinery socialized service	Service5	Adopted = 1, not adopted = 0	0.421	0.494
The land situation	Maize sown per capita	Area	Maize sown area/(number of family agricultural laborers + number of family workers outside the home)	3.507	5.216
	Land Quality	Quality	Poor land = 1, land of moderate to low quality = 2, land of moderate quality = 3, land of moderate to high quality = 4, very fertile land = 5	2.963	0.853
	Degree of land fragmentation	Block	Number of plots of arable land (blocks)	4.702	4.648
Household situation of farmers	Age of household head	Age	Actual age of head of household (years)	51.838	10.272
	Education level of household head	Edu	Illiterate = 1, elementary school = 2, middle school = 3, high school = 4, college = 5, college or above = 6	2.776	0.929
	Health status of the head of household	Health	Good = 1, fair = 2, poor = 3, incapable of work = 4	1.416	0.628
	Training in family farming	Train	No training in agricultural production and management = 0, training in agricultural production and management = 1	0.180	0.384
	Family Cadre Status	Staff	No = 0, village cadres = 1, township cadres = 2, county-level or above cadres = 3	0.149	0.414
Instrumental variable	Average acreage of agricultural machinery assets	Asset	Present value of agricultural machinery assets per acre for farm households	285.226	649.815
	Village agricultural machinery service adoption level	Average service	The average adoption rate of socialized agricultural machinery services among farmers in the village other than this farmer	1.068	1.507
Region dummy variable	Eastern Region	Prov1	Is it located in the eastern region? Yes = 1; No = 0	0.395	0.489
	Central Region	Prov2	Is it located in the central region? Yes = 1; No = 0	0.223	0.417
	Western Region	Prov3	Is it located in the western region? Yes = 1; No = 0	0.222	0.415
	Northeast Region	Prov4	Is it located in the northeast region? Yes = 1; No = 0	0.160	0.366

The sample farmers showed varying degrees of adoption of socialized agricultural machinery services, including those for tillage, sowing, plant protection, irrigation and drainage, and harvesting. The mean values for the adoption of these services were 0.569, 0.324, 0.309, 0.094, 0.135, and 0.421, respectively. Household heads had an average age of 52 years and tended to have received education at primary or junior high schools. The majority of household heads were in good health, and the farming households had relatively low ownership of agricultural machinery. After this part of this paper, the socialized agricultural machinery service is replaced by service.

3. Results

3.1. Overall Estimation

Services and labor transfer have an endogenous relationship of mutual cause and effect. Rural labor can be transferred to cities and towns for non-agricultural employment because of the availability of services to replace labor on farmland. Conversely, rural labor transfer can also provide conditions for services. Relatedly, it is impossible for the study to capture all individual characteristic variables such as labor employment, income, and risk preferences of production and business decision makers and other members of farm households, and the above-omitted variables may affect the decision set of farm households to choose agricultural machinery socialization services, which in turn leads to farm households' agricultural machinery socialization services choice to be related to the disturbance term. The unidirectional effect of agricultural machinery socialization services on labor transfer needs to be separated in the econometric model. Therefore, the one-way effect of agricultural machinery socialization services on labor transfer needs to be separated in the econometric model.

Considering that there may be mutual causality as well as omitted variable problems between services and farm labor shifts, thus creating endogeneity problems, the IV-Tobit model and GMM model were used to analyze the effect of services on farm labor shifts. The results of the first stage estimation are not presented due to space limitations. The regression results based on the IV-Tobit model and GMM model to analyze the effect of services on labor shifts of farm households are presented in columns (1) and (3) in Table 2. The prerequisite for applying the instrumental variables approach is the existence of endogenous explanatory variables, for which a Hausman test is required, with the original hypothesis that all explanatory variables are exogenous. The Hausman test value for this model is 10.94 and rejects the original hypothesis of the non-existence of endogenous variables at a 5% level of significance, indicating that the introduction of this instrumental variable is necessary. The Wald test value is 176.03, showing that the hypothesis of the non-existence of endogeneity is rejected at a 1% level of significance, again proving the problem of the endogeneity of variables. The weak instrumental variables test was determined by the presence of a positive effect of instrumental variables on services at the 1% significance level in the first stage regression in the instrumental variables method, and the F value of the joint significance test = 266.4 ***, referring to the rule of thumb proposed by Stock and Yogo (2005), which states if the F statistic of this test is greater than 10, then the original hypothesis of the variable corroborates that there is no weak instrumental variable problem.

The second-stage results of the instrumental variables regression illustrate that: after excluding the endogeneity problem between variables, there is a positive effect of services on farm household labor transfer, which passes the significance test at the 1% statistical level; it verifies the research hypothesis of this study, indicates that services have a facilitating effect on farm household labor transfer, and further elucidates that services are a significant factor in promoting farm household labor transfer. It further explains that services are a significant factor in promoting labor transfer of farmers. The service is conducive to integrating farmers into the agricultural production division-of-labor system, promoting the modernization of farmers' maize production and guiding farmers into the development track of modern agriculture, so that farmers' willingness to transfer labor will be enhanced.

In terms of control variables, the age of the household head has a significant negative effect on the labor transfer of farm households, probably due to the fact that older farm households have certain labor constraints, and their physical condition is not suitable for heavy labor. In contrast, the non-farm employment of rural laborers in China is mainly manual labor, and older farmers are less inclined to move to urban areas for non-farm employment. Conway et al. [34] also showed that young farmers at the early stage of the life cycle are more likely to obtain non-farm employment. Moreover, the age of the household head also indicates his or her experience in maize farming, and older farmers with more experience in maize farming, traditional dependence on maize production, and expected uncertainty about obtaining income from non-farm employment are reluctant to shift their labor force.

Table 2. Impact of services on labor transfer of farm households.

Variable	IV-Tobit Model		GMM Model	
Service	0.103 *** (0.029)		0.116 *** (0.033)	
Service degree		0.068 *** (0.016)		0.070 *** (0.015)
Age(log)	−0.152 *** (0.051)	−0.094 *** (0.030)	−0.099 *** (0.032)	−0.095 *** (0.034)
Edu	−0.017 (0.012)	0.006 (0.011)	−0.011 (0.008)	0.005 (0.007)
Health	−0.017 (0.017)	−0.010 (0.015)	−0.008 (0.009)	−0.008 (0.011)
Train	−0.009 (0.025)	−0.018 (0.023)	−0.001 (0.001)	−0.016 (0.015)
Staff	0.022 (0.024)	0.011 (0.021)	0.014 (0.015)	0.008 (0.017)
Quality	0.004 (0.011)	0.014 (0.010)	0.001 (0.006)	0.007 (0.007)
Area(log)	−0.112 *** (0.015)	−0.095 *** (0.031)	−0.055 *** (0.009)	−0.042 *** (0.008)
Block(log)	0.002 ** (0.001)	0.002 ** (0.001)	0.002 ** (0.001)	0.001 ** (0.000)
Asset(log)	−0.004 ** (0.002)	−0.006 ** (0.003)	0.001 (0.002)	−0.006 *** (0.002)
Region dummy variable	Controlled	Controlled	Controlled	Controlled
Constant	0.787 *** (0.226)	0.434 *** (0.106)	0.614 *** (0.135)	0.429 *** (0.139)
Sample size	1048	1048	1048	1048
R^2			0.252	0.170
Wald test	176.03 ***	204.83 ***	270.87 ***	236.85 ***

Note: *** and ** are significant at the levels of 1% and 5%, respectively; the values in parentheses are standard errors. The same follows for below.

Maize sowing area per capita has a significant negative effect on farm labor shifting. Maize production has a certain seasonality, and each production step needs to be operated at the appropriate time [35]. When the per capita area of maize sown by farmers is large, it requires both agricultural machinery and manual work supervision with the cooperation of farm household labor during the limited suitable operation time, thus inhibiting the transfer of farm household labor. The per capita maize sowing area also reflects the human–land relationship of farm households; when the per capita maize sowing area of farm households is small, their labor will be shifted from agricultural production to non-agricultural industries, which confirms the study of Sun Dingqiang and Feng Zixi [36].

The degree of land fragmentation has a significant positive effect on farm labor shifts. Land fragmentation consumes the travel time of laborers between various non-contiguous plots, and these additional consumptions require more agricultural labor inputs if a certain

level of output is to be guaranteed [37]. At the same time, land fragmentation can also be detrimental to the replacement of labor by agricultural machinery operations, which can increase the supply of agricultural labor and inhibit the transfer of farm labor.

The average agricultural machinery assets per mu has a significant negative impact on the transfer of farm labor. The average agricultural machinery assets per mu owned by farmers implies that they have certain a sunk cost of agricultural operation and investment lock, and the transfer cost of farm labor is higher, which hinders the transfer of farm labor. The number of agricultural machinery assets per mu owned by farmers also affects the adoption intensity of services. Farmers with less average agricultural machinery assets per mu have weaker ability to self-serve food production and tend to adopt services, which in turn promotes the transfer of farm labor.

Robustness tests were conducted using replacement indicators, as shown in columns (2) and (4) in Table 2. The agricultural machinery socialization service variable in the baseline regression was whether agricultural machinery socialization services were used in any of the five segments of farmers' maize production. Further, to improve the measurement accuracy of the agricultural machinery socialization service variable, the ratio of the scale of agricultural machinery socialization services purchased by farmers in maize production to the maize sown area was used to characterize the agricultural machinery socialization service variable. The results illustrate that neither the application of different measures (whether farmers adopt the service or the ratio of adoption) nor the application of different estimation methods (IV-Tobit model or GMM model) significantly changed the results of the model. The socialized services of agricultural machinery still have a positive effect on the labor transfer of farm households and pass the significance test at 1% statistical level, which proves the robustness of the estimation results in columns (1) and (3) in Table 2.

3.2. Impacts of Services on Labor Transfer of Farm Households in Different Segments

In fact, the degree of specialization of services in different segments differs in the way they allocate labor and other factors, and their effects on the labor transfer of farm households are different. The IV-Tobit model and GMM model were used for estimation, and the core explanatory variables were whether to adopt the services in tillage, seeding, plant protection, irrigation and drainage, and harvesting, and the average adoption level of services in tillage, seeding, plant protection, irrigation and drainage, and harvesting of other farmers in the village besides this farmer was taken as the variable of services in tillage, seeding, plant protection, irrigation and drainage, and harvesting, respectively. The instrumental variables in the first-stage estimation and the estimated coefficients of the average adoption levels of agricultural machinery socialization services in tillage, seeding, plant protection, irrigation, drainage, and harvesting in the village were all highly significant for the corresponding agricultural machinery socialization services variables.

The estimation results in Table 3 show that services in tillage, seeding, irrigation, drainage, and harvesting have significant positive effects on farmers' labor shifts, indicating that farmers' adoption of services in tillage, seeding, irrigation, drainage, and harvesting is beneficial to farmers' labor shifts. Among them, the services in tillage had the highest influence on the labor transfer of farmers, followed by sowing and harvesting, and the services in irrigation and drainage had a low influence on the labor transfer of farmers. This result is consistent with the actual situation because the concentration of labor demand in the tillage, sowing, and harvesting segments is higher and the intensity of demand is higher [38], and the mechanization level of the tillage, sowing, and harvesting segments is an important indicator for the Ministry of Agriculture and Rural Development to measure the overall mechanization level in China.

However, the socialized service of agricultural machinery in plant protection links does not have a significant impact effect on the labor transfer of farmers. As the application technology of agricultural machinery in plant protection link is yet to be developed, the combination of agricultural machinery and agronomy is not enough, resulting in serious pesticide drift loss in the spraying process of plant protection machinery. Only 30% of

the pesticide deposited to the maize crop [39], and many places need to repeat pesticide spraying manually, making it difficult for farmers to be completely liberated from the heavy maize plant protection operation.

Table 3. Impacts of services on labor transfer of farm households in different segments.

Variable	IV-Tobit Model	GMM Model
Service1	0.119 *** (0.047)	0.114 *** (0.042)
Service2	0.101 *** (0.038)	0.095 *** (0.032)
Service3	0.037 (0.029)	0.034 (0.030)
Service4	0.071 *** (0.029)	0.062 *** (0.024)
Service5	0.086 *** (0.029)	0.081 ** (0.040)
Age(log)	−0.089 ** (0.043)	−0.073 ** (0.034)
Edu	0.009 (0.010)	0.006 (0.007)
Health	0.013 (0.014)	0.013 (0.012)
Train	0.001 (0.001)	0.001 (0.001)
Staff	0.005 (0.019)	0.004 (0.015)
Quality	0.017 * (0.009)	0.009 (0.007)
Area(log)	−0.066 *** (0.012)	−0.047 *** (0.009)
Block(log)	0.005 ** (0.002)	0.003 (0.002)
Asset(log)	0.003 (0.003)	0.003 (0.002)
Region dummy variable	Controlled	Controlled
Controlled	0.677 *** (0.182)	0.625 *** (0.141)
Sample size	1048	1048
R^2		0.193
Wald test	237.86 ***	269.65 ***

Note: ***, **, and * are significant at the levels of 1%, 5%, and 10%, respectively; the values in parentheses are standard errors. The same follows for below.

3.3. Robustness Analysis

Farmers' decision of whether to adopt services is not randomly given, but is influenced by a variety of factors, which may also affect farmers' labor transfer decisions, thus generating a sample selectivity bias [40]. There is a mutual causal endogeneity problem between services and farmers' labor transfer, so in this section, in order to overcome both the sample selectivity bias and endogeneity problems, the endogenous switching regression model (ESR) constructed by Maddala (1983) is used to conduct a robustness analysis of the impact of services on the labor shifts of farm households. The model was chosen for the following reasons: first, to solve the self-selection problem of farmers' decision to adopt services; second, to effectively identify the factors influencing labor transfer between farmers in the adoption group and those in the non-adoption group, and to conduct differential analysis; and third, to use counterfactual analysis to evaluate the effect of services on farmers' labor transfer. For the agricultural machinery socialization service variable, to satisfy the matching mechanism of the endogenous switching regression model, the dependent variable of

the estimating equation must be a binary dummy variable, and most of the existing literature also uses a binary dummy variable to measure the adoption of agricultural machinery socialization service behavior by farmers [41,42]. In this section, the agricultural machinery socialization service variable is set as whether farmers adopt agricultural machinery socialization services, i.e., if farmers adopt agricultural machinery socialization services in any of the five segments of maize production, the agricultural machinery socialization service variable is one, otherwise, it is zero. The estimation results of the agricultural machinery socialization service adoption decision model and the farm labor transfer effect model are shown in Table 4, and the inter-equation independence test (LR test) rejects the decision model at the original hypothesis, which argues the decision model and the farm labor transfer effect model are independent of each other at the 5% statistical level. The Wald test of the model is significant at the 1% statistical level, indicating that it fits well and there is a problem of sample selectivity bias caused by unobservable variables, and the application of the endogenous switching regression model is reasonable and reliable.]ρ_{u0} and ρ_{u1} are the correlation coefficients between the decision model and the error terms of the labor transfer effect model for farmers who adopt services and farmers who do not adopt services, where the ρ_{u0} is estimated to be negative and significant at the 1% statistical level, indicating that the labor transfer of non-adopted agricultural machinery socialization service farmers is lower than the labor transfer level of general farmers in the sample. This result is consistent with the reality because the most fundamental role of agricultural machinery socialization services is its substitution of agricultural labor, and since the comparative returns of the agricultural sector have been lower than those of the non-agricultural sector for a long time, farmers as a rational group of economic people are "profit-oriented" and will tend to adopt services to replace manual labor and then shift to non-agricultural industries.

To improve model identification, the variable "average level of adoption of services in villages" was introduced as an instrumental variable in the decision model of farm households' adoption of services. The factors related to human capital (education of household head and agricultural training of household) and agricultural operation (land quality and per capita maize sowing area) and the instrumental variable (average level of adoption of agricultural machinery socialization services in villages) had a significant positive effect on farm households' adoption of agricultural machinery socialization services; agricultural machinery assets had a significant negative effect on farm households' adoption of agricultural machinery socialization services. Comparing the estimation results of the labor transfer effect model between farmers in the adopted group and those in the non-adopted group, we can see that the age of the household head had a significant negative effect on the labor transfer of farmers in the non-adopted group, probably due to the physical constraints of older farmers and the fact that they did not adopt services, which affects their labor transfer. The age of the household head had a significant positive effect on the labor transfer of farmers in the adoption group. The degree of land fragmentation of farmers and their adoption of services showed a significant negative relationship. The degree of land fragmentation had a greater impact on the adoption of the service group because the services are mainly based on the scale of machinery and the fragmentation of farming plots is not conducive to the use of mechanical equipment and farmland infrastructure. The increase in land fragmentation will stimulate farmers to reallocate agricultural production factor inputs among different scattered plots, such as reducing modern service inputs and increasing inputs to labor capital, which will inhibit the transfer of farm labor. The higher education level of the household head, better land quality, and smaller maize sowing areas promoted the labor transfer of farmers who adopted services compared with those who did not. In addition, the lower education level of the household head, the presence of cadres in the family, and the smaller agricultural machinery assets promoted labor transfer among farmers who did not adopt services.

Table 4. Estimation results of the endogenous switching regression model.

Rural Household	Decision Model (Whether to Adopt the Service)		Rural Household Labor Transfer Effect Model Adoption Services		Service Not Adopted	
Variables	**Coefficient**	**Standard Error**	**Coefficient**	**Standard Error**	**Coefficient**	**Standard Error**
Age(log)	0.236	0.345	0.094 *	0.050	−0.205 ***	0.047
Edu	0.116 **	0.052	0.032 ***	0.012	−0.023 **	0.010
Health	0.016	0.071	0.003	0.014	0.005	0.016
Train	0.073 **	0.035	−0.010	0.024	0.006	0.024
Staff	−0.083	0.163	−0.010	0.021	0.052 **	0.023
Quality	0.039 ***	0.010	0.027 ***	0.010	−0.017	0.011
Area(log)	0.084 ***	0.026	−0.038 ***	0.012	−0.026	0.017
Block(log)	−0.045 ***	0.012	−0.006 **	0.003	−0.002 **	0.001
Asset(log)	−0.075 ***	0.015	−0.002	0.003	−0.006 **	0.003
Average service	0.627 ***	0.109	-	-	-	-
Region dummy variable	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Constant	−2.622 ***	0.955	−1.277 ***	0.208	1.184 ***	0.205
$\ln\sigma_{u0}$	-		-		−1.598 ***	0.034
ρ_{u0}	-		-		−0.259 ***	0.098
$\ln\sigma_{u1}$	-		−1.962 ***	0.031	-	
ρ_{u1}	-		−0.016	0.134	-	
Log likelihood value	−106.994					
LR test	6.13 **					
Wald test	15.66 **					

Note: ***, **, and * are significant at the levels of 1%, 5%, and 10%, respectively; the values in parentheses are standard errors. The same follows for below.

Based on the above empirical estimation results of the endogenous switching model for services, the average treatment effect was derived by excluding the effect of other factors by measuring the farm labor transfer expectation under the counterfactual condition assuming non-adoption, assuming adoption, and the actual condition of adoption and non-adoption for a total of four scenarios (Table 5).

Table 5. Average treatment effect of socialized services of agricultural machinery on labor transfer of farm households.

Farmers Category	Decision-Making Stage		Treatment Effect	
	Adoption Services	Service Not Adopted	ATT	ATU
Service adopter	0.330	0.235	0.095 ***	-
Not service adopter	0.375	0.188	-	0.186 ***

Note: ATT and ATU represent the average treatment effect of households that adopt agricultural machinery socialization services and households that do not adopt agricultural machinery socialization services, respectively. *** is significant at the levels of 1%, respectively; the values in parentheses are standard errors. The same follows for below.

Overall, the average treatment effect of farmers' adoption of services on their labor transfer was statistically significant and positive at the 1% level. Based on the counterfactual hypothesis, when farmers who adopted services did not implement corresponding service adoption behavior, their farm labor transfer level would decrease by 0.095; when farmers who did not adopt services applied services, their farm labor transfer level would increase by 0.186. The above indicates that the adoption of services by farmers can significantly promote their labor transfer.

3.4. Heterogeneity Analysis

The impact of services on the labor transfer of farm households is analyzed above, but the regression results only represent the overall average effect of the impact and cannot reflect the possible heterogeneous effect of its effect. On the one hand, the differentiation of farm households has gradually become a common phenomenon in rural China [43], and the differentiation allows farming households to differ in their farming behavior, changing from homogeneous farming households to pure farming households and part-time farming households. The number of family laborers and the time spent on agricultural labor are different for farmers with different part-time jobs, while services are essentially hired labor, and inadequate labor supervision is likely to lead to inefficient agricultural machinery operations, thus causing different effects of adopting services on the labor transfer of farmers. Referring to the international classification of farming households, the studied farming households were classified as purely farming households if their non-agricultural income did not exceed 10% of their total income, and those whose non-agricultural income exceeded 10% of their total income were classified as part-time farming households. Group regressions were conducted, and the empirical results are shown in Table 6.

Table 6. Impacts of socialized services of agricultural machinery on labor transfer of farm households under different concurrent business conditions.

Variables	Pure Agricultural Households		Multiple Occupations Farmers	
	IV-Tobit Model	GMM Model	IV-Tobit Model	GMM Model
Service	0.211 ***	0.187 ***	0.067 ***	0.059 ***
	(0.070)	(0.062)	(0.014)	(0.016)
Age(log)	−0.173 ***	−0.124 **	−0.159 ***	−0.121 ***
	(0.028)	(0.056)	(0.047)	(0.036)
Edu	0.006	0.006	−0.024 **	−0.018 **
	(0.038)	(0.012)	(0.011)	(0.008)
Health	−0.128 **	−0.103 ***	0.001	0.001
	(0.057)	(0.037)	(0.015)	(0.013)
Train	0.081	0.072	0.013	0.017
	(0.083)	(0.069)	(0.024)	(0.025)
Staff	0.019	0.007	0.030	0.023
	(0.071)	(0.028)	(0.024)	(0.017)
Quality	0.090 **	0.020	0.021	0.018
	(0.041)	(0.013)	(0.017)	(0.015)
Area(log)	−0.203 ***	−0.196 ***	−0.073 ***	−0.068 ***
	(0.048)	(0.062)	(0.022)	(0.019)
Block(log)	0.011 **	0.002	0.001	0.001
	(0.005)	(0.002)	(0.001)	(0.001)
Asset(log)	0.003	0.001	0.003	0.003
	(0.011)	(0.003)	(0.003)	(0.002)
Region dummy variable	Controlled	Controlled	Controlled	Controlled
Constant	2.933 ***	1.498 ***	0.876 ***	0.724 ***
	(0.941)	(0.521)	(0.206)	(0.153)
Sample size	304	304	744	744
R^2		0.397		0.137
Wald test	54.89 ***	66.98 ***	51.76 ***	86.59 ***

Note: *** and ** are significant at the levels of 1% and 5%, respectively; the values in parentheses are standard errors. The same follows for below.

From column (1) of Table 6, it can be seen that based on the IV-Tobit model, services significantly increased the labor transfer of purely agricultural households by 0.211 on average. While replacing the estimation method, it was found that services still showed a significant positive effect on the labor transfer of purely agricultural households, and the estimation results were largely consistent, further confirming the existence of services on the labor transfer of purely agricultural households. Based on the IV-Tobit model, it was found

that the services significantly increased the labor transfer of part-time farming households by 0.067 on average, and the estimated coefficients were also generally consistent when the GMM model was used for robustness testing.

It can be seen that the coefficients of the impact of services on labor transfer of farm households, analyzed in terms of farm households' part-time employment, were greater in the pure farm household group than in the part-time farm household group, and the impact coefficients all passed the significance test. Since services are still essentially hired labor, it is difficult for farm households to adopt services to avoid the loss of maize production efficiency due to information asymmetry and opportunistic motives of service providers [44–46].

The topographic conditions of farmland owned by farmers were also considered to be an important factor affecting the labor transfer of farmers, as the topographic conditions of farmland affect the ease of farming and the willingness of farmers to engage in agricultural business. Farmers have different household land resource endowments, different degrees of dependence on the land, and different quantities and qualities of labor devoted to maize production, resulting in the heterogeneity of labor transfer from services to farmers in different terrain conditions. Based on the group regression of the effect of services on the labor transfer of farm households under different terrain conditions, the empirical results are shown in Table 7.

Table 7. Effects of services on labor transfer of farmers under different terrain conditions.

Variables	Flatland Plains		Sloping Hill	
	IV-Tobit Model	GMM Model	IV-Tobit Model	GMM Model
Service	0.199 *** (0.053)	0.167 *** (0.036)	0.207 (0.135)	0.143 (0.107)
Age(log)	−0.179 *** (0.054)	−0.126 *** (0.035)	−0.029 (0.109)	−0.036 (0.063)
Edu	0.021 * (0.012)	−0.013 (0.008)	−0.005 (0.023)	−0.005 (0.015)
Health	−0.029 (0.019)	−0.016 (0.011)	0.034 (0.029)	0.022 (0.019)
Train	0.001 (0.002)	−0.001 (0.001)	0.001 (0.003)	−0.001 (0.004)
Staff	0.028 (0.026)	0.020 (0.016)	−0.095 * (0.055)	−0.046 * (0.027)
Quality	0.004 (0.012)	0.002 (0.007)	0.043 (0.029)	0.033 (0.027)
Area(log)	−0.091 *** (0.017)	−0.044 *** (0.010)	−0.195 *** (0.031)	−0.093 *** (0.015)
Block(log)	0.006 *** (0.002)	0.004 ** (0.002)	−0.002 (0.005)	0.002 (0.002)
Asset(log)	0.001 (0.003)	0.001 (0.002)	0.010 (0.007)	0.009 (0.007)
Region dummy variable	Controlled	Controlled	Controlled	Controlled
Constant	0.882 *** (0.229)	0.676 *** (0.147)	0.436 *** (0.153)	0.419 *** (0.121)
Sample size	879	879	169	169
R^2		0.273		0.289
Wald test	104.34 ***	188.77 ***	93.22 ***	327.26 ***

Note: ***, **, and * are significant at the levels of 1%, 5%, and 10%, respectively; the values in parentheses are standard errors. The same follows for below.

On average, the services significantly increased the labor transfer of flatland farmers by 0.199. Plain areas are suitable for agricultural machinery operations, and the application of services significantly reduced the labor time of flatland farmers engaged in maize production, allowing labor to devote time to non-agricultural industries, resulting in a

part-time labor transfer. The development of services provided sufficient motivation for the labor transfer of flatland farmers and optimized the conditions for labor transfer.

Services do not yet have a significant impact effect on the labor transfer of sloping mountain farmers. As a factor to replace agricultural labor, services are also relatively difficult to replace factors in areas with a high proportion of sloping lands. Faced with the complex topography of sloping mountainous areas, where it is desirable to have a high mechanization and finishing effect, making it difficult to promote agricultural machinery operations, the operational efficiency of agricultural machinery, especially large agricultural machinery, in sloping mountainous areas is restricted to a greater extent [47], which is not conducive to the development of services. The role of services in sloping mountainous areas is weakened for both large-scale and small-scale farmers so that it does not have a significant impact on the labor transfer of farmers. In general, the services mainly promoted the labor transfer of flatland farmers, and did not promote the labor transfer of sloping mountain farmers, or promoted it less, and all of them did not pass the significance test.

4. Discussion

In economies with limited land resources, the use of agricultural machinery has resulted in the displacement of tenant farmers. Conversely, in economies with abundant land resources, the adoption of agricultural machinery has affected traditional land tenure. The employment impact of mechanization on agriculture is often perceived as negative [48]. However, in Asia, small farms can benefit from using farm machinery services instead of investing in expensive farm machinery, which could save them a lot of money [49,50]. According to Otsuka [51], mechanization of large farm machinery is more likely to be adopted by larger farms, without altering the family contract responsibility system and farmers' land property rights. Service scale operation compensates for the issue of land fragmentation of farmers' family operations, providing a new approach to moderate agricultural-scale operation beyond land-scale operation. Thus, small-scale land has the potential for scale efficiency. Several empirical studies conducted by scholars show that agricultural machinery is suitable for small-scale farming, and it can be used for services as well, breaking the constraints of "ridge" [52].

As stated by the Chinese Ministry of Agriculture and Rural Affairs, by late 2016, approximately 97% of China's farm families (around 260 million households) had land operations not exceeding 50 mu. In China, where the mean farm size is a mere 0.5 ha, services have both engaged farm families in labor division tasks and enabled swift agricultural mechanization. Under the restrictions of the family joint production responsibility system and limited farming operations, China's agriculture has forged a unique path of mechanization through services, without considerable enlargement of the per capita land operation scale, thereby guaranteeing national food security. Notably, without altering the fundamental management system's premise, the specialized labor division in agricultural production stages and the advancement of services have liberated labor from the land to facilitate the seamless integration of small-scale farmers with modern agriculture [27].

Based on the neoclassical theory of farmers' behaviors, it is assumed that farmers' behavioral decisions are based on economic rationality. Considering the constraints imposed by a farming household's resource endowment, an expanding price gap between labor in the agricultural and non-agricultural sectors leads to a growing opportunity cost for agricultural production. Consequently, to maximize profit, farmers will autonomously choose to shift their labor into the non-agricultural domain. Concurrently, advancements in social services and the proliferation of agricultural mechanization not only facilitate the substitution of labor moving towards the non-agricultural sector, but also elevate the opportunity cost of labor as opposed to machinery within the agricultural sector. This, in turn, spurs decisions that further encourage the transition of labor towards non-agricultural pursuits.

Classical economics acknowledges the theory of specialized division of labor as a crucial driver for enhancing labor efficiency and fostering economic growth. This phe-

nomenon, encompassing specialization and service provision, arises from technological advancements and the evolving dynamics of social labor distribution. Under the condition of the limited endowment of farmers' own time, equipment, and technology level, farmers trust or outsource the maize production process to service organizations that have mechanical equipment, labor, and technology. It changes the scarcity of agricultural machinery for farmers (especially small-scale farmers), making it a more affluent element than labor and, further, playing the role of agricultural machinery as a substitute for farmers' labor. That is, the more agricultural machinery that is invested, the less the number of labor required, given the same level of production technology. When agricultural machinery is invested in grain production in a limited way, the economic cost of replacing labor with machinery is high in the case of the insufficient transfer of farm labor, and the cost of labor is lower than the cost of machinery, making grain production in a labor-intensive way more economically efficient. With technological progress, the cost of agricultural machinery manufacturing is massively reduced, and the cost of labor is increased by non-farm employment opportunities. At this time, under the role of the service market, socialized services help to realize the "division" of agricultural machinery. This can effectively increase the machinery input per unit area of land for all kinds of farmers, so that the machinery cost is lower than the labor cost, which will help to replace labor with machinery, thus forming more surplus agricultural labor and promoting the transfer of labor of farmers.

5. Limitations of the Study

Services play an essential role in helping economic structure transformation, regulating resource allocation, and promoting the labor transfer of farmers. The shortcoming of this study is that, due to the sample limitation, this study cannot introduce more effective control variables. Subsequently, we will design questionnaires based on the development of services combined with various industries to obtain more comprehensive research data and explore the more profound role of services on labor transfer in a broader dimension.

6. Conclusions

The study on the impact of services on the labor transfer of maize farmers can help deepen the understanding of farmers' decision-making behaviors and promote the adoption of services by the majority of farmers. Services can effectively solve the dilemma of "who should grow the land and how to grow the land" and are an important tool for developing modern agriculture. Based on the theory of specialized division of labor, we use the 2019 farm household survey data to overcome the causal endogeneity between services and labor transfer of farm households by using the instrumental variable method and systematic generalized moment estimation (GMM) to analyze the impact of services on labor transfer of farm households and explore the differences in the impact effect in different terrain conditions and part-time degree of cohorts. The endogenous transformation model (ESR) is also applied to construct a counterfactual framework to further analyze the impact effect of services on the labor transfer of farm households.

The results show that the socialized service of agricultural machinery can effectively promote the transfer of peasant household labor forces. In addition, under the counterfactual hypothesis, when the farmers who adopt the socialized service of agricultural machinery do not implement the corresponding socialized service of agricultural machinery, their labor transfer level will decline. However, when farmers do not adopt the socialized service of agricultural machinery, their labor force transfer level will rise. However, the effect of agricultural machinery socialization service has link heterogeneity. The effect intensity of agricultural machinery socialization services on the labor force transfer of rural households is as follows: tillage and preparation link, sowing link, harvesting link, irrigation and drainage link, while the plant protection link has no significant impact on the labor force transfer of rural households. Compared to farmers with other terrain conditions and part-time employment, agricultural machinery socialization services have a more significant effect on the labor force transfer of flat and pure agricultural households.

Therefore, we should focus on supporting the key links and weak links of food production to participate in the socialization of agricultural machinery services, such as agricultural mechanization being an important part of the plowing link, sowing link, harvest link, the development prospect of plant protection link, and so on. Seize the opportunity of high-standard farmland construction, and actively guide farmers in China's plain areas to use agricultural machinery socialization services. For pure agricultural households with abundant labor endowment, labor-intensive agricultural machinery socialization services, such as tillage and sowing, can be considered to release surplus agricultural labor force and transfer it to non-agricultural industries. In the face of the reality that small-scale farmers in China will still exist for a long time, emphasis should be placed on improving the cognition of small-scale farmers to the socialized service of agricultural machinery. More small-scale farmers can safely use the socialized service of agricultural machinery, so as to promote the integration of small-scale farmers into the development track of modern agriculture.

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Appendix A

The principal maize-growing nations are predominantly located in the Americas, East Asia, and South Asia, including the United States, Brazil, Argentina, Mexico, China, and India. From 1990 to 2019, the U.S. led the world in maize production, accounting for 30.22% of the global yield in 2019. Over the past three decades, China's maize output has consistently ranked second, trailing only the United States. It has grown substantially from 0.97 billion tons in 1990 to 261 million tons in 2019, an increase of 169.07%. China has maintained a maize production level of over 200 million tons for eight years in a row since 2012, achieving 261 million tons in 2019.

In particular, China's maize production reached 264 million tons in 2016, compared to 216 million tons in 2014, an increase of 22.22%. The Chinese government reduces the maize-planting area by adjusting the structure, on the one hand, and digests the excess maize stock by increasing the maize consumption capacity on the other hand. Such an increase or decrease adjustment makes China's maize supply-and-demand situation transform from a structural surplus to the current production shortage. From 2017 to 2019, China's maize production fell back to maintain a balanced maize supply-and-demand transition, which is not only related to the maize industry but also to national food security.

Table A1. World maize production in major producing countries, 1990–2019.

Year	World	United States	Brazil	Mexico	India	Argentina	China
1990	48,362.07	20,153.20	2134.78	1463.54	896.17	540.00	9721.39
1991	49,440.76	18,986.78	2362.43	1425.15	806.44	768.48	9914.78
1992	53,378.93	24,071.92	3050.61	1692.93	999.21	1070.05	9577.29
1993	47,722.11	16,098.58	3005.56	1812.53	960.10	1090.10	10,311.00
1994	56,866.35	25,529.50	3248.76	1823.58	888.44	1036.00	9967.41
1995	51,729.90	18,797.00	3626.70	1835.29	953.40	1140.40	11,236.16
1996	58,614.61	23,451.78	2965.28	1802.36	1076.90	1051.83	12,786.54
1997	58,441.19	23,386.43	3294.80	1765.63	1081.60	1553.68	10,464.76
1998	61,508.18	24,788.20	2960.18	1845.47	1114.77	1936.07	13,319.76
1999	60,743.47	23,954.86	3223.95	1770.64	1150.96	1350.41	12,828.72
2000	59,203.87	25,185.39	3232.10	1755.69	1204.32	1678.07	10,617.83
2001	61,515.24	24,137.67	4196.25	2013.43	1316.02	1535.94	11,425.60
2002	60,355.19	22,776.69	3594.08	1929.78	1115.17	1471.21	12,018.89
2003	64,505.52	25,622.90	4832.73	2070.14	1498.43	1504.45	11,599.79
2004	72,951.79	29,987.56	4178.76	2167.02	1417.20	1495.08	13,043.43
2005	71,419.11	28,226.26	3511.33	1933.87	1470.99	2048.26	13,949.85
2006	70,793.72	26,750.29	4266.17	2189.32	1509.70	1444.55	15,173.14
2007	79,353.24	33,117.73	5211.22	2351.28	1895.54	2175.54	15,241.89
2008	82,979.22	30,591.15	5893.33	2432.01	1973.14	2201.69	16,603.21
2009	82,081.98	33,192.11	5071.98	2014.28	1671.95	1312.14	16,410.76
2010	85,216.06	31,561.79	5536.43	2330.19	2172.58	2266.31	17,754.08
2011	88,703.47	31,278.89	5566.02	1763.54	2176.00	2379.98	19,290.42
2012	87,556.32	27,319.24	7107.28	2206.93	2226.00	2119.66	20,571.93
2013	10,1680.26	35,127.19	8027.32	2266.40	2425.95	3211.92	21,862.19
2014	10,3961.97	36,109.11	7988.16	2327.33	2417.00	3308.72	21,581.21
2015	10,5260.87	34,548.63	8528.31	2469.40	2257.00	3381.77	26,515.73
2016	11,2735.13	41,226.22	6418.83	2825.02	2590.00	3979.29	26,377.78
2017	11,3865.40	37,109.60	9791.07	2776.32	2589.99	4947.59	25,925.63
2018	11,2472.19	36,426.22	8236.65	2716.94	2875.29	4346.23	25,734.87
2019	11,4848.73	34,704.76	10,113.86	2722.82	2771.51	5686.07	26,095.77

Note: Data from FAO. Unit: million tons.

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A New Mode of a Natural Convection Solar Greenhouse Dryer for Domestic Usage: Performance Assessment for Grape Drying

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Abstract: It is known that the natural convection (NC) solar drying process is a simple and cheap method for drying foodstuffs, but it is not preferable for common users in the case of drying high-moisture content agro-products due to the slow rate of drying. Meanwhile, the forced convection (FC) drying process is most appropriate for such products, but its economic feasibility may be affected due to high initial and maintenance costs. Therefore, the present study proposed a controlled natural convection (CNC) drying mode using a solar greenhouse dryer (SGD) for drying grapes with two types of cover materials, glass and Plexiglas, through intermittent operation with a PV system to save energy as a simple and inexpensive domestic dryer instead of the common forced convection SGD and the conventional natural convection SGD. The obtained results of the new CNC drying mode using a Plexiglas SGD showed a higher drying rate than the NC drying mode and are close to the FC drying mode using the same cover material. The initial moisture content of the grapes was reduced from 5.91 g water/g dry matter to the final moisture content of 0.15 g water/g dry matter within 12 h and 15 h for the CNC and NC drying modes, respectively, using the Plexiglas SGD. Moreover, the thermal drying efficiency for the two mentioned drying modes was 12.5 and 9.7%, respectively. The Page model was found to be the most appropriate model to predict the kinetics of the SGD in all drying modes, regardless of the cover type. The new CNC drying mode using the Plexiglas SGD achieved the lowest cost per kg of dried grapes (1.26 USD/kg), the highest total saved costs over the lifespan of the dryer (USD 245.46) and the shortest payback period (1.08 years) compared to the other two dryers, NC-SGD and FC-SGD. Generally, the CNC-SGD had good performance over the NC-SGD because it is not affected by the fluctuation in the volume, velocity and direction of the inlet ambient air/wind during drying grapes as a high-moisture content product without external heating sources or complicated parts. Thus, the proposed drying system has the advantage in terms of simplicity, cheapness and saving energy compared to FC-SGD.

Keywords: solar greenhouse dryer; grape drying; new drying mode; controlled natural convection; thermal performance; drying kinetics

1. Introduction

Simply put, the availability of energy is considered key to the progress and flourishing of any nation on the level of health, education, industry and economy [1]. At the same time, the global population was 8 billion in 2022, and is predicted to reach 9.7 billion in 2050 [2]. Thus, societies around the globe will necessarily be subject to major challenges regarding energy and water demands alongside the food supply and security. Utilizing and implementing renewable energy sources is the most effective, green and sustainable path to mitigate greenhouse gases (GHG), which contribute to global warming [3].

The drying process is one of the most simple and widely used processes as a preservation technique for agro-products. It helps to increase shelf life, improves quality and reduce losses during storage [4,5], in addition to providing advantages to the dried products such as making them lightweight and easy to store, transport and use [6]. Generally, the drying

techniques available globally can be classified based on the source of heat into open-sun or natural drying, firewood (biomass) drying, fossil fuel drying, electrical drying and solar drying [7,8]. Farmers have used open-sun drying since ancient times as an energy-free and cheap method for drying their agro-products. However, this method has several disadvantages, such as (i) needing a large occupation space and long drying time [9], (ii) suffering from a loss of quality [10], (iii) heavy thermal energy losses [11], (iv) uncontrolled drying process [12] and (v) poor final products due to contamination by dust and dirt as well as the attacks of insects, birds, rodents and domestic animals [13–16]. The drying process in the industrial sector is an intensive energy-consuming operation because it requires a massive amount of thermal energy for heating and dehydrating products [17]. Generally, the thermal drying process consumes about 10–20% of the industrial sector's total energy consumption in developed countries [18]. Nevertheless, a significant part of the world's total energy consumption (about 30%) comes from the agricultural sector, of which ~4% is used for drying agricultural products [19]. Hence, the drying sector is a big consumer of energy [20]. In light of this, the use of large amounts of fossil fuels in the drying process to meet the required heat for this sector leads to major concerns from economical and environmental perspectives. The high preliminary and running costs of fossil fuel-driven dryers are considered a big barrier for small-scale farmers to accept such dryers [21]. The farmers usually cannot afford fossil fuel-powered dryers due to their high capital and operating costs in developing-economy countries [22]. In these countries, 80% of food is produced by small farmers [23].

Solar dryers can be classified based on the hot air circulation method/or operation mode, the mode of heat transfer to the product and the dryer's design (Figure 1).

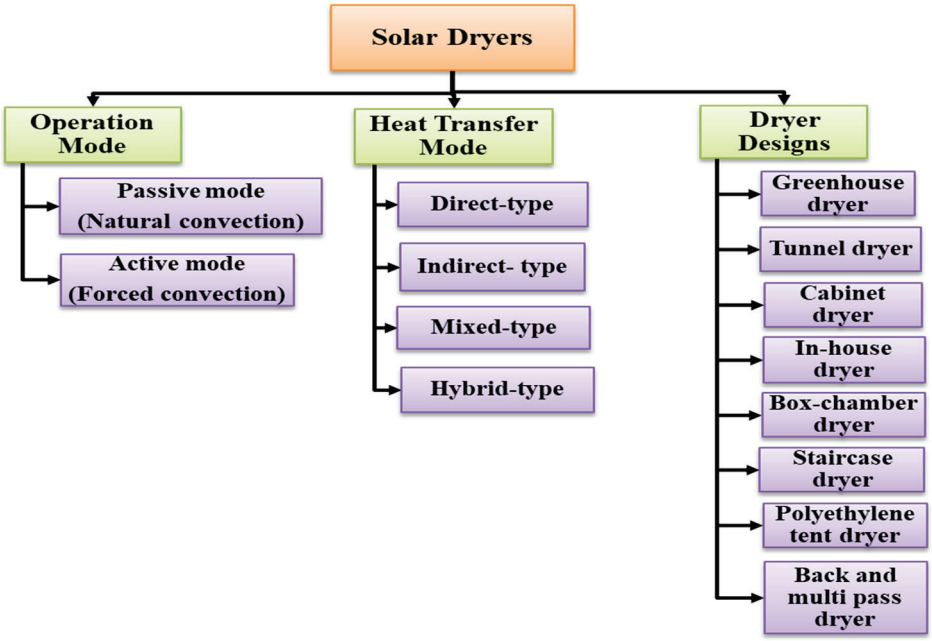

Figure 1. Solar dryer classification from [24,25].

Out of the various solar drying methods, the solar greenhouse dryer (SGD) is one of the oldest and most widespread methods for crop preservation [26] as a sustainable option for drying products due to its low cost and energy savings [27]. SGDs work on the concept of the greenhouse effect by trapping long-wave solar radiation within the dryer to produce the heat required for drying [28]. SGDs offer a controlled environment for the drying process in terms of the relative humidity and temperature required for shortening the drying time, making them more suitable for crop drying [29].

Moreover, SGDs are widely accepted by farmers due to their large capacity and low operational costs. The low or no power requirement makes such a type of solar dryer

a prospective option for installation on farms in remote areas [30]. Therefore, SGDs are classified as direct-type dryers based on the heat transfer mode through which the moisture content can be removed, either by the natural or forced convection mode. If they are combined with a solar air heater and solar panels, they come under the mixed-mode and hybrid types [31]. They can be used throughout the year, making them more effective regarding the economic aspect. The payback period of an SDG is about ~2.5 years [32]. The natural-mode greenhouse drying process depends on the thermosyphon effect theory. At the same time, an exhaust supports the SGD, which operates under the forced convection drying mode with fan installation to ventilate the humid air from the drying chamber [33]. The forced convection mode for SGDs offers better control and optimum drying conditions inside the dryer with the help of a fan or blower [34]. The natural convection mode for SDGs is used for relatively low-moisture content crops, whilst forced-mode SGD is used for high moisture content crops [35]. One of these crops is grapes due to their high moisture content.

Grapes have various advantages such as high nutrient levels and antioxidant content that may protect against chronic diseases such as diabetes and certain types of cancer, as well as reducing the blood sugar [36]. Grapes are perishable fruit with a high moisture content. The proper and efficient drying method plays a vital role in storing such perishable fruits for a long period in the form of raisins with high-quality properties that are needed for better market value. In the last two decades, limited studies have investigated drying grapes using different operation heat transfer modes. These works include using an indirect cabinet solar dryer under forced convection with a solar air heater (SAH) [37–41], a set of SAHs [42], combined SAH with an electrical heater [43,44], mixed-mode [38,45,46] and a mixed-mode natural convection dryer with PCM [47,48]. Despite the efficacy of indirect solar dryers for drying grapes, SGDs are still more efficient for dehydrating grapes in a considerably short time due to the natural greenhouse effect inside SGDs. In the literature, few studies focused on drying grapes using SGDs (Table 1).

Table 1. Previous studies focused on grape drying using SGDs.

Reference	Location	Shape of SGD/ Cover Type	Operating Mode	Max. Solar Radiation/Avg. Temperature inside SGD	Variety of Grape (Pre-Treatment Solution)	Load/Drying Range and Time	Drying Efficiency
El Khadraoui et al. [31]	Borj Cedria, (36°43′ N, 10°25′ E), Tunisia	Chapel-shaped/Plexiglas	Mixed-mode forced convection using flat plate SAH	~808 W/m^2/49.88 °C	Sultana (1% NaOH)	130 kg/From 5.49 gWater/g dry matter to 0.22 (gWater/g dry matter) in 50 h	N.A
Fuller and Charters [49]	Northern Victoria (35°57′ S 144°36′ E) Australia	Tunnel-shaped/Polyethylene sheets, two layers	Forced convection	~23 MJ/m^2 /60 °C	Sultana (untreated)	From 76% to 13% in 288 h	15–17%
Barnwal and Tiwari [50]	New Delhi (28°35′ N, 77°12′ E), India	Roof type even span/ Polyethylene sheets	Hybrid PV/T Forced convection	N.A	Thompson Seedless (untreated)	8 kg/(N.A)	38.40–43.6%
Rathore and Panwar [51]	Udaipur (27° 42′ N, 75° 33′ E), India	Tunnel-shaped/Polyethylene sheets	Natural convection	~950 W/m^2 /~65 °C	Thompson Seedless (untreated)	320 kg/From 85% to 16% in 168 h	30%
Hamdi et al. [52]	Borj Cedria, (36°43′ N, 10°25′ E), Tunisia	Chapel-shaped/Plexiglas	Mixed flow/Forced convection	795 W/m^2/28.08 °C–55.94 °C	Sultana (treated with 1% NaOH)	130 k/From 5.5 g water/g dry matter to 0.22 (g water/g dry matter) in 128 h	N.A
Tiwari et al. [53]	New Delhi (28°35′ N, 77°12′ E), India	Single-slope PV/T solar greenhouse dryer	Hybrid PV/T Forced convection	~890 W/m^2/~60 °C	Seedless (N.A)	N.A/1618 gWater to 594 gWater in 144 h	15–30%
Gopinath et al. [54]	Tamil Nadu (9°34′ N, 77°40′ E), India	Parabola-shaped/Poly-carbonate	Forced convection	N.A/45 °C for without PCM, 47.50° for with 100 g PCM and 58 °C for 200 g PCM	Seedless (treated with 6% K_2CO_3 and 0.5% olive oil)	N.A/From weight 80.20% −18.60% -Without PCM = 34 h -With PCM 100 g = 22 h With PCM 200 g = 10 h	N.A
Nagarajan and Premkumar [55]	Coimbatore-Tamil Nadu (11° N, 76° 57′ E), India	Tunnel-shaped/poly-carbonate	Forced convection using SAH	~830 W/m^2/35 °C–75 °C	Grapes (variety not determined)	1 kg/From 75% to 7% within 48 to 72 h	N.A

The perishable and high moisture content of agro-products such as grapes is prolonged due to the waxy layer that covers the grape peel [56]. Thus, the forced-convection SGD (FC-SGD) is mostly suitable for grapes. In this mode, the SGD is often augmented with heating auxiliaries such as air solar collectors/heaters, electrical heaters or mixed modes for operation, as well as using PCM for drying grapes to produce raisins. However, these methods may harm the drying process from the economic aspect, which can reduce the propagation of SGDs worldwide.

The available literature in Table 1 shows that the natural convection SGD (NC-SGD) or the passive mode is rarely used as a sole operation mode without augmentation of auxiliary heating systems for drying the mentioned products. Thus, the challenge of using NC-SGD for drying such high-moisture content agro-products in an efficient way and short time will be raised against the end users, who prefer utilizing NC-SGD due to its advantages including high capacity, low installation cost and operational costs that suit small-scale farms. Therefore, there is an urgent need for more exploratory works to develop, enhance and assess the performance of such inexpensive NC-SGD to be exploited for drying perishable high-moisture agro-products for small-scale domestic drying purposes powered by solar energy to suit the population disconnected from the grid in rural, remote and isolated areas.

In light of the above, the novelty of this work is presenting a new drying mode of natural convection SGD for drying high-moisture content agro-products (i.e., grapes) as a standalone drying system for domestic purposes in an attempt to avoid the drawbacks NC-SGD represents in terms of a slow drying process as well as the high installation operation and maintenance of FC-SGD. The proposed system was provided with an automatic control unit (ACU) to keep the parameters of the internal environment inside the dryer at an appropriate level during typical days for drying grapes without using an external heating source (i.e., solar collectors, heaters, etc.) or complicated parts. Therefore, the new proposed drying system will not be affected by fluctuations in the volume, velocity and direction of the ambient air/wind even in the late hours of the drying period. Moreover, the new drying mode of using controlled natural convection SGD (CNC-SGD) will allow the user to avoid tracking the direction of ambient air/wind that may occur when using CN-SGD. Additionally, the proposed drying system has the advantages of simplicity, cheapness and saving energy due to intermittent operation compared to the FC-SGD,

Hence, the objectives of the present work are to (i) fabricate an even-span-type solar greenhouse dryer (SGD) from two different materials, glass and Plexiglas, as well as evaluate its thermal performance for drying grapes under different operational modes; (ii) establish a simple, low-cost and easy-to-operate passive dryer as a new operational mode for solar drying that will be called hereafter the controlled natural convection SGD (CNC-SGD), which represents the novelty of the present work; (iii) compare the thermal performance of the new mode CNC-SGD to the forced convection (FC-SGD) and conventional natural convection (CN-SGD) drying modes in terms of thermal performance, drying kinetics and drying efficiency and (iv) perform an economic assessment to determine the best drying mode from an economic perspective.

2. Materials and Methods

2.1. Solar Drying Setup

In the present study, three operational modes of SDG were used to produce raisins through solar drying of seedless grapes of the Sultana variety on a small scale and for domestic purposes. Two different materials for fabricating SDG were tested; glass and Plexiglas (transparent acrylic glass). The three operational modes were used, including the conventional natural convection drying mode, forced convection drying mode and the new fully controlled natural convection mode. The two SGDs were fabricated and developed at a private workshop at the location of experiments in Zagazig City, Egypt (30.57° N latitude, 31.50° E longitude) throughout the summer season of 2021. The SGD had a loading capacity of about 1.500 kg of grapes. This study's main components of solar drying systems included the SGD, a solar air heater, PV system and automatic controller with sensing system.

2.1.1. Solar Greenhouse Dryer (SGD)

The practical experiments were conducted in two identical even-span-type SGDs that were fabricated and tested simultaneously to evaluate their effects on drying efficacy in the different mentioned drying modes. Each dryer had a 1.20 m length, 0.60 m width,

0.60 m height for the vertical wall and 0.75 m height from the center. Each SGD had a drying chamber containing a wooden table covered with woven mesh made of stainless steel with dimensions of 110 cm L × 45 cm W to hold the grapes at 40 cm above the floor of the chamber. The drying chamber's floor was made of two wooden sheets, each 3 cm in thickness, and packed with 5 cm of glass wool as an insulator to reduce heat losses from the drying chamber floor to the surroundings. A kind of porous cloth (fabric material) was placed on the woven mesh to circulate air from the bottom to the top of the drying chamber and then to the air vent located on the top roof of SGD. The rooftop and walls of the SGD were covered either by glass or Plexiglas sheets with the same thickness, 5 mm. The used SGDs were oriented in the east–west direction.

2.1.2. Solar Air Heater (in Case of Forced Convection Drying Mode)

The heater mainly consisted of a rectangular wooden container (120 cm length, 60 cm width, 20 cm Depth), a transparent glass cover of 5 mm in thickness sealed to the wooden container using thermal silicon, an absorber plate with welded metallic pipes (heating pipes) and a compact 10 cm layer of glass wool packed into the gap between the back internal side of the wooden container and the bottom surface of the absorber. As seen in Figure 2, the enclosure of the SAH was divided into two parts; the first one was the upper part, which represented the hot air collecting chamber that received the hot air from the heating pipes. This upper chamber was provided with a built-in centrifugal DC fan (power 10.56 W and diameter of 80 mm) to stream the desired flow rate of hot air into the SGD. This can be achieved by changing the fan speed through a controllable dimmer (speed regulator). The fan was installed at the bottom of the collecting air chamber on an outlet hole 8 cm in diameter connected to an insulated thermal duct with the same diameter to transfer the hot air from the hot air chamber to the drying chamber. The absorber occupied the second part, with welded metallic pipes that were placed 2 cm beneath the glass cover. A total of 40 pipes made of copper 100 cm in length and 2.54 cm in diameter were welded to the absorber plate (120 cm length, 60 cm width, 0.2 cm thickness), which was also made of copper. The pipes and absorber plate were painted with synthetic black matt paint. Each pipe was connected to a circular air intake hole with the same diameter allocated at the bottom side of the SAH; thus, there were 40 intake holes for the easy intake of ambient air into the heating pipes.

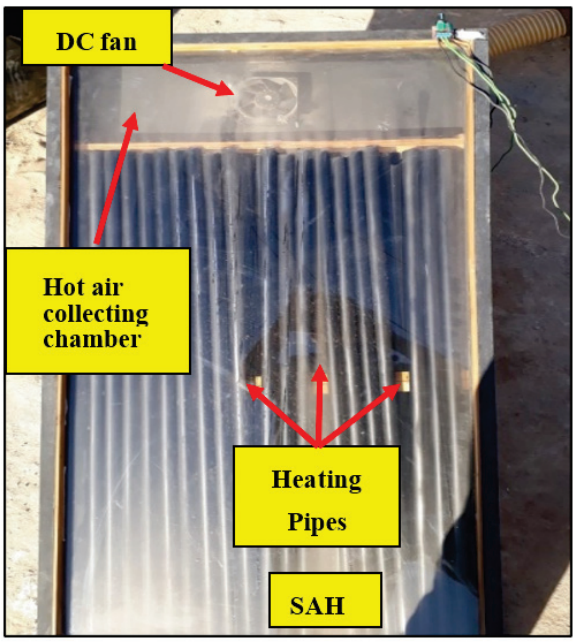

Figure 2. Photograph of SAH used for forced convection drying mode.

2.1.3. PV System

In the present study, a PV system was used to control two drying modes, the forced convection mode and the fully controlled natural convection mode. The PV system consisted of a polycrystalline photovoltaic (PV) solar module with a maximum power of 40 W (model SLP070-12U), a total surface area of 0.382 m^2 and a maximum efficiency of 19%. The solar PV module was rated by its DC output power. The PV module and its specifications are detailed in Table 2.

Table 2. The specifications of the solar PV module.

Parameters of PV Module	Specifications
Type	Polycrystalline Silicon
Dimensions (mm)	651 L × 526 W × 35 T
Weight (g)	5500
Maximum Power, P_{max} (W)	40
Optimum Operating Voltage, V_{MP} (V)	17.40
Optimum Operating Current, I_{mp} (A)	2.48
Open Circuit Voltage, V_{OC} (V)	21.70
Short Circuit Current, I_{sc} (A)	2.56

The output voltage of the PV module was set by a voltage regulator (with a maximum of 5 A). It stabilized the solar panel's outside voltage to reach 12 volts to protect the centrifugal fans from increased voltage difference and damage. A dimmer (speed regulator) was used to control the speed of forced blowing air (in the case of the forced convection drying mode).

2.1.4. Automatic Control Unit (ACU)

The new drying mode of fully controlled natural convection is considered an attempt to achieve the advantages of the conventional natural convection drying process, including the cheapness and simplicity in design and low initial and running costs. Meanwhile, the new drying mode aims to eliminate drawbacks of the conventional mode such as the full dependence on the ambient air velocity, the continuous orientation to face the wind direction and the long drying time for high-moisture content products (e.g., grapes). Moreover, the new drying mode aims to reduce the fabrication, repair and maintenance of the auxiliary parts required for the forced convection drying mode. Thus, an automatically controlled unit (ACU), Figure 3, was designed and retrofitted with the conventional natural convection SGD to control the operation of an air vacuum fan installed on the outlet vent.

The motherboard is considered the head of a system, as depicted in Figure 3. The ACU switched the fan on or off according to the pre-adjusted programmed temperature and humidity to ensure constant environment conditions inside the dryer to make the SGD independent of fluctuations in the ambient conditions.

According to the description of the ACU components (Table 3), the output voltage of the PV module was set by a voltage regulator to a maximum of 15 V. This suited the consumption of the ACU. Then, a voltage regulator (7805) was fixed in the unit to regulate the DC current to 12 volts for the DC vacuum fan consumption.

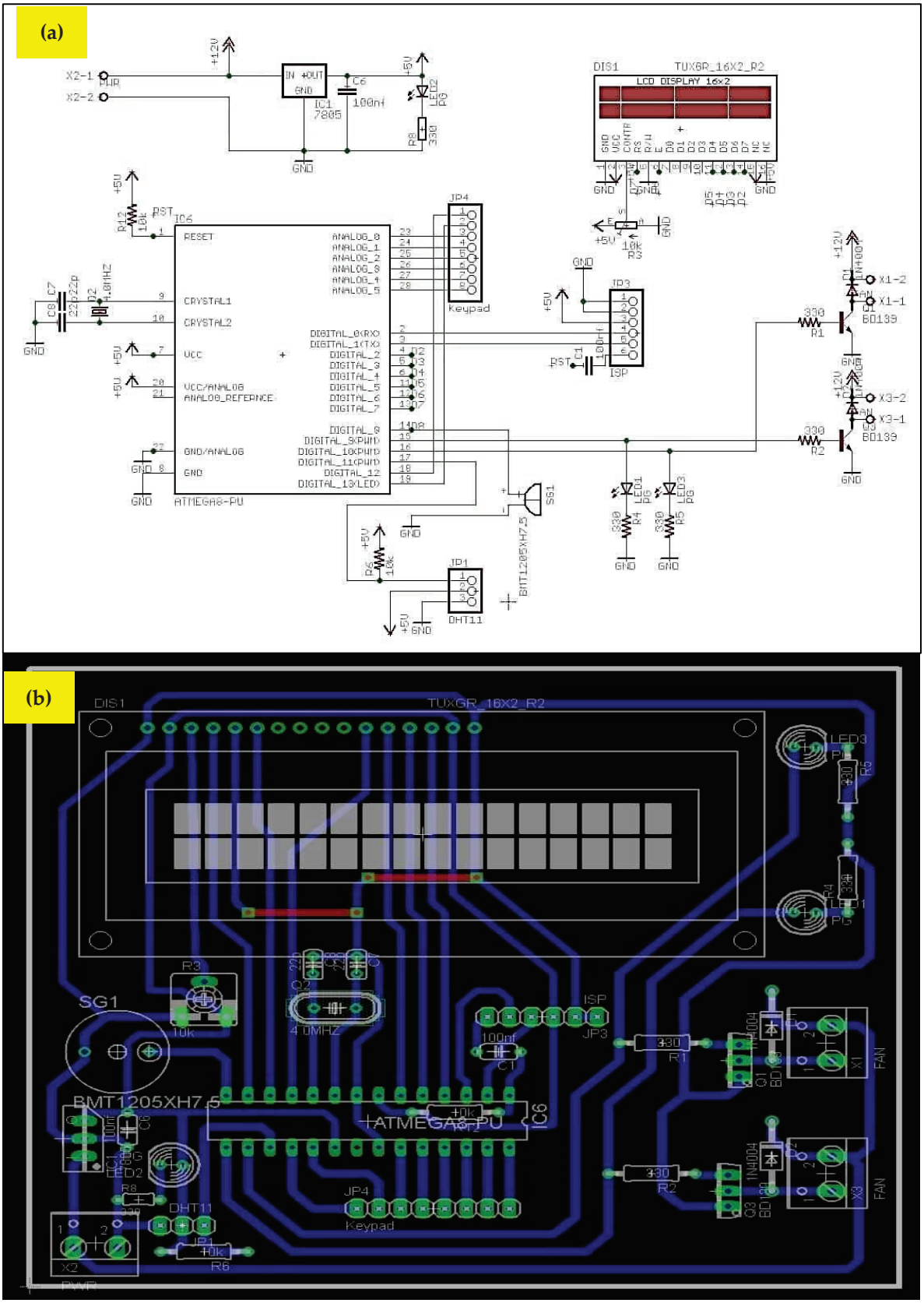

Figure 3. Views of: (**a**) electronic circuit, (**b**) the motherboard of ACU.

Table 3. The ACU components.

SI No.	Component	Description
1	LCD 16 × 2	Display of module
2	ATMEGA 328p	High-performance, low-power AVR® 8-bit microcontroller
3	Crystal oscillator 16 MH_Z	Designed to handle off-chip crystals that have a frequency of 4–16 MHz
4	Voltage regulator 7805	• 5 V positive voltage regulator • Minimum input voltage is 7 V • Maximum input voltage is 25 V • Operating current(I_Q) is 5 mA
5	Transistor BD 139	Designed for audio amplifiers and drivers utilizing complementary or quasi-complementary circuits
6	Capacitor 22p	Used with crystals for loading purposes
7	Red LED	Indicator
8	DHT 11	Temperature + humidity sensor
9	Keypad 4 × 4	• Maximum voltage across each segment or button: 24 V • Maximum current through each segment or button: 30 mA • Maximum operating temperature: 0 °C to + 50 °C • Ultra-thin design • Easy interface • Long life
10	Fan	Air ventilation fan (Exhaust fan)

The ACU was linked to a sensor installed inside the enclosure of the solar greenhouse dryer to detect the temperature and relative humidity of the interior air. The ACU was adjusted in advance to a particular temperature (55 °C) as the average maximum value from earlier works presented in Table 1, as was the relative humidity (max. 50%). The exhaust vacuum fan operated automatically to expel the internal drying air into the ambient area once the temperature or relative humidity of the interior air reached its pre-adjusted programmed value to avoid the accumulation of humid air inside the dryer or the over-drying phenomena due to the excess temperature of the internal air.

2.2. Experimental Procedure

In the present study, seedless grapes (Sultana variety) were dried to produce raisins. A sample of grapes was selected after separating their bunch and discarding the stems as well as the spoiled grapes. The selected grapes were washed with water to clean them of the dust and filth that may be stuck on grapes. After that, the grapes were pretreated by soaking them in an alkali solution of NaOH 5%, and then they were heated to a temperature of 90° for 30 s. This process was repeated consecutively three times to crack the grapes' peel. This process is essential to shorten the drying time by increasing the water permeability of the grapes' peel [57]. Afterwards, the grapes were washed with fresh water at ambient temperature and dried with a clean cotton cloth. Then, the pretreated grapes were distributed in a thin layer on the metallic mesh that was located within the SGD. The sample of dried grapes was weighed using a digital electronic balance (WANT balance) every 4 h throughout the drying period to determine the moisture loss. However, there were no measurements taken at night for the consecutive drying days, wherein the partially dried grapes were left inside the dryer throughout the night of the consecutive drying days with an insulation blanket. At the end of each experiment, the dried products were packed in polyethylene bags and stored at −4 °C prior to laboratory analysis [58]. The dry matter of grapes was determined by placing the dried product in an oven for 12 h at 120 °C [31]. All the experiments of the present work were carried out on clear and sunny days throughout the months of July to August 2021, from 8:00 am to 4:00 pm on the typical experimental days. When the drying process started, the fresh grapes had an average

moisture content on dry basis of 5.91 $g_w/g_{dry\ matter}$ and when it finished, the moisture content of the dried grapes reached a final level of 0.15 $g_w/g_{dry\ matter}$. Moreover, every single experiment was repeated three consecutive times, and then the obtained results were averaged.

2.3. Measuring Instruments

The meteorological parameters as well as the temperature, humidity and velocity of air during the solar drying process were measured to evaluate the performance of SGD under different operational conditions. Temperatures of the enclosure of SGD and woven mesh were measured using K-type thermocouples. Temperatures, the velocity of outlet hot air of SAH (in the case of forced convection mode) and output humid air from SGD were recorded using a velocity meter, while the solar irradiance was measured using a solar power meter. The relative humidity of ambient air and drying air (air in the enclosure of SGD) were measured as well. The range, resolution and accuracy of the measuring equipment are shown in Table 4.

Table 4. Description of the measuring equipment.

Parameter	Equipment	Measuring Range	Resolution	Accuracy
Temperature	Digitalthermometer, 4 channels (TENMARS, TM747DU, Taiwan)	−100–+1300 °C for K-type	0.1 °C	±0.1% rdg +0.7 °C
Temperature and relative humidity (RH) of ambient air	Digital temperature–humidity meter with probe (Pro'sKit NT-312, Taiwan)	Temperature: −50–+70 °C RH: 20–90%	0.10 °C 1% RH	±1% °C ±5% RH
Solar radiation intensity (pyranometer)	Digital data logging solar power meter (TENMARS, TES-132, Taiwan)	0–2000 W/m^2	1 W/m^2	±10 W/m^2
Air velocity (anemometer)	Digital hot-wire air velocity meter and probe (TENMARS, TM-4002, Taiwan)	0.01–25 m/s	0.01 m/s	±3% rdg, ±1.6% FS
Weight of grape sample	Digital electronic balance (WANT WT-N, China)	Up to 5000 g	0.10 g	±2 d at max capacity

2.4. Solar Drying Modes

The solar drying process of grapes using the glass and Plexiglas SGDs was carried out with the three drying modes described below:

2.4.1. Natural Convection Mode for SGD (CN-SGD)

This mode is considered the simplest and cheapest method for drying agro-products using SGD. In this mode (Figure 4a), the SGD was provided with one circular port (8 cm in diameter) as an inlet for ambient air, which was drilled at the bottom edge of the wall of SGD that faced the wind direction in the experimental location. Meanwhile, the humid air vent (square port 8 cm × 8 cm) was located in the opposite top roof of the SGD to increase the buoyancy force, which helps in creating an air draft inside the enclosure of SGD.

2.4.2. Forced Convection Mode for SGD (FC-SGD)

In this mode, three speeds of the centrifugal fan of SAH were used to provide the SGD with different airflow rates (Figure 4b). A voltage regulator set the voltage outside the PV panel to a maximum of 12 volts to suit the consumption of the fan. Then, a dimmer (speed regulator) switch was used to change the voltage. Consequently, the fan speed was set to 12, 9 and 5 V to obtain outlet hot air with mass flow rates of 0.06, 0.04 and 0.03 kg/s, respectively, from SAH.

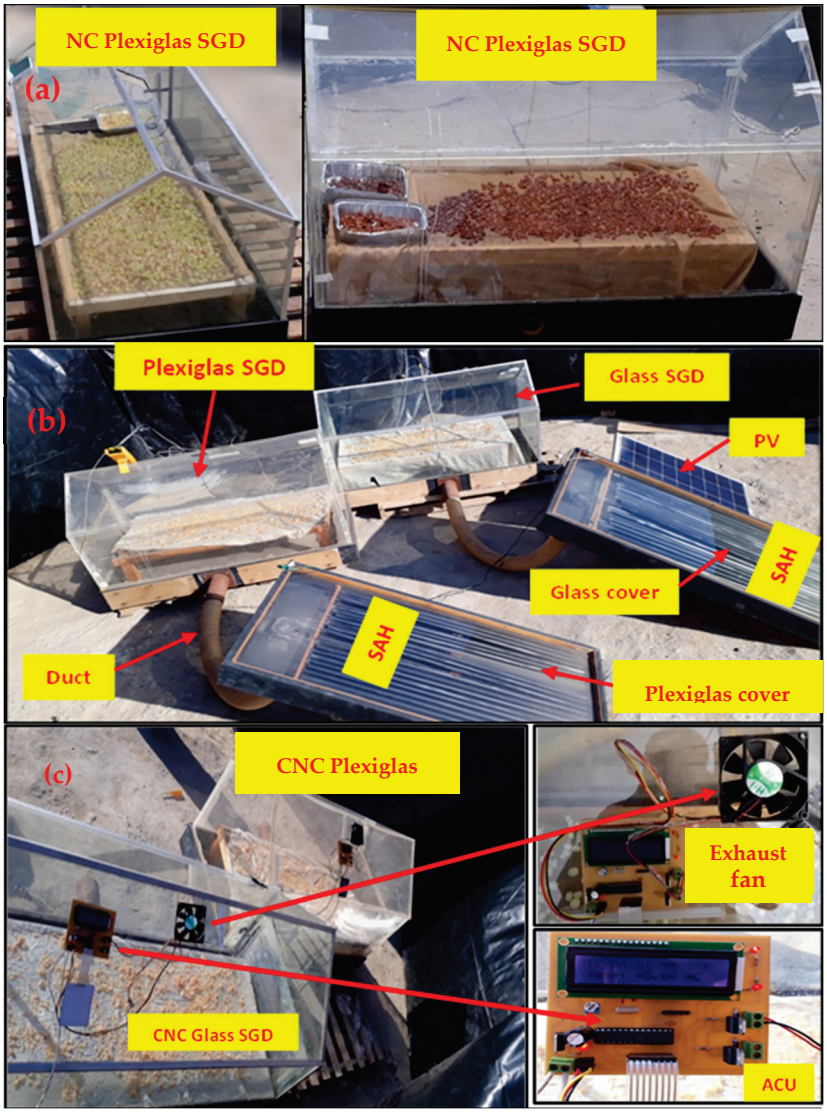

Figure 4. The designs of SGD for drying grapes: (**a**) natural convection (NC) mode, (**b**) forced convection (FC) mode, (**c**) controlled natural convection (CNC) mode (new mode).

2.4.3. Controlled Natural Convection Mode for SGD/New Mode (CNC-SGD)

Regarding the new mode, a similar SGD to that used in the conventional natural mode was equipped with a fan (DC 12 Volts/0.25 A) that acted as an exhaust air fan to vacuum an ambient air stream with a constant velocity of 2 m/s across the enclosure of the SGD. The exhaust air (humid air) fan was installed on the top roof of the SGD exactly on the humid air vent and connected to the automatic control unit (Figure 4c). The ACU operated the fan when it was essential to change the temperature and relative humidity values rather than the automatic pre-adjusted values. Thus, the intermittent operation of the exhausted air vacuum fan precisely preserved the temperature and relative humidity of the drying air inside the SGD.

2.5. Calculations and Determinations

2.5.1. Thermal Efficiency of SAH

The thermal efficiency of the used SAH is defined as the accumulated useful energy extracted from the solar collector throughout the experimental time divided by the total solar radiation incident on the collector. The thermal efficiency of the SAH (η_c) can be determined using the equation given by Sexina et al. [59]:

$$\eta_c = \frac{\dot{m}_a \times Cp_a(T_{co} - T_{ci})}{I_c \times A_c} \times 100 \tag{1}$$

where $\dot{m}_a$, Cp_a, T_{co}, T_{ci}, I_c and A_c are, respectively, the mass flow rate of air (kg/s), specific heat of air (J/kg K), outlet temperature of the solar air heater (°C), inlet temperature of the solar air heater (°C), total incident solar radiation intensity on the solar air heater(W/m^2) and surface area of the solar air heater/collector (m^2).

2.5.2. Drying Kinetics

The moisture content (M) on the dry basis, moisture ratio (MR) and drying rate (DR) can be determined using Equations (2)–(5) as follows:

$$M = \frac{m_p - m_d}{m_d} \tag{2}$$

$$MR_{exp} = \frac{M_t - M_e}{M_0 - M_e} \tag{3}$$

where m_p, m_d, M_0, M_e and M_t are, respectively, the mass of the product, the corresponding dry matter, the initial moisture content, the moisture content in the equilibrium state and the moisture content at moment t.

Nevertheless, because M_e is very small compared to M_t and M_0, MR is simplified according to [60,61] as:

$$MR_{exp} = M_t / M_0 \tag{4}$$

where MR_{exp} is the experimental moisture ratio. The drying rate (DR) is estimated on the basis of the ratio of the difference in two consecutive values of M_t and time difference (Δt), as given by [62]:

$$DR = \frac{M_{t+\Delta t} - M_t}{t} \tag{5}$$

The experimental values of MR_{exp} for the three drying modes used in the present study were fitted to the following five thin drying mathematical models: the Lewis model: $MR = \exp\left(-\grave{k}t\right)$ [63], Page model: $MR = \exp\left(-k\acute{t}\grave{n}\right)$ [64], Henderson and Pabis model: $MR = \grave{a}\ \exp\left(-\grave{k}t\right)$ [65], Wang and Singh model: $MR = 1 + \grave{a}t + \grave{b}t^2$ [66] and parabolic model: $MR = \grave{a} + \grave{b}t + \grave{c}t^2$ [67]. To compare the fitness of the mentioned drying models in order to select the proper model that describes the behavior of the drying process of the product for generalizing the drying curve [68], values of the coefficient of determination (R^2), chi-squared (X^2) and root mean square error ($RMSE$) were estimated using the equations below [69,70]:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i}\right)^2} \tag{6}$$

$$X^2 = 1 - \frac{\sum_{i=1}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - n} \tag{7}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N}} \tag{8}$$

where n, N, MR_{exp} and MR_{pre} are, respectively, the total number of observations, number of constants, experimental moisture ratio, % (wb), and predicted moisture ratio, % (wb).

2.5.3. Performance of the Dryer

The drying thermal efficiency (η_d) of the SGD can be calculated using the following equation [71]:

$$\eta_d = \frac{(M_i - M_b) \times h_l}{(A_d \times I_v \times D_b)} \times 100 \tag{9}$$

where M_i, M_b, h_l, A_d, I_v and D_b are, respectively, the initial mass of one batch of grapes (kg), mass of dried grapes from one batch (kg), latent heat of vaporization (kJ/kg), area of dryer (m^2), average incident solar radiation intensity on dryer (W/m^2) and time taken for drying one batch of grapes sample.

2.6. Economic Assessment

In the present study, the economic analysis was performed based on the fact that SGDs are used only during the warmer months of the year. This assessment was mainly based on the cost in the country in which the present study was performed. Therefore, the annual production in the present analysis will be estimated for the warmer period in Egypt from May to September. The cost of SGD based on the cover material and operating modes is tabulated (Table 5).

Table 5. Cost of the SGD's components (USD) with different drying modes using two types of covering materials.

Component	No. of Pieces	Cost (USD)	Notes
Plexiglas SGD	1	40	-
Glass SGD	1	37	-
Plexiglas SAH	1	35	For Plexiglas FC mode only
Glass SAH	1	32	For Glass FC mode only
Air duct	2	10	For Glass and Plexiglas FC modes
PV panel	1	25	For Glass and Plexiglas FC and CNC modes
Voltage regulator, dimmer and wires	2	10	For Glass and Plexiglas FC modes
ACU and exhaust fan	2	10	For Glass and Plexiglas CNC modes
Wooden platform	2	25	For Glass and Plexiglas CN modes
Assembly cost	-	24	For all designs
Total cost	NC-SGD	USD 86 (Glass)	USD 89 (Plexiglas)
	FC-SGD	USD 148 (Glass)	USD 154 (Plexiglas)
	CNC-SGD	USD 106 (Glass)	USD 109 (Plexiglas)

The drying cost per mass unit of grapes (USD/kg) by using the annualized cost method was performed for an economic evaluation of SGD with the three operating modes using the glass SGD and Plexiglas SGD. The lifespan (j) of the used SGD, SAH and PV panel was taken as 10 years [72]. The annualized cost (C_a) can be calculated using equations adopted from [73]:

$$C_a = C_{ac} + C_{O\&M} - S_a + C_{re} \tag{10}$$

Since SGDs are used on the domestic scale, the running cost (C_{re}), which is represented in the annual labor daily wage for operating the dryer, will be ignored. The number of days using the dryer per year will be 120 days (hottest period of the year from May to August).

C_{ac} is the annualized capital cost, which can be calculated using equation the below:

$$C_{ac} = C_{CC} \times CRF \tag{11}$$

where C_{cc} is the capital cost of the dryer (USD) and CRF is the capital recovery factor that can be estimated as:

$$CRF = \frac{i(1+i)^j}{(1+i)^j - 1} \tag{12}$$

where i is the discount rate, which is 9.25% (Central Bank of Egypt, 2021) and j is the life span of the drying system (assumed to be 10 years).

The annual operating and maintenance cost ($C_{O\&M}$) is taken as 6% of annualized capital cost (C_{ac}) as:

$$C_{O\&M} = 0.06 \times C_{ac} \tag{13}$$

The annualized salvage value (S_a) is calculated as:

$$S_a = S \times SFF \tag{14}$$

where S is the salvage value taken as 10% of the annual capital cost (C_{ac}) of the dryer [30] and SFF is the sinking fund factor, which can be estimated as:

$$SFF = \frac{i}{(1+i)^j - 1} \tag{15}$$

Thus, the drying cost per 1 kg of dried grapes (C_d) is determined using the following relation:

$$C_d = \frac{C_a}{P} \tag{16}$$

where P is the annual mass of dried grapes (kg/year) produced by the dryer and can be estimated as:

$$P = \frac{M_b \times D}{D_b} \tag{17}$$

To calculate the money saving for the dryer across its life, the saving per day for the base year for the dryer (S_{db}) can be calculated using Equations (16) and (17) [53]:

$$C_{ds} = C_{fp} \times \frac{M_i}{M_b} + C_d \tag{18}$$

$$S_{db} = \frac{(C_{mr} - C_{ds})}{D_b} \tag{19}$$

where C_{mr} is the price of 1 kg of dried grapes (raisins) in the local market (USD 9).

Then, the total savings (S_j) for the dryer after (j) number of years can be calculated as given by [68]:

$$S_j = S_{db} \times D \times (1+i)^{j-1} \tag{20}$$

The payback period (N_p) is determined using the following equation [68]:

$$N_p = \frac{ln\left(1 - \frac{C_{cc}}{S_1}(i-d)\right)}{ln\left(\frac{1+d}{1+i}\right)} \tag{21}$$

Note: d is the inflation rate (5.21 %, The Central Bank of Egypt, 2021).

3. Results and Discussions

3.1. Fluctuation in Solar Radiation Intensity (SRI)

Figure 5 shows the variation in the total incident solar radiation intensity (SRI) on the horizontal plane during the drying period of 8 to 16 h on each experimentation day. The variation in SRI is shown for outside the SGD, inside the glass and in the Plexiglas with the different drying modes. The SRI increased gradually before noon to reach its peak value at noon from 12 to 12:30 pm on each typical day. Since the drying process is accomplished chiefly over two days, at least for the high-moisture content products, the average SRI of two consecutive days for each drying mode using the glass and Plexiglas SGDs was recorded. The average SRI outside and in the Plexiglas SGD during the drying period (8 h/day) was 745.22, 753.33 and 744.94 W/m^2 for the experimental days of NC-SGD, FC-SGD and CNC-SGD, respectively, while the average SRI inside the glass SGD was 663.99, 673.83 and 658.95 W/m^2, and in the Plexiglas SGD, it was 630.42, 636.79 and 628.31 W/m^2 for the same mentioned modes, respectively. The data show that the transmissivity of glass and Plexiglas are about 89 and 85%, respectively.

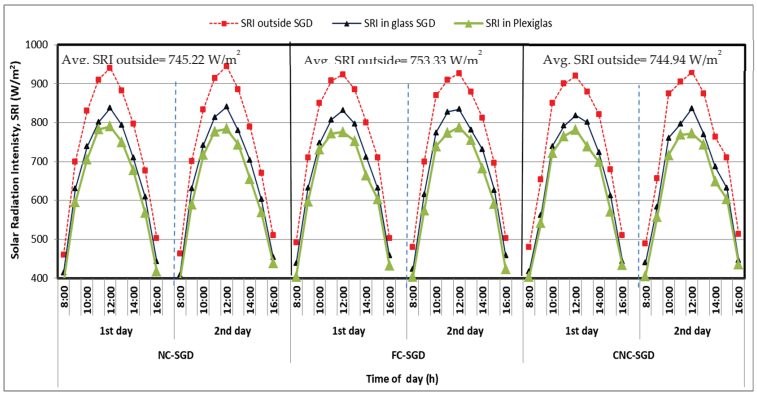

Figure 5. Changes in incident SRI in glass and Plexiglas SGDs during typical experimentation days with different drying modes.

3.2. Thermal Performance of SAHs (for FC Drying Mode)

The SAHs were tested under three different air mass flow rates ($\dot{m}_a$), 0.03, 0.04 and 0.06 kg/s, through a set of preliminary outdoor experiments to determine the most suitable air flow rate for the forced convection drying mode. The obtained results showed that the maximum achievable temperature for the hot air was achieved by using the air mass flow rate of 0.03 kg/s. As illustrated in Figure 6a, the maximum and average incident solar radiation intensity on the plane surface (I_c) of the SAHs was 940 and 789.7 W/m^2, respectively. In the present study, the ambient temperature was considered as the inlet air temperature (T_{ci}) for both SAHs, with the glass and Plexiglas covers. The inlet air temperature was measured and found to be in the range of 32.8–41.1 °C during the typical day drying period from 8 to 16 h, while the outlet air temperature (T_{co}) ranged from 36 to 61 °C and from 36.8 to 62.1 °C for the SAH with the glass and Plexiglas cover, respectively.

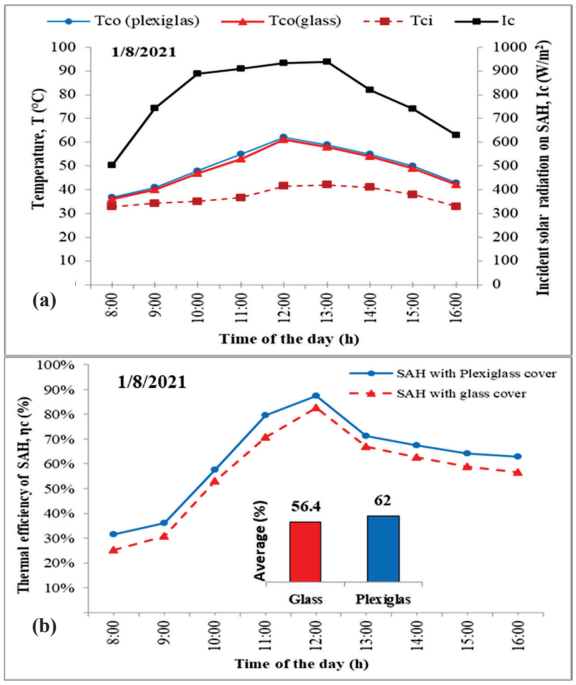

Figure 6. Thermal performance of SAH at a air mass flow rate of 0.03 kg/s. (**a**) Variation in solar radiation and temperatures of SAH; (**b**) thermal efficiency of SAH.

Figure 6b shows that the thermal efficiency (η_c) of the SAHs throughout the daily drying period using an air mass flow rate of 0.03 kg/s reached its maximum value at noon (12 h). Afterwards, it started to reduce gradually, although the solar radiation intensity

increased, reaching its peak value at 12:30 h. This can be attributed to thermal losses. The average thermal efficiency was found to be 56.40 and 62% for the SAH covered with glass and Plexiglas, respectively. Hence, it is clear that the SAH with the Plexiglas cover showed a better thermal performance compared to the same SAH covered by glass. In summary, the Plexiglas SAH showed higher thermal efficiency than the glass SAH by about 9% at $\grave{m}_a$ = 0.03 kg/s.

3.3. Variation in Temperature and Relative Humidity of Ambient Air and Across SGD

Figure 7 illustrates the variation in the temperatures of ambient air (T_a) and drying air inside the glass dryer (T_g) and inside the Plexiglas dryer (T_p), as well as the relative humidity of ambient air (RHa) and humid air inside both the glass dryer (RH_g) and Plexiglas dryer (RH_p). The ranges of the measured temperature and relative humidity for the ambient air were 30–41.40 °C and 40–65% for the natural convection drying mode, while these values were 30.50–41 °C and 42–69% for the forced convection drying mode and 31.3–39.3 °C, 27–64% for the new controlled natural convection drying mode. As a general pattern, the ambient temperature had an opposite trend to the ambient relative humidity till around noon, wherein the ambient temperature in the first hour of the drying period (8 h) was low, while the ambient relative humidity was at a high level, as shown in Figure 7. This pattern continued till 14 h, and then both the ambient temperature and relative humidity decreased. Afterwards, the ambient relative humidity began to increase slightly in the last hour of the drying period (16 h), while the ambient temperature continued to decrease. The obtained ranges of the temperature and relative humidity inside the Plexiglas SGD were found to be 38–52.3 °C and 26–54% for NC-SGD, 45–59 °C and 17–36% for FC-SGD and 42–55.6 °C and 20.4–42% for CNC-SGD. On the other hand, these ranges for the glass SGD were 38–50 °C and 29–52% for NC-SGD, 43–55 °C and 19–39% for FC-SGD and 41.3–55.3 °C and 19–41.3% for CNC-SGD. It should be noted that the highest average temperature for the interior air inside the Plexiglas SGD was 53 °C for FC-SGD, followed by 50.40 °C for CNC-SGD, and the lowest temperature was 46.50 °C for NC-SGD, while inside the glass dryer, the temperatures were 51.20, 50.20 and 44.70 °C for the mentioned modes, respectively. FC-SGD had the highest achieved temperature inside both the Plexiglas and glass dryers under all drying modes due to the vital role of SAH in providing the dryer with an adequate hot air stream. Meanwhile, the new drying mode of CNC showed higher temperatures across the enclosure of the dryer compared to the conventional natural convection drying mode, which were very close to the temperatures inside the FC-SGD whether the dryer was covered with glass or Plexiglas. This occurred despite the fact that the CNC-SGD did not have an auxiliary heating tool (e.g., SAH).

Concerning the relative humidity across the enclosure of dryer, the results showed that the average relative humidity of interior air inside the Plexiglas SGD was found to be 24.80, 25.1 and 35.40% for FC-SGD, CNC-SGD and NC-SGD, respectively, while these averages inside the glass SGD were 24.8, 25.70 and 35.7% for the drying modes mentioned above, respectively. It was observed that CNC-SGD achieved approximately equal values for the relative humidity inside both the glass and Plexiglas dryers. These values were found to be very close to values achieved by the FC drying mode, and the relative humidity was lower than the NC drying mode by about ~10%.

Since higher temperature ranges and lower ranges of relative humidity inside the dryer lead to quick moisture removal, as reported by Badaoui et al. [69], thus, the new mode (CNC) achieved a high difference between the temperature and relative humidity of drying air inside the Plexiglas and glass SGDs, like the FC drying mode. This means that the CNC mode can enhance the drying efficiency and shorten the drying time and can be used for drying products with high moisture content instead of the slow NC drying system or even the high-cost FC drying system.

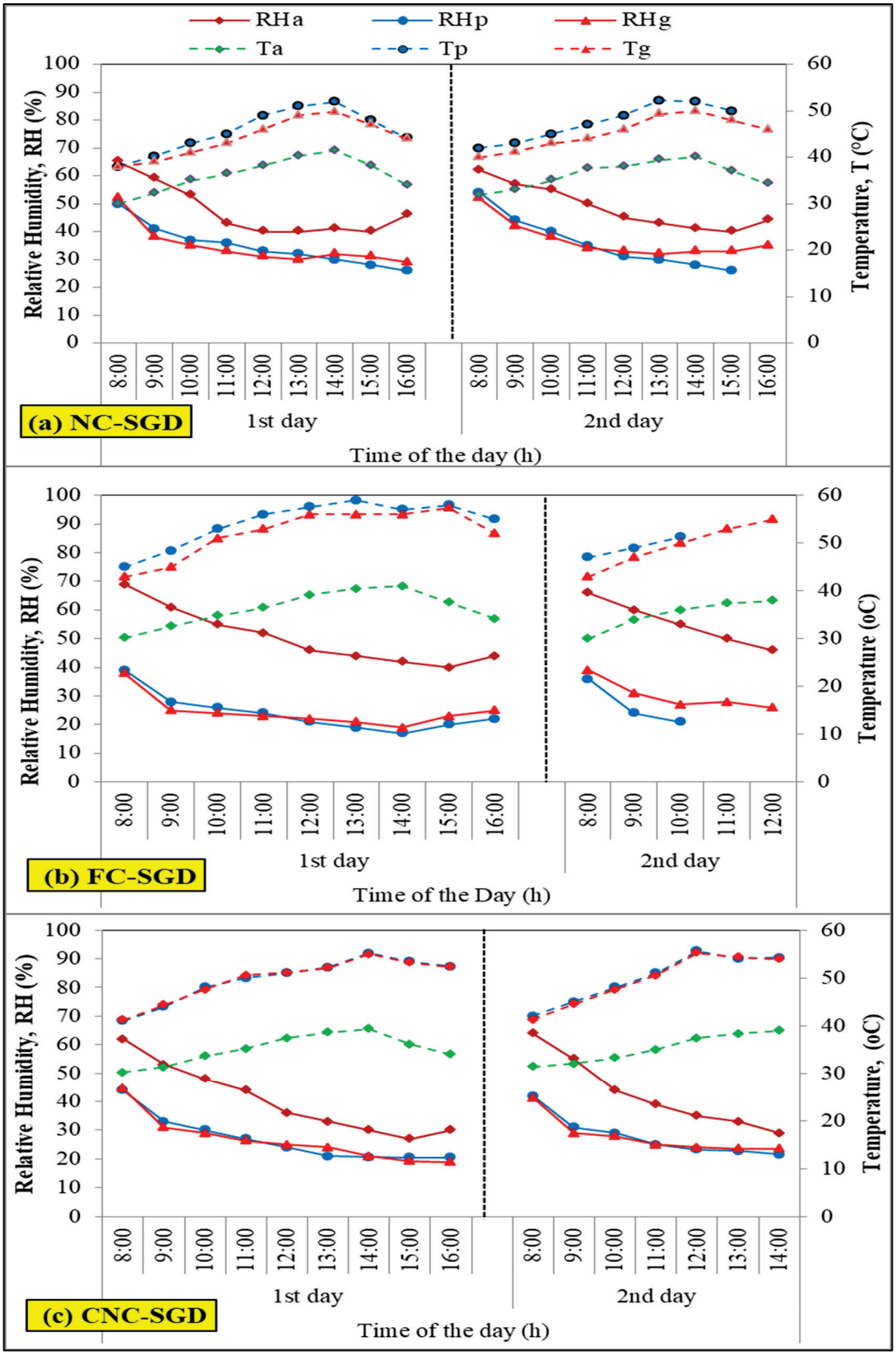

Figure 7. Variation in temperatures and relative humidity of air across the glass and Plexiglas SGDs in drying modes (**a**) NC, (**b**) FC ($\dot{m}_a = 0.03$ kg/s) and (**c**) CNC.

3.4. Variation in Moisture Content, Drying Rate and Moisture Ratio during Grape Drying

Figure 8a depicts the variation in the grapes' moisture content throughout the drying period, which was extended to two consecutive days for each drying experiment using Plexiglas and glass SGDs with the different drying modes. As a general pattern, it was noticed that the moisture content removal rate was quite slow in the first 3 h of the drying process, which can be attributed to the high relative humidity and low temperature of the drying air inside the SGD at the beginning of the drying process. Afterwards, it declined continuously with the drying time without a constant-rate drying period, which was in agreement with the results given by El Khadraoui et al. [31], accompanied by a low drying rate at end of the drying process (i.e., the second day).

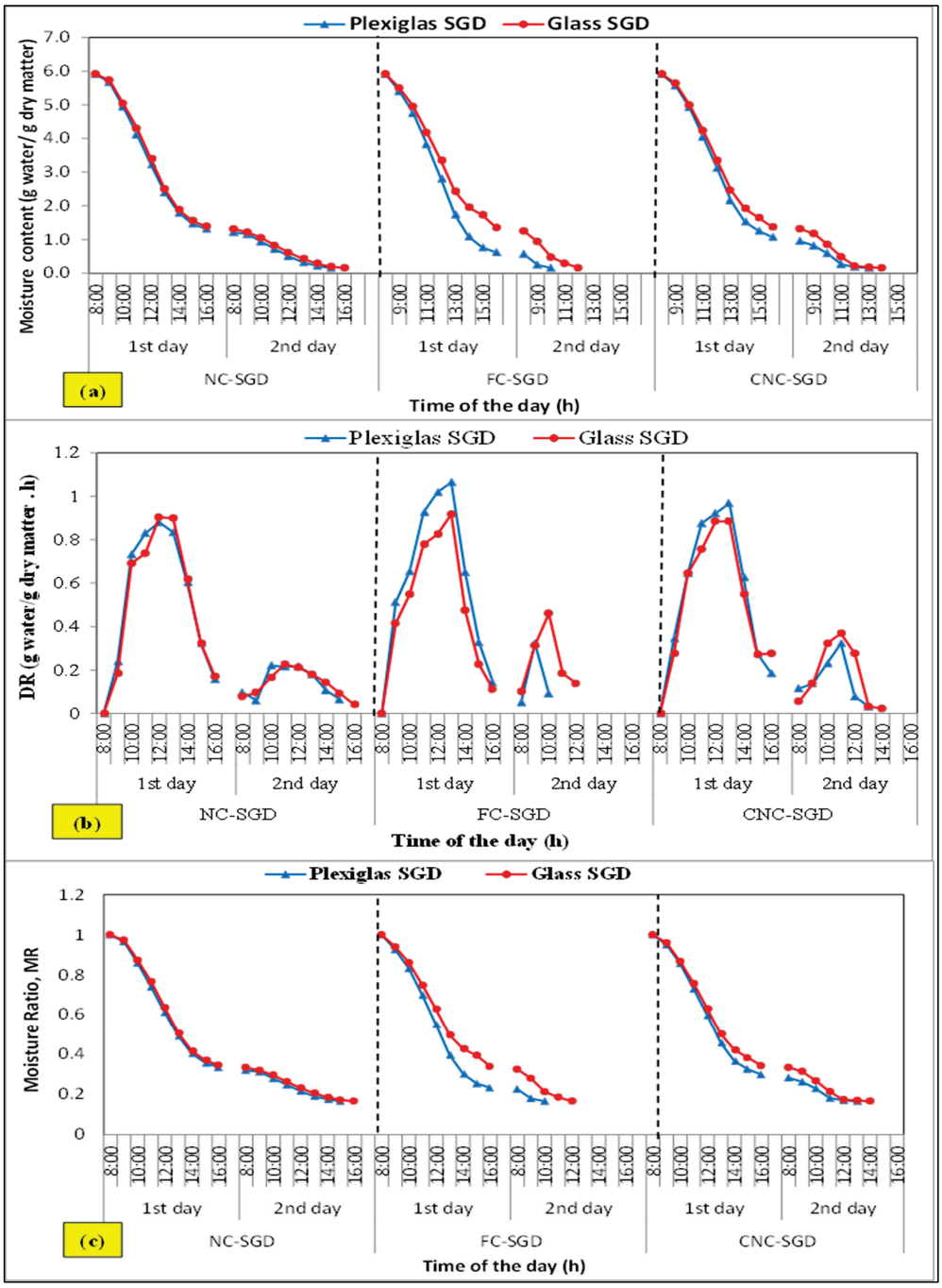

Figure 8. Drying behavior of the Plexiglas and glass SGD with different drying modes: (**a**) moisture content, (**b**) drying rate, (**c**) moisture ratio.

In the case of the glass SGD, the obtained results showed that the initial moisture content of grapes on the dry basis of 5.91 (g water/g dry matter) was reduced a the final moisture content of 0.15 (g water/g dry matter) in 16, 12 and 13 h (see the drying time in Figure 9) by using the three drying modes of NC, FC and CNC, respectively (Figure 8a), whereas the initial moisture content of grapes was reduced inside the Plexiglas SGD to the same final moisture content in about 15, 10 and 12 h by using the three mentioned drying modes, respectively.

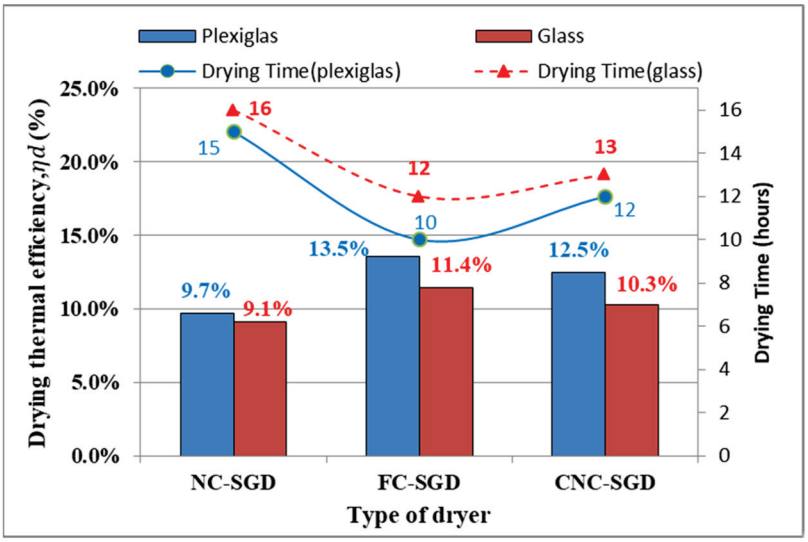

Figure 9. The overall drying thermal efficiency and drying time of the Plexiglas and glass SGDs with different drying modes.

The drying rate of the grapes against the drying time is depicted in Figure 8b. As a general trend for the three drying modes, a rapid drying rate is observed till the peak point around noon. Afterwards, it decreased to reach the lowest rate in the last hour of the drying time without a constant drying period, which is in agreement with El Khadraoui et al. [31] and Hamdi et al. [52]. This is because the drying process in the falling down process is controlled by the internal water diffusion from the interior of the grape to the surface, which is in agreement with Akpinar [74]. The drying rate of CNC-SGD is higher than CN-SGD and very close to the highest rate of FC-SGD, although CNC-SGD had no extra heating device like the FC drying mode did. Thus, the new drying mode of CNC, whether covered by glass or Plexiglas, is considered a potential feature represented in the full control of the recommended temperature and relative humidity inside the dryer throughout the entire period of drying.

The variation in the moisture ratio during the practical experiments (MR_{exp}) for the three drying modes, NC, FC and CNC, vs. the drying time in typical days of the experiment is shown in Figure 8c. Figure 8c depicts that the moisture ratio of the grapes during the drying process has the same trend as that of the moisture content with the three drying modes. The curves of the experimental MR_{exp} were regressed to five thin-layer drying models, which will be discussed in detail in the upcoming Section 3.5, to identify the best model that achieves the lowest difference between the experimental and predicted MR values.

Figure 9 shows the overall drying thermal efficiency (ηd) for the three drying modes, NC, FC and CNC. The FC drying mode had the highest efficiency of 11.4 and 13.5% for glass and Plexiglas SGDs, respectively. This may be due to the significant effect of SAH, besides the heat of direct irradiance, which leads to a rapid drying rate. Meanwhile, the new drying mode CNC also achieved a rapid drying rate of 10.3 and 12.5% for glass and Plexiglas SGDs, respectively, without any additional heating device, whereas the NC drying mode

had the lowest efficiencies of 9.1 and 9.7% for the two types of glass and Plexiglas SGDs, respectively.

It is clear that the CNC drying mode shows better performance for drying high-moisture products such as grapes compared to the NC drying mode, while it can also be used as a good alternative to the complicated FC drying system, which has the SAH and the other components that require more occupation area and high initial and operating costs.

3.5. The Mathematical Thin-Layer Drying Model for Grapes

Five mathematical thin-layer drying models were fitted to experimental values of the moisture ratio to find out the best model able to describe the behavior of the drying process of the Sultana grapes with the three drying modes, NC, FC and CNC, whether the dryer was covered by glass or Plexiglas, as shown in Figure 10. The evaluation of the performance of the used empirical equations of the thin layer models was carried out using three statistical indicators: the coefficient of determination (R^2), chi-squared (X^2) and root mean square error (RMSE). The constants of models and values of statistical indicators are shown in Table 6. From the obtained data, it is clear that the equation of the Page model is considered the best fitting equation to describe the thin-layer drying process of Sultana grapes with all drying modes of NC, FC and CNC, whether in case of using glass or Plexiglas as the covering material, as depicted in Figure 10 and Table 6 in bold font. Concerning the new drying mode of CNC, Table 6 shows a good agreement between the experimental values of the moisture ratio and the predicted ones, where statistical criteria values for the Plexiglas SGD were R^2 = 0.9775, X^2 = 0.006 and RMSE = 0.0242, but for the glass SGD, they were R^2 = 0.9716, X^2 = 0.0010 and RMSE = 0.0299.

Table 6. The constants of the different thin-layer models and the statistical indicators for drying grapes using the glass and Plexiglas SGDs.

Drying Mode	Model Name	Type of Cover	Constants					R^2	X^2	RMSE
			k'	n'	a'	b'	c'			
NC-SGD	Lewis	Plexiglas	0.1405					0.7237	0.0741	0.2640
		glass	0.1375					0.7000	0.0686	0.2545
	Page	Plexiglas	0.4015	0.9702				0.9479	0.0018	0.0395
		glass	0.3496	1.0102				0.9373	0.0022	0.0443
	Wang and Singh	Plexiglas			−0.162	0.0074		0.8810	0.0517	0.2063
		glass			−0.178	0.0086		0.9068	0.0488	0.2016
	Henderson and Pabis	Plexiglas	0.3200		0.6780			0.9665	0.0129	0.1068
		glass	0.3060		0.6828			0.9669	0.0134	0.1092
	Parabolic	Plexiglas			0.8193	−0.1618	0.0074	0.8810	0.0116	0.0976
		glass			0.8686	−0.1784	0.0086	0.9068	0.0183	0.1236
FC-SGD	Lewis	Plexiglas	0.2010					0.8614	0.0660	0.2450
		glass	0.1747					0.8561	0.0596	0.2346
	Page	Plexiglas	0.5200	1.0030				0.9926	0.0001	0.0094
		glass	0.4525	0.9555				0.9893	0.0002	0.0147
	Wang and Singh	Plexiglas			−0.235	0.0150		0.9450	0.0309	0.1523
		glass			−0.193	0.0104		0.9311	0.0372	0.1709
	Henderson and Pabis	Plexiglas	0.5010		0.8977			0.9871	0.0016	0.0386
		glass	0.3900		0.8944			0.9822	0.0014	0.0364
	Parabolic	Plexiglas			0.8654	−0.2351	0.0150	0.9450	0.0059	0.0730
		glass			0.8475	−0.1926	0.0104	0.9311	0.0066	0.0780
CNC-SGD	Lewis	Plexiglas	0.1643					0.7933	0.0691	0.2533
		glass	0.1579					0.7874	0.0626	0.2418
	Page	Plexiglas	0.4425	0.9854				0.9775	0.0006	0.0242
		glass	0.3886	1.0030				0.9716	0.0010	0.0299
	Wang and Singh	Plexiglas			−0.186	0.0096		0.9142	0.0421	0.1835
		glass			−0.172	0.0082		0.9073	0.0397	0.1797
	Henderson and Pabis	Plexiglas	0.3880		0.7786			0.9779	0.0065	0.0779
		glass	0.3620		0.8321			0.9758	0.0044	0.0644
	Parabolic	Plexiglas			0.8390	−0.1860	0.0096	0.9142	0.0082	0.0873
		glass			0.8392	−0.1722	0.0082	0.9073	0.0087	0.0901

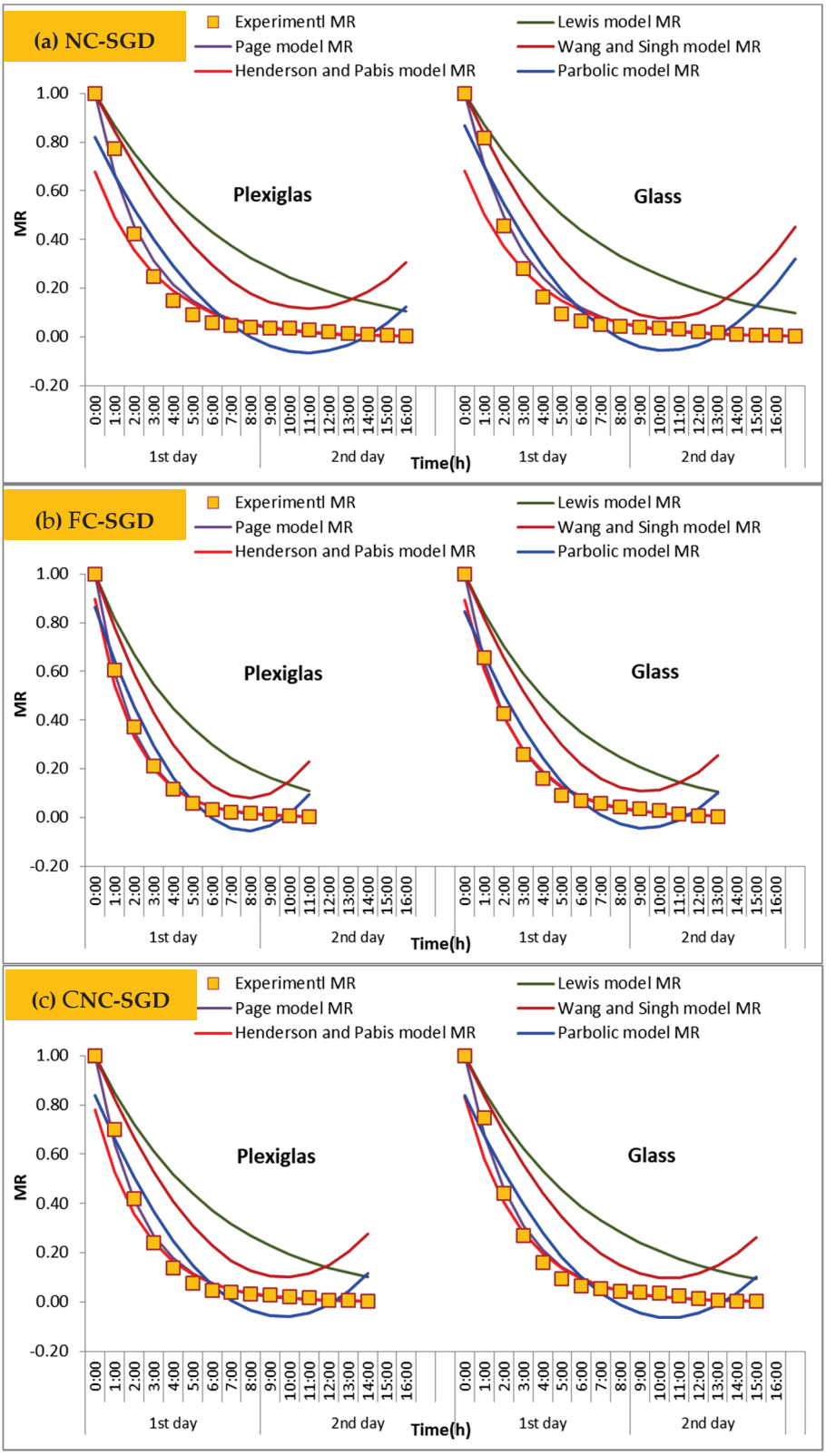

Figure 10. The variation in the experimental and predicted MR versus the drying time using glass and Plexiglas SGDs with the different drying modes.

3.6. Economic Assessment

The economic assessment was performed for the Plexiglas and glass SGDs with the three drying modes of NC, FC and CNC to obtain deep insights into the best operational

mode of an SGD suitable for domestic/small-scale drying purposes from an economic perspective. The economic assessment was carried out in terms of the criterion cost of 1 kg of the dried grapes/solar-dried raisins (C_d), the total saved cost over the lifespan of the dryer (S_j) and the payback period (N_p) to recover the invested costs. From Figure 11a–c, it can be observed that the Plexiglas SGD achieved better results for the economic parameters with all drying modes compared to the glass SGD.

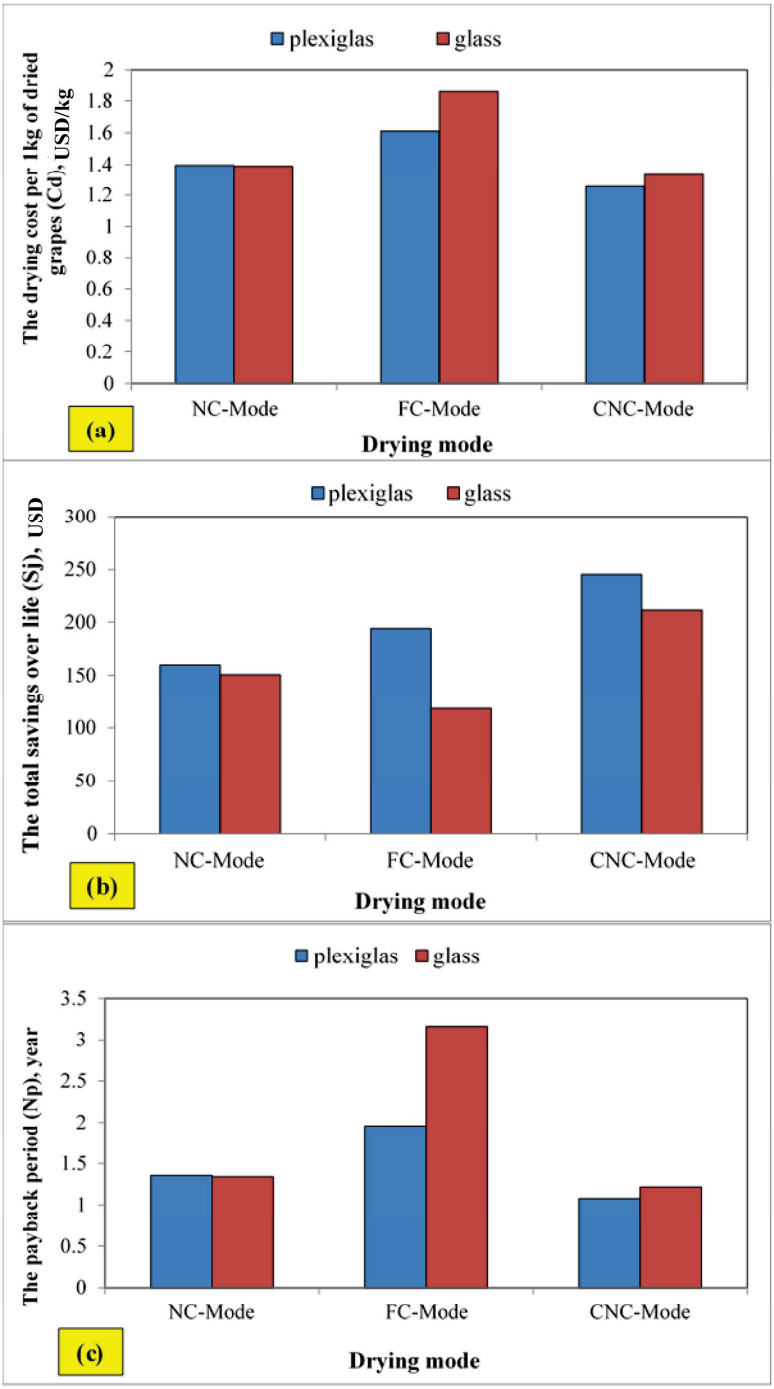

Figure 11. Economic assessment of Plexiglas and glass SGDs with different drying modes: (**a**) drying cost per unit of mass of dried grapes, (**b**) total saving cost, (**c**) payback period.

The calculations of the economic assessment revealed that the glass SGD using the FC drying mode had the highest value of C_d (1.86 USD/kg), low S_j (USD 117.96) and the longest N_p (3.16 years) compared to the other two drying modes. This can be attributed

to the heating auxiliary collector (SAH), in addition to its fittings and the photovoltaic (PV) system. Although the CNC-SGD was operated using a PV system like FC-SGD, the lowest value of C_d (1.26 USD/kg), the highest value of Sj (USD 245.46) and the shortest N_p (1.08 year) were achieved in case of using the Plexiglas CNC-SGD.

Despite the fact that the NC-SGD has lower initial, operating and maintenance costs than the two other dryers, FC-SGD and the new CNC-SGD, whether using the glass or Plexiglas cover, it has lower thermal performance and a slow drying rate because it depends completely on the fluctuating direction and velocity of the ambient air.

It is clear that the development and conversion of conventional NC-SGD to the new fully controlled natural convection drying mode (CNC) gave the advantage to this new mode of controlling the pre-adjusted recommended temperature and humidity inside the SGD continuously throughout the entire drying period daily (8 h). This led to more evaporation of water from grapes at a uniform and quick rate and, consequently, a productivity and drying time higher and shorter, respectively, than the NC drying mode and slightly lower than the FC mode, particularly by using the Plexiglas SGD due to its ability to conserve the accumulated heat inside the dryer for a longer time. Moreover, the new drying mode of CNC is not augmented with a heating device, which reduces the initial cost, and leads to a lower C_d, higher S_j and shorter N_p than the FC mode.

4. Conclusions

The present study proposed a new drying mode named controlled natural convection (CNC) for drying grapes (Sultana variety) as a high-moisture content agro-product using a direct solar greenhouse dryer (SGD) with two types of cover material, glass and Plexiglas. The thermal performance of the new drying mode using a solar greenhouse dryer (CNC-SGD) was investigated to be used as a potential alternative for the conventional natural convection solar greenhouse dryer (NC-SGD), which is featured as a slow drying mode, and also compared to the expensive and complicated forced convection solar greenhouse dryer (FC-SGD). CNC-SGD was provided with an automatic control unit operated by a PV system to assure full control of the operating conditions inside the dryer. In general, the obtained results revealed that the Plexiglas SGD showed better results compared to the glass SGD under all operating conditions. In the case of the CNC mode using the Plexiglas SGD, the obtained results showed that the initial moisture content of grapes on the dry basis of 5.91 g water/g dry matter was reduced to a final moisture content of 0.15 g water/g dry matter in about 12 h with a thermal drying efficiency of 12.5%, which is very close to the FC drying mode (10 h and 13.5%) and higher than the NC drying mode (15 h and 9.7%).

The Page model was found to be the most appropriate mathematical model to describe the behavior of the drying process of the NC, FC and CNC modes whether with the Plexiglas SGD or glass SGD. A good agreement between the experimental and predicted MR values was found in the new CNC mode using the Plexiglas SGD, as $R^2 = 0.9775$, $X^2 = 0.0006$ and RMSE = 0.0242.

Concerning the economic assessment, the new CNC drying mode using the Plexiglas SGD has the lowest cost per 1 kg of dried grapes (1.26 USD/kg), the highest saved costs over the lifespan of the dryer (USD 245.46) and the shortest payback period (1.08 year), whilst the highest cost per 1 kg of dried grapes (1.86 USD/kg), the lowest saved costs (USD 117.96), and the longest payback period (3.16 years) was recorded for the FC mode with the glass SGD.

In light of the above, it is obvious that the operation of an SGD—particularly the Plexiglas SGD—with the new drying mode of CNC is considered a good alternative drying method to an SGD with both the FC and NC drying modes from the thermal and economic perspectives for drying high-moisture content agro-products such as grapes.

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Nomenclature

A_c	Surface area of the solar air heater/collector (m^2)
A_d	Area of dryer (m^2)
$\grave{a}$	Experimental constant
$\grave{b}$	Experimental constant
$\grave{c}$	Experimental constant
Cp_a	Specific heat of air (J/kg K)
C_a	Annualized cost (USD)
C_{ac}	Annualized capital cost (USD)
C_{cc}	Capital cost of dryer (USD)
C_d	Drying cost per 1 kg of dried grapes (USD/kg)
C_{ds}	Cost of 1 kg of solar dried grapes (USD/kg)
C_{fg}	Fresh product rate (USD/kg)
$C_{O\&M}$	Annualized operating and maintenance cost (USD)
C_{mar}	Commercial cost of 1 kg of the dried grapes (raisins) in the market (USD)
C_{re}	Annualized running cost (USD)
CRF	Capital recovery factor
D	Number of days for drying in use in one year (days)
DR	Drying rate (kg/kg. h)
D_b	Time taken for drying one batch of grapes sample (h)
d	Inflation rate (%)
h_l	Latent heat of vaporization (kJ/kg)
Ic	Total incident solar radiation intensity on the solar air heater(W/m^2)
Iv	Average incident solar radiation intensity on the dryer (W/m^2)
i	Discount rate (%)
j	Lifespan of the drying system (years)
$\grave{k}$	Experimental constant
M	Moisture content (g)
M_0	Initial moisture content of product on dry basis (kg water/kg dry matter)
M_b	Mass of dried grapes from one batch (kg)
M_e	Moisture content at equilibrium state on dry basis
M_i	Initial mass of one batch of grapes (kg)
M_t	Moisture content of product at time t on dry basis (kg water/kg dry matter)
MR_{exp}	Experimental moisture ratio, % (wb)
MR_{pre}	Predicted moisture ratio, % (wb)
$\dot{m}_a$	Mass flow rate of air (kg/s)
m_d	Mass of dry matter (kg)

m_p	Mass of product (kg)
N_p	Payback period (years)
$\grave{n}$	Experimental constant
P	Annual mass of dried grapes produced by the dryer (kg/year)
R^2	Coefficient of determination
RH_a	Relative humidity of ambient air (%)
RH_g	Relative humidity of air inside the glass dryer(%)
RH_p	Relative humidity of air inside the Plexiglas dryer(%)
S	Salvage value (USD)
S_1	Savings during first year using solar dryer (USD)
S_a	Annualized salvage value (USD/year)
S_{db}	Savings per day during base year using solar dryer (USD)
SFF	Sinking fund factor
T_a	Ambient temperature (°C)
T_{ci}	Inlet temperature of solar air heater (°C)
T_{co}	Outlet temperature of solar air heater (°C)
T_g	Temperature inside the glass dryer (°C)
T_p	Temperature inside the Plexiglas dryer (°C)
t	Time (s)
X^2	Chi-squared
Greek symbols	
η_c	Thermal efficiency of solar air heater (%)
η_d	Drying thermal efficiency (%)
Δt	Time interval (h)
Abbreviations	
FC-SGD	Forced convection solar greenhouse dryer
FC	Forced convection
CNC-SGD	Controlled natural convection solar greenhouse dryer
CNC	Controlled natural convection
NC-SGD	Natural convection solar greenhouse dryer
NC	Natural convection
GHG	Greenhouse gases
RH	Relative humidity
RMSE	Root mean square error
SAH	Solar air heater
SGD	Solar greenhouse dryer
SRI	Solar radiation intenisty

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Research on the Assessment Method of Sugarcane Cultivation Suitability in Guangxi Province, China, Based on Multi-Source Data

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Abstract: Conducting suitability assessment for sugarcane cultivation is of great significance for optimizing the sugarcane cultivation structure and industrial layout. In this paper, based on the requirements of sugarcane growth and development on climate, terrain, and other environmental conditions, as well as the influence of natural disasters, a total of 11 specific indicators in terms of climate factor, terrain factor, and disaster factor were selected to construct a sugarcane cultivation suitability assessment system based on the analytic hierarchy process (AHP). Then, using Guangxi Province, China, as an example, a suitability assessment for sugarcane cultivation was conducted using multi-source data on climate, terrain, and hazards over the past 30 years. The results showed that among 11 indicators, including annual average temperature, elevation had the largest contribution rate, followed by precipitation during the period of $\geq$20 °C, slope, and the autumn drought frequency. From the spatial distribution, 37% of the provincial regions were suitable for sugarcane cultivation, mainly distributed in Chongzuo City, Nanning City, Qinzhou City, and Beihai City. In total, 44% of the provincial regions were moderately suitable for sugarcane cultivation, mainly distributed in Hezhou City, Laibin City, and Liuzhou City. Additionally, only 19% of the provincial regions were unsuitable for sugarcane cultivation, mainly distributed in Baise City, Hechi City, and Guilin City, with the terrain factor being the main influencing factor of sugarcane suitability assessment. In order to make reasonable use of land resources and increase sugarcane yield, it is suggested that sugarcane cultivation areas should be adjusted to the central and southern regions such as Chongzuo City, Nanning City, Beihai City, and Qinzhou City, and other industries should be developed in the northern regions which are not suitable for sugarcane cultivation.

Keywords: sugarcane; cultivation suitability; assessment cultivation; multi-source data

1. Introduction

Sucrose is a natural monosaccharide derived from plants such as sugarcane and sugar beet. It is widely used in the food, beverage, pharmaceutical, and cosmetic industries. The production and supply of sucrose is critical to ensuring the domestic supply of food and agricultural products and is an indispensable part of the national economy and food production [1]. Sugarcane, as the main raw material for sugar production, is an important economic crop worldwide. It is also a tropical and subtropical crop [2]. In addition to its use as a raw material for the production of sugar, sugarcane has a wide variety of uses and benefits, including for bioenergy, fiber materials, and medical materials. Therefore, sugarcane plays an important role in human life and economic development [3]. In China,

sugarcane is the main sugar crop, accounting for more than 90% of the country's sugar production [4,5]. Guangxi Province, as the main sugarcane producing region in China, has for many years had a sugarcane acreage and yield exceeding 60% of the national total, ranking first in the country. Therefore, the sugarcane industry in Guangxi Province is not only an important pillar of the region's economic development but also plays an important role in promoting the development of the national sugarcane industry [6]. Therefore, the scientific assessment of the suitability of sugarcane cultivation in Guangxi Province is of great importance, especially in providing important information and references for resolving the conflicts between people and land and sugarcane cultivation.

In the past, domestic and foreign scholars have mostly used the comprehensive weighted index method to study the suitability of crop cultivation. They established an appropriate assessment system by considering multiple factors such as soil, meteorology, and economics; determined the weight of each factor using methods such as AHP; and finally, obtained the suitability of crop cultivation based on GIS. For example, Hikmet et al. [7], Huang et al. [8], Deng et al. [9], and others have conducted research on the suitability of various crops such as wheat, torreya, and rice. In addition, domestic and foreign scholars have also used this method to study the suitability of sugarcane cultivation. For example, Mubashir et al. [10] assessed the suitability of sugarcane cultivation in the Bijnor region of India based on 10 factors, including rainfall, soil texture, drainage, soil depth, slope, distance to the main road, distance to the nearest sugar factory, erosion hazards, flood risks, and pH. Jim et al. [11] assessed the suitability of sugarcane cultivation in central Bukidnon, Philippines, based on six factors including soil depth, water-holding capacity, slope direction, soil texture, slope, and elevation. Xie et al. [12] assessed the suitability of sugarcane cultivation in the Jiangzhou District, Chongzuo City, Guangxi Province, based on four factors: soil, topography, climate, and economy. In addition to the above methods, some scholars have used different methods to study the suitability of sugarcane cultivation. For example, Tan et al. [13] used 44 years of meteorological station statistics combined with the characteristics of sugarcane cultivation to study the optimization of the meteorological disaster layout for the sugarcane industry in Guangxi Province. Liu et al. [14] compared and analyzed 35 years of measured data from 14 meteorological stations in Hainan with the main climate indicators for sugarcane cultivation and assessed the climate suitability for sugarcane cultivation in Hainan Province. An analysis of previous sugarcane cultivation suitability studies shows that there are more studies using climate and terrain factors to assess the suitability of sugarcane cultivation, including recent references and data from international reports. However, due to the special geographical environment and frequent meteorological disasters in Guangxi Province, it is necessary to include a disaster factor in the assessment of sugarcane cultivation suitability. However, there are few reports in the current research on sugarcane cultivation suitability that combines the disaster factor with climate and terrain.

In this paper, we hypothesize that climate factors, terrain factors, and disaster factors are key factors that affect the suitability of sugarcane cultivation in Guangxi Province, China. Specifically, we expect that temperature, precipitation, terrain elevation difference, slope, aspect, disaster frequency, altitude, and other factors will significantly affect the suitability of sugarcane cultivation, and we further hypothesize that the direction and degree of these effects may vary across different regions of Guangxi Province. Our study aims to verify these hypotheses through the construction of an assessment system and the analysis of the results, and to provide decision-making support for optimizing the sugarcane cultivation structure.

2. Materials and Methods

2.1. Research Area Overview

Guangxi Province is located in the southern region of China, between 104°28′~112°04′ E and 20°54′~26°23′ N, bordering Guangdong Province to the east, facing the Beibu Gulf to the south and across the sea from Hainan Island, adjacent to Yunnan Province to the

west, connected to Hunan Province to the northeast, and bordering Guizhou Province to the northwest [15]. It is located at a low latitude and a large north–south latitude, with significant climate differences across the region [16]. It belongs to the subtropical and tropical monsoon climate zone of Central and South Asia, with an average annual temperature of 16.5–23.1 °C, an average annual precipitation of 1000–2800 mm, and an average annual sunshine duration of 1169–2219 h [17]. The unique climate provides favorable conditions for the cultivation of various crops such as sugarcane, citrus, bananas, and rice. Sugarcane is the main economic crop in Guangxi Province and the main source of income for farmers [18]. Guangxi Province is mainly composed of different types of landforms, such as mountains, hills, tablelands, and plains. The central and southern parts of Guangxi Province are mainly hilly and flat land, with a basin-like shape, and are known as the "Guangxi Basin". Under the combined influence of solar radiation, atmospheric circulation, and geographic environment, Guangxi Province has formed a climate characterized by distinct dry and wet seasons, moderate sunshine, few winters and many summers, frequent disasters, and prominent droughts and floods, with abundant wind energy resources along the coast and in the mountains [19]. The scope of this study covers the whole of Guangxi Province, China, as shown in Figure 1.

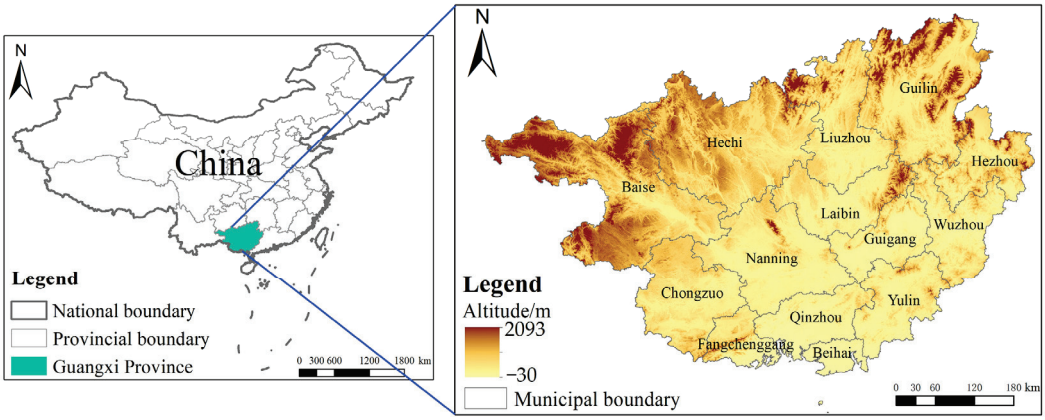

Figure 1. Geographical location and elevation distribution map of study area.

2.2. Construction of Suitability Assessment System for Sugarcane Cultivation

The growth of sugarcane is affected by various factors, including climate, terrain, and disasters. Climatic factors such as precipitation, temperature, light, and humidity have a significant impact on the growth rate of sugarcane, photosynthesis efficiency, and incidence of pests and diseases [12,14,20–27]. Terrain factors such as altitude, soil texture, slope, slope direction, and soil moisture have a direct impact on the growing environment, soil quality, and water supply of sugarcane [10–12,28,29]. Disaster factors such as drought, flood, freeze, pests, and diseases have a direct impact on sugarcane yield and quality [13,30–34]. Among them, annual average temperature [20–25] can reflect the temperature conditions throughout the growing season, and annual average minimum temperature [20,23,25] reflects the sensitivity of sugarcane to low temperature. The ≥20 °C accumulated temperature [20–23,25–27] reflects the effective temperature obtained by sugarcane during the growing season [35], and the number of consecutive days with average temperature ≥25 °C [20,25,27] reflects the influence of high temperature on sugarcane growth. Precipitation during the period of ≥20 °C [20,24,25] reflects the influence of water on sugarcane during the growing season. Altitude [11,28] reflects the influence of height difference on sugarcane growth, and slope [10,11,29] reflects the influence of slope gradient on water and soil nutrients. Slope direction [11,28] reflects the influence of slope orientation on sunlight and temperature. Spring drought [13,30–32] reflects the cultivation and emergence situation of spring sugarcane, and autumn drought [13,30–32] reflects the elongation and sugar accumulation situation of sugarcane in the later stage. Frost [13,33,34] reflects the influence of low-temperature environments on sugarcane. The frequency of disasters can more comprehensively reflect the occurrence of disasters in the region and is more repre-

sentative and operational [36]. These indicators consider sugarcane growth from different perspectives. Comprehensive consideration can more accurately reflect the growth status of sugarcane. Therefore, in this paper, these 11 indicators have been used as indicators for assessing the suitability of sugarcane.

Using the 11 selected indicators, a suitability assessment system for sugarcane cultivation in Guangxi Province was established based on the AHP. The system is a three-level hierarchical structure model, including the target level, the criterion level, and the indicator level. Thus, the sugarcane suitability assessment flowchart is shown in Figure 2. The weight of the indicators in the hierarchical structure was obtained through the expert rating method, and the sugarcane suitability criteria for each indicator in the indicator level were determined by referring to previous relevant studies [12–14,20–27]. According to the classification criteria, each indicator was classified into four levels based on its suitability for sugarcane: most suitable, suitable, moderately suitable, and unsuitable. Due to the different units and scales of the different indicators in the indicator layer, it is necessary to convert the indicator data into dimensionless indicator scores in order to facilitate subsequent calculations. In this paper, we used the assignment method to convert them into dimensionless scores, with the most suitable level assigned 100 points, the suitable level assigned 75 points, the moderately suitable level assigned 50 points, and the unsuitable level assigned 25 points. Based on the above description of the construction of the indicator system, the indicator system used in this paper can be obtained, as shown in Table 1.

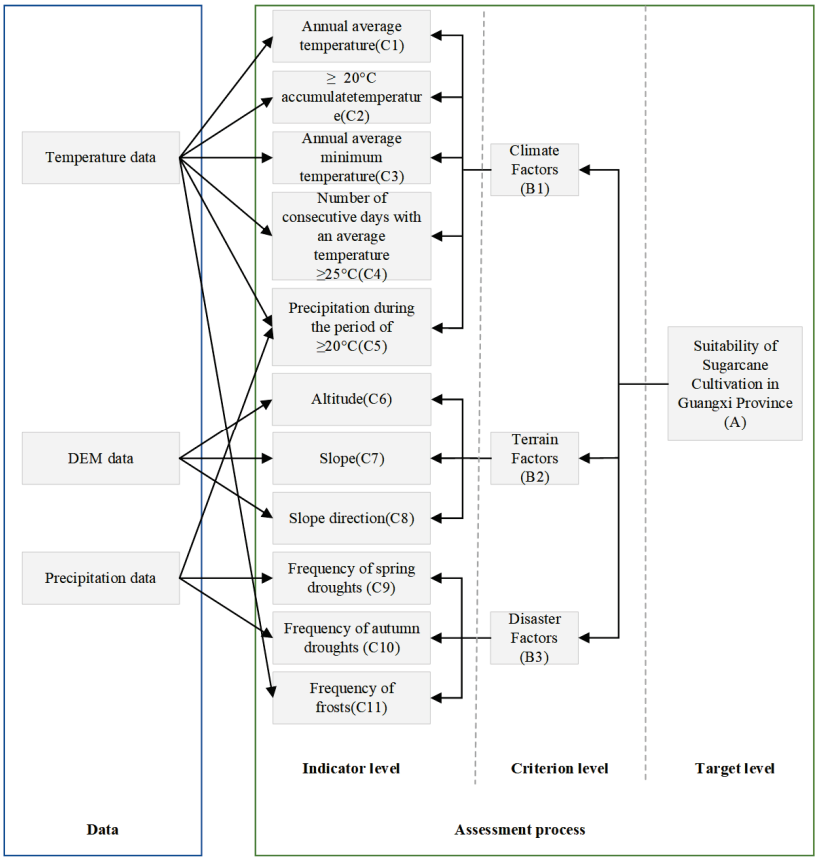

Figure 2. Sugarcane planting suitability assessment flowchart.

In Table 1, the occurrence of spring drought is characterized by a precipitation of less than 30 mm in March, the occurrence of autumn drought is characterized by the consecutive number of days with a daily precipitation of less than 5 mm from September to October exceeding 25 days, and the occurrence of frost is characterized by using the lowest temperature below 0 °C occurring continuously for more than one day in January to February.

Table 1. Indicators system for suitability assessment of sugarcane cultivation in Guangxi Province.

Target Level	Criterion Level	Weight	Indicator Level	Weight	Most Suitable Level 100 Points	Suitable Level 75 Points	Moderately Suitable Level 50 Points	Unsuitable Level 25 Points
Suitability of sugarcane cultivation in Guangxi Province (A)	Climate factors (B1)	0.31	Annual average temperature (C1)/°C	0.079	(21, +∞)	(19, 21]	(18, 19]	(−∞, 18]
			≥20 °C accumulated temperature (C2)/°C	0.245	(5000, +∞)	(4000, 5000]	(3000, 4000]	(−∞, 3000]
			Annual average minimum temperature (C3)/°C	0.137	(0, +∞)	(−1.0, 0]	(−1.5, −1.0]	(−∞, −1.5]
			Number of consecutive days with an average temperature ≥25 °C (C4)/days	0.137	(150, +∞)	(130, 150]	(110, 130]	[0, 110]
			Precipitation during the period of ≥20 °C (C5)/mm	0.402	(1200, +∞)	(1100, 1200]	(1000, 1100]	[0, 1000]
	Terrain factors (B2)	0.49	Altitude (C6)/m	0.540	(−∞, 150]	(150, 250]	(250, 350]	(350, +∞)
			Slope (C7)/°	0.297	(−∞, 6]	(6, 15]	(15, 25]	(25, +∞)
			Slope direction (C8)	0.163	Flat terrain, southern slope	Southeastern slopes, southwestern slopes	Eastern slope, western slope, northeastern slope, northwestern slope	Northern slope
	Disaster factors (B3)	0.20	Frequency of spring droughts (C9)/%	0.297	(0, 10]	(10, 25]	(25, 50]	(50, 100]
			Frequency of autumn droughts (C10)/%	0.540	(0, 20]	(20, 40]	(40, 60]	(60, 100]
			Frequency of frosts (C11)/%	0.163	(0, 10]	(10, 25]	(25, 50]	(50, 100]

2.3. Determining the Weight of Indicators

In this paper, a hierarchical structure model based on the AHP was constructed on assess the suitability of sugarcane cultivation in Guangxi Province. The model took the suitability assessment of sugarcane cultivation in Guangxi Province as the target level, with climate, terrain, and disaster factors as the criterion level, and 11 subdivided assessment indicators as the indicator level. The quantitative assessment of each level of indicators was then carried out using the expert rating method, and the relative weights between indicators were calculated. Specifically, a pairwise comparison matrix was established based on the subjective judgments of experts on the relative importance of each indicator [37–39]. According to the results of the experts' relative importance of each indicator, the weight value of each indicator was calculated using the square root method [40–42]. After obtaining the weight values, the consistency index (CI) and the random consistency ratio (CR) of the judgment matrix must be tested [43–45]. The larger the CI, the worse the consistency, while a CR less than 0.1 indicates that the judgment matrix has a satisfactory consistency [46,47].

In this paper, four judgment matrices were constructed to measure the relationship between the target level and the criterion level, and the relationship between the criterion level and the indicator level. Using these judgment matrices, we obtained the weights and their consistency test results, as shown in Table 2. It can be seen that all judgment matrices passed the consistency test, providing a reliable foundation and support for the establishment of the assessment system. In the table, we have used A for the target level, B for the criterion level, and C for the indicator level.

Table 2. Weight and consistency test results of judgment matrices.

Judgement Matrix	CI	CR	Judgement Matrix Weights
A-B	0.0268	0.0462	B1:0.31 B2:0.49 B3:0.20
B1-C	0.0075	0.0067	C1: 0.079 C2:0.245 C3: 0.137 C4:0.137 C5:0.402
B2-C	0.0046	0.0079	C6:0.540 C7:0.297 C8:0.163
B3-C	0.0046	0.0079	C9:0.297 C10:0.540 C11:0.163
Consistency test passed			

2.4. Comprehensive Assessment and Classification Standards

This paper used temperature, precipitation, and DEM data to assess the suitability of sugarcane cultivation. Temperature data were obtained from the ERA5 land dataset [48], while precipitation data were obtained from the CHIRPS precipitation dataset [49]. Daily average temperature, daily minimum temperature, and daily precipitation data for the past 30 years (1990–2019) were obtained using the Google Earth Engine (GEE) platform. The spatial resolution of the temperature data was 25 km, while the spatial resolution of the precipitation data was 5 km. The DEM data were sourced from the ALOS PALSAR data in the NASA Earth Science database [50], which were obtained using the download tool provided on the NASA Earth Science database website (https://earthdata.nasa.gov/ (accessed on 25 October 2022)). The DEM data had a time range of 2009 and a spatial resolution of 12.5 m.

The data processing in this paper consisted of three steps. The first step was to process the raw data to obtain usable indicator data. The elevation data were obtained directly from the DEM data, while the slope and slope direction data were derived using surface analysis techniques in GIS based on the DEM data [51–53]. In addition, the remaining eight indicators were calculated using the daily average temperature data, daily minimum temperature data, and daily precipitation data based on the GEE platform [54–58]. The second step was to optimize the indicator data to obtain assessment data. This included spatial interpolation [59–61] of the temperature and precipitation data to smooth the data and unify the spatial resolution of all indicator data to 100 m. The third step was to perform weighted calculations on the assessment data to obtain the final assessment scores. Specifically, the indicator data were assigned values according to the classification standards of the indicator level, and the indicator scores were weighted and summed using the weighted sum equation [62–64] (see Equation (1)) to obtain the criterion level scores. The criterion level scores were then weighted and summed using the weighted sum equation (see Equation (2)) to obtain the final assessment scores.

$$X_B = \sum_{i=1}^{n} w_{C_i} x_{C_i}, \tag{1}$$

$$X_A = \sum_{i=1}^{k} w_{B_i} x_{B_i}, \tag{2}$$

where w_{C_i} is the weight of the indicator level, x_{C_i} is the value of the indicator level, X_B is the value of the criterion level, n is the number of indicator levels contained in each criterion level, w_{B_i} is the weight of the criterion level, x_{B_i} is the value of the criterion level, X_A is the value of the target level, and k is the number of criterion levels contained in the target level.

In response to the inconsistency of assessment systems among different countries and regions, which hinders international academic exchange, the Food and Agriculture Organization of the United Nations (FAO) proposed the "guidelines for land evaluation" system at the Wageningen Expert Consultation in 1972. It was pointed out that the land suitability class reflects the degree of suitability within the guidelines, and it can be divided into three levels: highly suitable, moderately suitable, and marginally suitable. In this study, we referred to the subdivision of the highly suitable class into two levels, namely most suitable and suitable, and renamed the marginally suitable class as not suitable. Finally,

four levels of sugarcane suitability were obtained in this study, namely most suitable, suitable, moderately suitable, and not suitable.

The classification standard for the assessment system in this paper is different from the classification standard for the indicator level. Initially, four discrete values were used as the classification standard for sugarcane suitability, which was not suitable for the continuous values of the criterion level and the target level to classify sugarcane suitability. Therefore, in order to more accurately reflect the suitability of sugarcane cultivation in Guangxi Province and the differences in suitability, it was necessary to adjust the classification standard for suitability levels. This paper adopted the classification standard for sugarcane cultivation areas in Guangxi Province proposed by Su Yongxiu et al. [20], which is shown in Table 3.

Table 3. Classification standard for suitability of sugarcane plantation.

Grade	Most Suitable Level	Suitable Level	Moderately Suitable Level	Unsuitable Level
Score/points	100	[75, 100)	[50, 75)	[25, 50)

3. Results and Analysis

3.1. Assessment of Sugarcane Cultivation Suitability Based on Climatic Factor

Based on the sugarcane cultivation suitability assessment system, the climate factor of sugarcane cultivation suitability in Guangxi Province was assessed. Firstly, the suitability score maps of five indicators were obtained (Figure 3a–e). By considering the weights of each indicator, the assessment score data of sugarcane cultivation suitability in Guangxi Province were obtained based on the climatic factor. Finally, the assessment score data were divided into different levels according to the classification standard for sugarcane cultivation suitability to obtain the assessment results (Figure 3f).

Analysis of Figure 3a–e shows that the northern region of Guangxi Province is mostly mountainous, with lower temperatures and less precipitation, resulting in lower scores for four indicators of sugarcane cultivation suitability, namely the annual average temperature, annual minimum temperature, $\geq$20 °C accumulated temperature, and precipitation during the period of $\geq$20 °C. On the other hand, the southern coastal area of Beihai City is heavily influenced by the ocean, with higher and more stable temperatures, resulting in higher scores for the indicator of the number of consecutive days with an average temperature $\geq$25 °C. An analysis of Figure 3f shows that the suitability for sugarcane cultivation in Guangxi Province based on the climatic factor shows a trend of distribution from south to north and along the latitude. Approximately 11.644 million hectares of land are suitable for sugarcane cultivation, mainly distributed in the southern and central regions, accounting for 49% of the total area of Guangxi Province. Approximately 8.188 million hectares of land are moderately suitable for sugarcane cultivation, mainly distributed in the southern part of the northern region, accounting for 35% of the total area. Approximately 3.819 million hectares of land are unsuitable for sugarcane cultivation, mainly distributed in the northern part of the northern region, accounting for 16% of the total area. This is due to the significant differences in climate between the northern and southern regions of Guangxi Province. The northern region is a high-altitude area, with lower temperatures and less precipitation, which is not suitable for growing sugarcane. In contrast, the central and southern regions have suitable temperatures and sufficient precipitation, making them suitable for sugarcane cultivation.

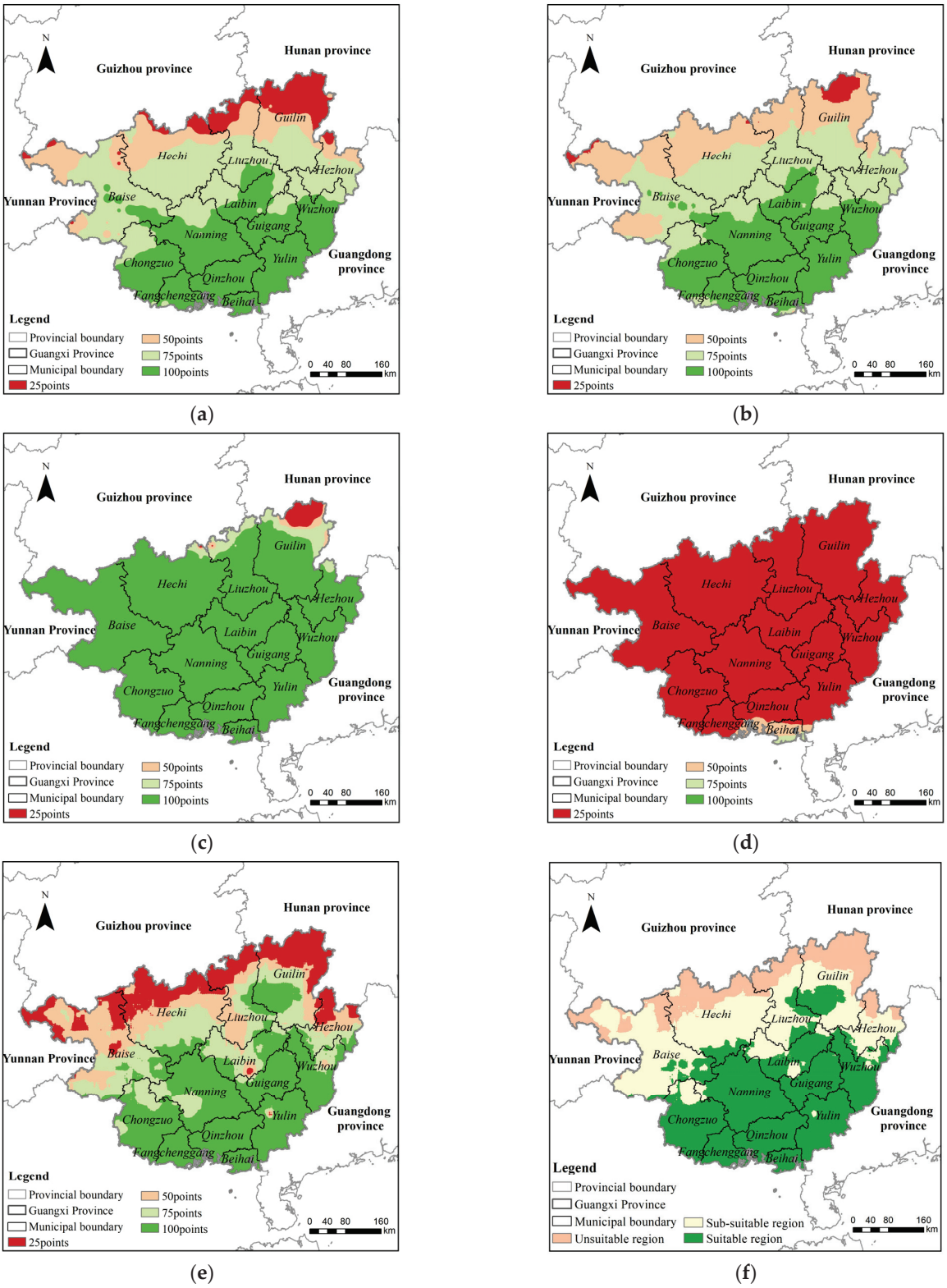

Figure 3. Analysis and comprehensive assessment of indicators based on the climate factors: (**a**) annual average temperature; (**b**) ≥20 °C accumulated temperature; (**c**) annual minimum temperature; (**d**) number of consecutive days with average temperature ≥ 25 °C; (**e**) precipitation during the period of ≥20 °C; (**f**) climate factor comprehensive assessment.

3.2. Assessment of Sugarcane Cultivation Suitability Based on Terrain Factor

Based on the sugarcane cultivation suitability assessment system, the terrain factor of sugarcane cultivation suitability in Guangxi Province was assessed. Firstly, the suitability score map of three indicators were obtained (Figure 4a–c). By considering the weights of each indicator, the assessment score data of sugarcane cultivation suitability in Guangxi Province were obtained based on the terrain factor. Finally, the assessment score data were divided into different levels according to the classification standard for sugarcane cultivation suitability to obtain the assessment results (Figure 4d).

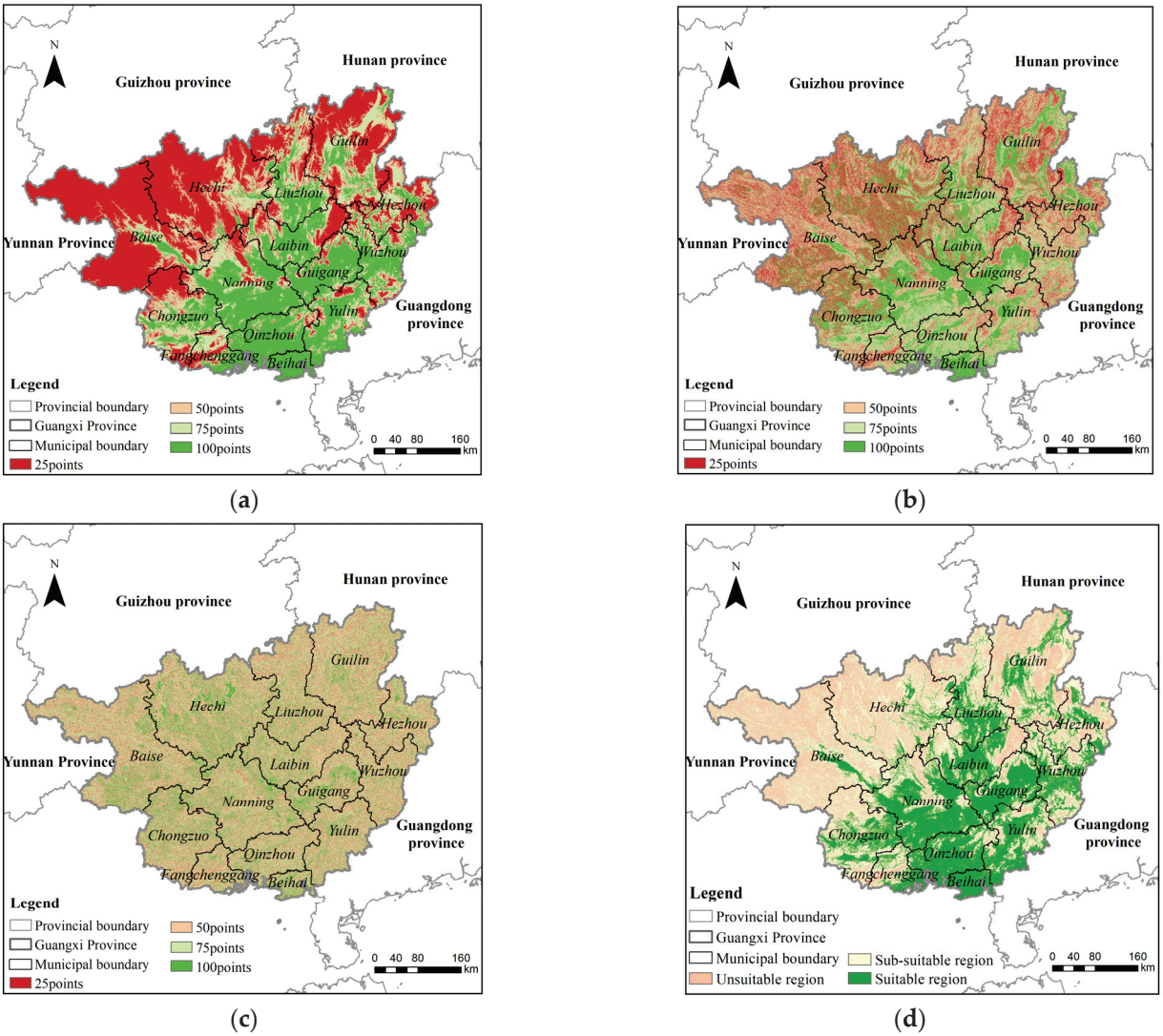

Figure 4. Analysis and comprehensive assessment of indicators based on the terrain factors: (**a**) elevation; (**b**) slope; (**c**) slope direction; (**d**) terrain factor comprehensive assessment.

Analysis of Figure 4a–c shows that the northern area of Guangxi Province, certain parts of southwestern Guangxi Province, and certain parts of eastern Guangxi Province are not conducive to sugarcane growth due to high altitude and steep slopes, resulting in lower suitability scores for the altitude and slope indicators in these areas. However, areas such as Hechi City, Chongzuo City, Laibin City, Guigang City, and Beihai City have a relatively flat terrain, more south-facing slopes, and sufficient sunshine, which are conducive to sugarcane photosynthesis and growth. Therefore, the slope direction indicator has a higher suitability score for sugarcane cultivation in these areas. Figure 4d shows that the suitability of sugarcane cultivation in Guangxi Province based on the terrain factor

tends to be unsuitable in the northwest and suitable in the southeast, but the distribution is scattered. Approximately 8.205 million hectares of land are suitable for sugarcane cultivation, mainly distributed in the southeastern region, accounting for 34% of the total area of Guangxi Province. About 6.115 million hectares of land are moderately suitable for sugarcane cultivation, scattered near the suitable cultivation areas, accounting for 26% of the total area of Guangxi Province. In addition, approximately 9.332 million hectares of land are unsuitable for sugarcane cultivation, mainly distributed in the northwest region, accounting for 40% of the total area of Guangxi Province. This is due to the general trend of the terrain in Guangxi Province, which is high in the northwest and low in the southeast, with scattered slope orientations. The high terrain in the northwest has lower temperatures and is unsuitable for sugarcane cultivation, while the flat terrain in the southeast has higher temperatures and is suitable for sugarcane cultivation.

3.3. Assessment of Sugarcane Cultivation Suitability Based on Disaster Factor

Based on the sugarcane cultivation suitability assessment system, the disaster factor of sugarcane cultivation suitability in Guangxi Province was assessed. First, the map of suitability scores of three indicators were obtained (Figure 5a–c). By considering the weights of each indicator, the assessment score data of sugarcane cultivation suitability in Guangxi Province were obtained based on the disaster factor. Finally, the assessment score data were divided into different levels according to the classification standard for sugarcane cultivation suitability to obtain the assessment results (Figure 5d).

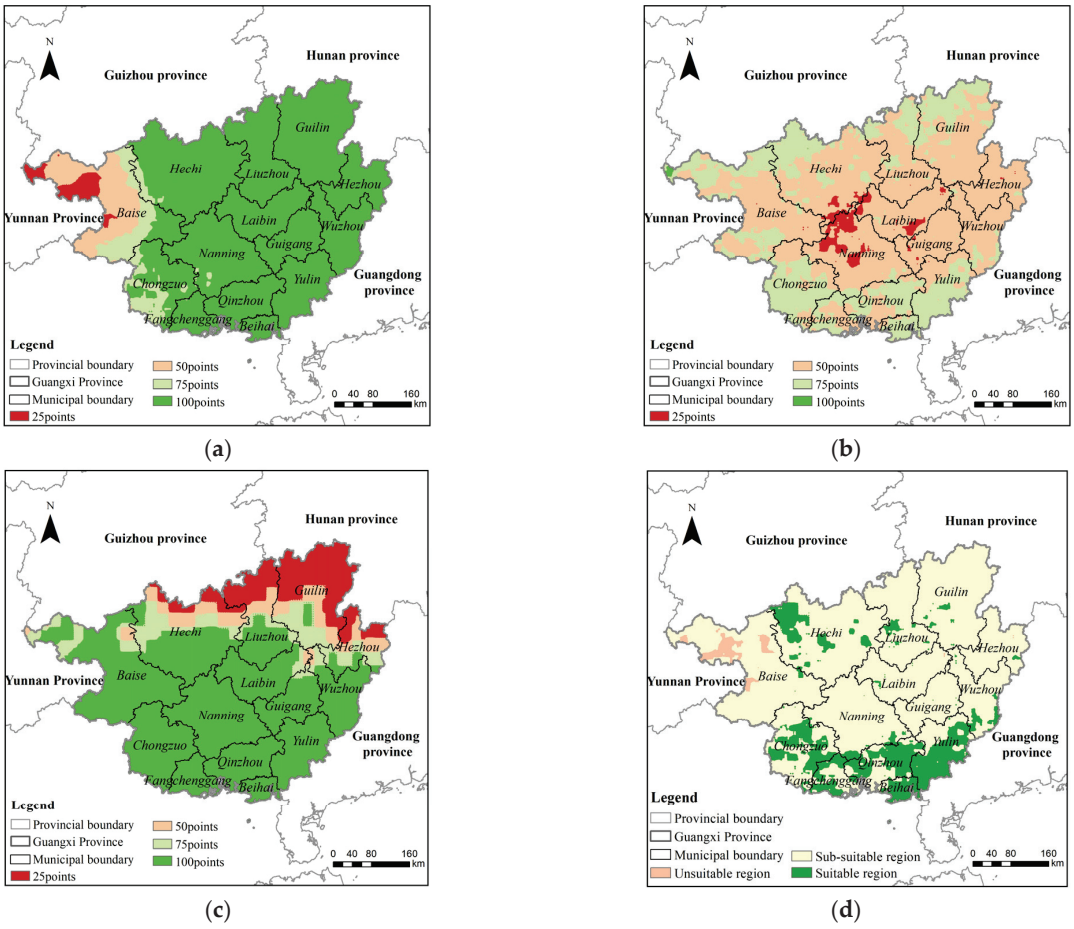

Figure 5. Analysis and comprehensive assessment of indicators based on disaster factors: (**a**) spring drought frequency; (**b**) autumn drought frequency; (**c**) frost frequency; (**d**) disaster factor comprehensive assessment.

Analysis of Figure 5a–c shows that there are significant differences in climate and terrain across Guangxi Province, resulting in different levels of disaster risk in different regions. The northwestern region is located in the monsoon climate zone and is particularly vulnerable to the influence of monsoon winds, especially in March; the monsoon airflow blows from the South China Sea, with relatively low relative humidity, dry air, and relatively low rainfall, resulting in a higher frequency of spring drought. The indicator of spring drought frequency has a relatively low score for assessing the suitability of sugarcane cultivation. The central region has a relatively flat terrain with stable airflow and a lack of stimulation of large-scale upward air currents, resulting in less rainfall and a higher frequency of autumn droughts; the indicator of autumn drought frequency has a relatively low score for assessing the suitability of sugarcane cultivation. The northeastern region is located in a high-latitude area with a relatively cold climate and is susceptible to the influence of strong cold air from the north in winter, which can lead to frost occurrences. Therefore, the indicator of frost frequency has a relatively low score for assessing the suitability of sugarcane cultivation. As can be observed in Figure 5d, the distribution of suitable sugarcane cultivation in Guangxi Province based on the disaster factor is suitable for the southern region, with a small part of the western region being unsuitable. Approximately 4.849 million hectares of land are suitable for sugarcane cultivation, mainly distributed in the south, accounting for 20.5% of the total area of Guangxi Province. About 307,000 hectares of land in the western region of Baise City are unsuitable for sugarcane cultivation, accounting for 1.3% of the total area of Guangxi Province. The remaining approximately 18.496 million hectares of land are relatively suitable for sugarcane cultivation, accounting for 78.2% of the total area of Guangxi Province. This is due to the southern region having more rainfall and higher temperatures, with a lower likelihood of spring droughts, autumn droughts, and frost. The complex terrain and lower rainfall in the western region of Baise City result in a higher frequency of spring and autumn droughts.

3.4. Comprehensive Assessment of Sugarcane Cultivation Suitability

3.4.1. Analysis of Suitability Assessment for Sugarcane Cultivation

By weighting and summing the score data and weights of the three factors of climate, terrain, and disasters for the suitability of sugarcane cultivation, a suitability score map for sugarcane cultivation in Guangxi Province was obtained. According to the classification standard for sugarcane cultivation suitability, the results of the suitability assessment for sugarcane cultivation in Guangxi Province are shown in Figure 6.

Analysis of Figure 6 shows that 37% of Guangxi Province's entire area is suitable for sugarcane cultivation, with an area of 8.732 million hectares mainly distributed in the southern and central regions including Qinzhou City, Beihai City, Chongzuo City, Nanning City, Laibin City, Guigang City, and Yulin City. Additionally, 44% of Guangxi Province's entire area is moderately suitable for sugarcane cultivation, mainly scattered in the central and northern regions, as well as the eastern edge regions, including places such as Baise City, Hechi City, Liuzhou City, and Guilin City, covering an area of 10.292 million hectares. Only 19% of Guangxi Province's total area is unsuitable for sugarcane cultivation, mainly concentrated in the northern part of Guangxi Province with an area of 4.628 million hectares. Overall, Guangxi Province gradually becomes more suitable for sugarcane cultivation from north to south, with Nanning City, Qinzhou City, Guigang City, Yulin City, Laibin City, and Chongzuo City being the regions with a relatively large suitable area for sugarcane cultivation, which should be areas of focus for the development of the sugarcane cultivation industry. On the other hand, many areas in the northern region are unsuitable for sugarcane cultivation, suggesting that other industries should be developed in these areas.

Comparing the results of our study with Su Yongxiu's study on the suitability of sugarcane cultivation in Guangxi based on climate and terrain factors, we found that the results of both studies are consistent. Both studies indicate that the northern region is not suitable for sugarcane cultivation, while the central and southern regions are suitable, with the suitability gradually increasing from north to south. The main difference between the

two studies is that our results appear more refined on the map due to the use of more detailed data.

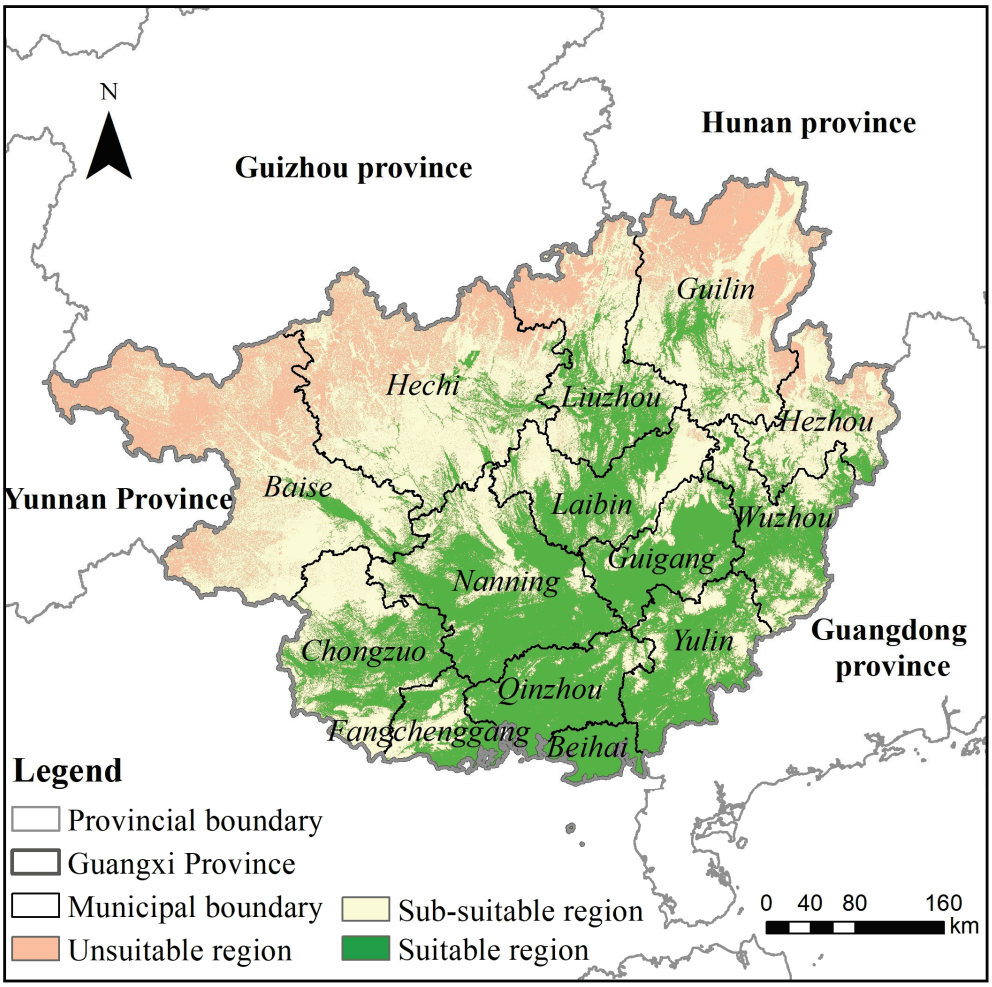

Figure 6. Distribution map of suitable areas for sugarcane cultivation in Guangxi Province.

3.4.2. Contribution Rate Analysis of Sugarcane Cultivation Suitability Assessment

In order to better understand the suitability assessment results for sugarcane cultivation in Guangxi Province, this paper used a contribution rate to measure the relative importance of each factor in the assessment. Specifically, the ratio between the score data of a particular factor for sugarcane cultivation suitability and the total sugarcane cultivation suitability score data in Guangxi Province was calculated. Contribution rate calculations were performed for each of the three factors, resulting in three contribution rate maps for the suitability of sugarcane cultivation. These maps are shown in Figure 7.

Analysis of Figure 7 shows that the climate factor has the greatest impact on the suitability assessment of sugarcane cultivation in western Guangxi Province, the southern part of the northern region, and some areas in the eastern region, with contribution rates ranging from 65% to 85%. The terrain factor has the greatest effect on the suitability assessment of sugarcane cultivation in the northeastern region, with contribution rates ranging from 36% to 71%. In contrast, the disaster factor has the greatest impact on the suitability assessment of sugarcane cultivation in the northern region, with contribution rates ranging from 32% to 43%. Therefore, the biggest influencing factor that makes the northern region unsuitable for sugarcane cultivation is disasters, while the impact of the climate factor on this region is relatively small. In contrast, in the central and southern regions, the terrain is the main factor influencing the suitability of sugarcane cultivation,

followed by the climate factor. Therefore, targeted management and control in different regions is required to ensure the stable development of sugarcane cultivation.

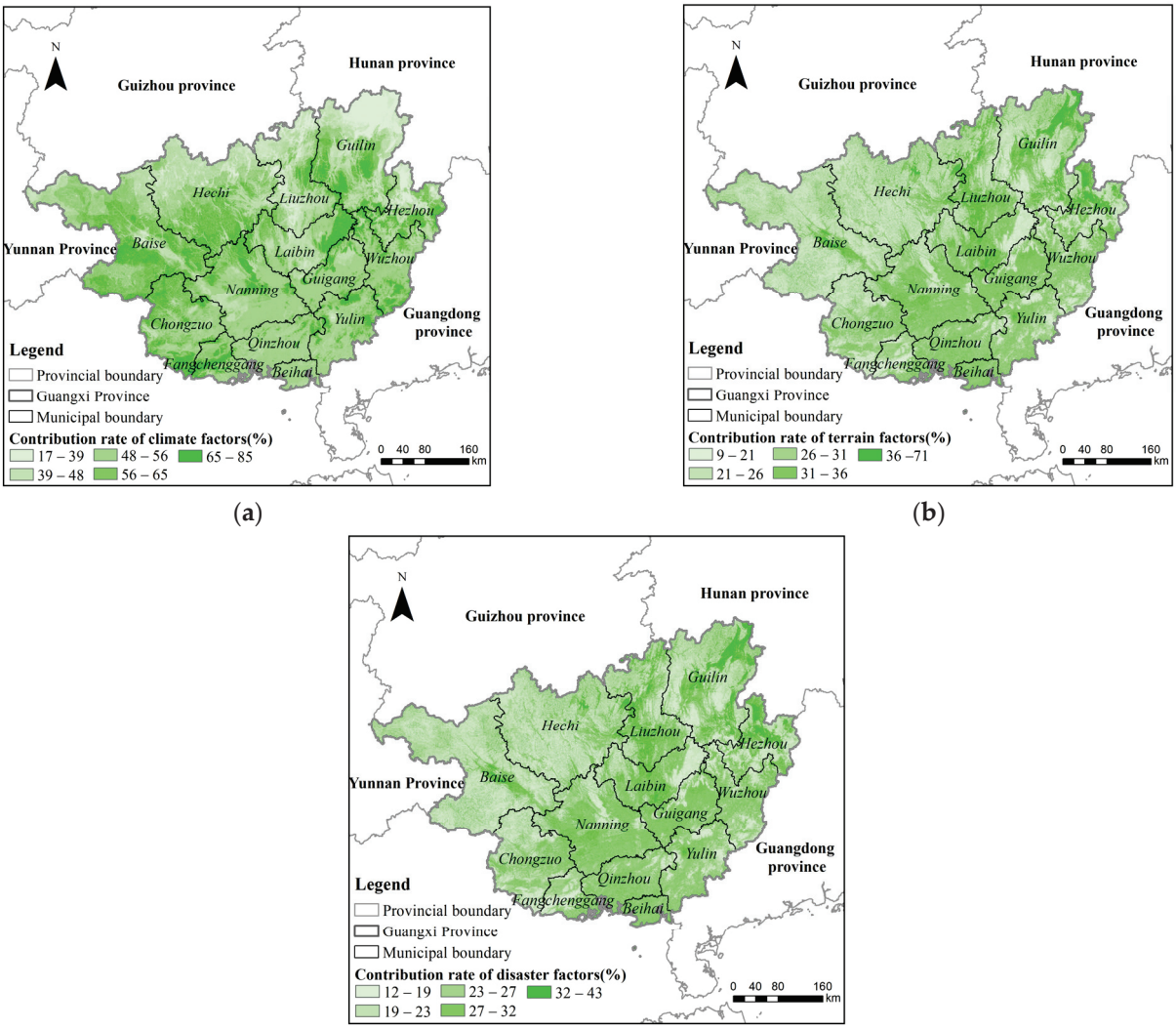

Figure 7. Contribution rates of three factors to the assessment of sugarcane cultivation suitability: (**a**) contribution rate of climate factor; (**b**) contribution rate of terrain factor; (**c**) contribution rate of disaster factor.

4. Conclusions and Discussion

This paper comprehensively considered the impact of climate, terrain, and disaster factors on the growth of sugarcane in Guangxi Province and selected 11 indicators as the assessment indicators for sugarcane suitability based on these three factors. AHP and GIS technology were used to construct an assessment system for sugarcane cultivation suitability, and this system was used to assess the suitability of sugarcane cultivation in Guangxi Province. The research results are as follows:

(i) In the suitability assessment system for sugarcane cultivation, 11 specific indicators of climate, terrain, and disaster factors were selected based on their effects on sugarcane growth. Among them, altitude had the highest contribution rate to the suitability of sugarcane cultivation, followed by precipitation during the period of ≥20 °C, slope, and autumn drought frequency. Among the three factors of climate, terrain, and disaster, terrain had the most significant impact on sugarcane cultivation suitability.

(ii) The central and southern regions of Guangxi Province are suitable for sugarcane cultivation, while the northern region is not. The area suitable for sugarcane cultivation is 8.732 million hectares, accounting for 37% of the total area of Guangxi Province. The area that is moderately suitable for sugarcane cultivation is 10.292 million hectares, accounting for 44% of the total area of Guangxi Province. The area unsuitable for sugarcane cultivation is 4.628 million hectares, accounting for 19% of the total area of Guangxi Province.

(iii) It is recommended to focus on the development the sugarcane industry in the regions of central and southern Guangxi Province that are suitable for sugarcane cultivation, such as Chongzuo City, Nanning City, Qinzhou City, Guigang City, Yulin City, and Beihai City. In these areas, the government can strengthen support and guidance for the sugarcane cultivation industry, help farmers improve their cultivation techniques and management skills, and promote the development of local agriculture and economic prosperity. In the northern regions, the government should support other industries to reduce dependence on sugarcane cultivation and ensure sustainable economic development in the area.

This paper assessed the suitability of sugarcane cultivation in Guangxi Province by comprehensively considering three factors: climate, terrain, and disasters, based on previous research. In order to address the issue of frequent disasters caused by extreme weather conditions throughout the year in Guangxi Province, this paper analyzed the impact of disasters on the entire growing season of sugarcane and combined this analysis with the effects of climate and terrain on sugarcane cultivation to provide a more comprehensive assessment of suitability. Additionally, to overcome the problems encountered in the past of using coarse meteorological station data for assessment, this paper used continuous and pixel-level precipitation and temperature data, which are more refined in time and space and can cover the assessment area in more detail, resulting in more detailed assessment results. However, the process of constructing the judgment matrix in the expert rating method relies on the experience of the experts, and the acquisition of weights is subject to some subjective interference. In order to assess the suitability of sugarcane cultivation more scientifically, we will continue to study how to obtain weights to reduce the influence of subjective factors, such as obtaining weights through the autonomous training of neural networks to optimize the assessment system and improve the accuracy of the results.

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Why Are Farmers Reluctant to Sell: Evidence from Rural China

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Abstract: The agricultural marketing behavior of farmers is crucial for the realization of production value. Based on survey data from 406 citrus farmers in Hubei Province, this paper empirically examines the effects of risk aversion and Internet use on farmers' marketing behavior in terms of fresh produce. The results show that, first, farmers are generally reluctant to sell, with reluctant sellers accounting for about one-third of the total sample, and most report high levels of Internet use. Second, risk aversion and Internet use have a significant impact on farmers' reluctance to sell. The higher the level of farmer risk aversion, the lower the reluctance to sell, while Internet use significantly increases the probability of farmers being reluctant to sell. Third, Internet use weakens the inhibiting effect of risk aversion on reluctance to sell. These findings help to clarify the factors influencing farmers' reluctance to sell and provide reference suggestions for promoting high-quality agricultural development and rural industrial revitalization.

Keywords: risk avoidance; Internet use; reluctant to sell; citrus growers

1. Introduction

China is one of the largest producers of fruit in the world. According to the latest data, China's orchards cover 12,646.28 hm^2, and total fruit production has reached 286,923.6 kt [1]. However, price fluctuations in the Chinese fruit market are very frequent. Since 2009, the monthly fluctuation of fruit prices in 36 major cities in China has exceeded 5.01%, peaking at 14.51% [2]. Meanwhile, the uncertainty of agricultural activities has increased dramatically due to frequent emergencies, such as extreme weather conditions and COVID-19, increasing the severity of the fruit market price risks faced by farmers.

Many researchers have studied farmers' selling strategies when market prices fluctuate. They have found that farmers' sales behavior often shows a strange phenomenon known as "reluctance to sell" when faced with market price fluctuations [3]. "Reluctance to sell" first appeared in relation to grain purchases. It refers to the fact that farmers are not satisfied with the price of agricultural products or expect the price to increase, which leads to wait-and-see behavior or a reluctance to sell [4]. "Reluctance to sell" is a subjective and rational behavior of farmers, i.e., farmers can sell but do not sell, rather than having difficulty selling. For small-scale farmers in developing countries, profit maximization and risk minimization are their primary goals [5]. Although reluctance to sell may reduce losses or increase revenue, it is often accompanied by greater risks. This seems to be inconsistent with the view that "farmers are rational people".

Most studies focus on farmers' reluctance to sell stored agricultural products such as grains. For example, Qi and Yu [6] analyzed the factors influencing farmers' reluctance to sell. Mattos and Fryza [7] found that risk appetite contributed to Canadian wheat farmers' reluctance-to-sell behavior. Using an experimental approach, Vollmer et al. [8] similarly demonstrated the risk appetite of farmers' reluctance to sell in relation to grain. Luo et al. [9] analyzed the impacts of storage losses and market development on the maize-selling behaviors of rural households in China. Peng and Xu [10] found that large-scale farmers who anticipate an increase in grain prices will choose to postpone grain

sales to potentially maximize profits. Risk-averse large-scale farmers will choose a multiperiod sales method, while risk-loving ones will choose a single-period delayed sales method. Additionally, there have been fewer studies on fresh agricultural products such as fruits. The optimal time to sell agricultural products may vary depending on the product type. Fresh produce is perishable and less easily transported than stored agricultural products. Sun et al. [11] argued that the higher the expected price and the greater the market risk perception, the more growers prefer the long-term storage of high-value agricultural products.

In summary, although scholars have carried out numerous studies on farmers' reluctance to sell, there is room for further advancement. First, most existing studies focus on explaining the influencing factors and phenomena of reluctance to sell but ignore the internal relations between the factors and lack a comprehensive and systematic analysis. Second, scholars mostly focus on the sales behavior of large-scale farmers, and there is less research on small farmers. The current research on the selling behaviors of farmers in developing countries largely revolves around small-scale farmers and the impact of their endowments, ignoring the roles played by information technology and farmers' subjective attitudes.

This study takes risk aversion and Internet use as its perspectives. It uses survey data gathered from farmers in the main citrus-producing areas of Hubei Province to empirically investigate how smallholder farmers in China determine the optimal time to sell in the context of information asymmetry and market price fluctuations, i.e., whether farmers exhibit reluctant selling behavior. Ultimately, our goal is to understand the selling behavior of fruit farmers in developing countries such as China, to help smallholders increase their income, and to provide recommendations for promoting quality agricultural development and rural revitalization.

Compared with previous studies, the innovation and contributions in this study include the following. First, this study reveals the special sales behavior of farmers, which differs from the definition of farmers' sales behavior in previous studies. This study mainly focuses on farmers' reluctant selling behaviors. Second, this study combines the actual scenario of China's fresh fruit market to construct an analysis framework for small-scale farmers' sales decisions. Simultaneously, based on prospect theory and information effect, this study reveals the trade-off relationship between profit and risk in small-scale farmers' sales decision-making processes and the importance of information acquisition, which helps to understand the characteristics of their sales behavior.

2. Theoretical Framework

2.1. Farmers' Agricultural Products Sales Decision

Suppose that each rural household decides the optimal timing for selling agricultural products based on three main factors: proportional transaction costs, TC^p; fixed transaction costs, TC^f; and expected market price, p_j'. As the number of agricultural products sold increases, the proportional transaction costs, TC_j^p, faced by the farmer in period j also increase. It depends on the market distance, d_j, trading time, t_j and other characteristic factors, z_j^p, expressed as follows:

$$TC_j^p = TC^p\left(d_j, t_j, z_j^p\right) \tag{1}$$

The fixed transaction costs are not related to the number of sales, but to the fixed cost of each family, z_j^f, which can be expressed as follows:

$$TC_{ij}^f = TC^f\left(z_j^f\right) \tag{2}$$

In particular, due to the particularity of citrus planting, the production costs of citrus fertilizers and pesticides can also be regarded as fixed transaction costs each year. In our survey practice, we also found that farmers usually ignore the factor inputs in the citrus-growing process when deciding when to sell, as it is a perennial plant and can bear fruit multiple times. In contrast, farmers are more concerned with labor prices, storage costs and other transaction costs that vary with the quantity sold. We include production costs in our discussion of fixed transaction costs.

Farmers usually make sales decisions based on market prices, $p_j^{'}$, $p_j^{'}$, related to market price information, $\bar{p}_j$, and price fluctuations, $M.M$, which depend on the expected sales volume, s_j, the quality of agricultural products, q_j, and the bargaining power of farmers, BP_j. The function form of $p_j^{'}$ can be expressed as follows:

$$p_j^{'} = \bar{p}_j \pm M(s_j, q_j, BP_j) \tag{3}$$

Because agricultural production is susceptible to various factors, such as the external environment, it is characterized by typical uncertainty. Therefore, by adding risk variables, λ, the final sales volume of farmers in the current period is $(s_j - \lambda_j g)$, where $\lambda_j g$ represents the random yield loss caused by uncertain risk factors in period j. According to the principle of profit maximization, the optimal sales decision conditions of rational smallholders in period j are as follows:

$$\max_j \Pi_{ij} = \left\{ (s_j - \lambda_j g) \cdot \left[\bar{p}_j \pm M(s_j, q_j, BP_j) - TC_j^p \left(d_j, t_j, z_j^p \right) \right] - TC_j^f \left(z_j^f \right) \right\} \tag{4}$$

When the current sales profits reach the maximum, farmers will choose to sell agricultural products. It can be seen that proportional transaction costs, fixed transaction costs, market prices and risk factors have a key impact on agricultural product sales decisions.

2.2. Sales Decision Framework for Small-Scale Fruit Grower

When small-scale farmers, who aim to maximize profits and minimize risk, face exogenous price shocks under information asymmetry, their reluctance to sell is manifested. Additionally, subsequent decisions are made taking into account their price expectations and risk-averse attitudes. Prospect theory suggests that people make decisions based on reference points; individuals are willing to take more risk when faced with losses and tend to be risk-averse when faced with gains. Individuals are more sensitive to losses than gains [12].

Farmers face multiple risks, such as natural disasters and price fluctuations, during agricultural production and operation. Individual risk preferences will directly impact their behavioral decisions [13]. According to behavioral bias theory, individuals are more likely to maintain the status quo and avoid risk when faced with a choice between benefits and risks [14]. A reluctance to sell may reduce losses or increase revenues. However, it is often associated with greater risks. Specifically, on the one hand, farmers may hesitate for too long and lose their initial gains due to a fall in prices. On the other hand, the large number of homogeneous agricultural products on the market during the waiting period will further crowd out the market space and lead to stagnating sales of agricultural products, resulting in greater losses. In addition, scholars have found typical heterogeneity in the risk preferences of farm households [15,16]. As smallholder farmers have a minimal risk tolerance, most tend to be risk-averse to reducing economic losses. Therefore, risk-averse farmers who are averse to losses will choose to sell their agricultural products promptly and are more likely to be willing to sell to avoid losses or suffer greater losses caused by risk factors such as price fluctuations and natural disasters. Based on this, we propose the following hypothesis:

H1: *The more risk-averse small-scale farmers are, the lower the possibility of reluctant sales of their produce.*

Price expectations are another key factor affecting farmers' marketing strategies. Price expectations refer to farmers' prediction of future market price level trends. Since small-scale farmers are generally less educated, they judge the future price trend of agricultural products through experience or other information obtained. The ability to make correct price expectations will determine whether small-scale fruit growers can successfully maximize profits.

According to basic economic theory, a lack of information can lead to a loss of economic efficiency [17]. However, most rural areas are remote and have poor communication with markets, and farmers often need more accurate information on current market prices to make their decisions. The advent of Internet technology has broken down information barriers and influenced farmer behavior through the effects of information and technology [18].

On the one hand, Internet use can enhance the flow of information and reduce the financial and time costs required for farmers to obtain and exchange information, thus reducing transaction costs [19]. Additionally, abundant information flow can help farmers judge market trends and increase their market participation [20,21]. On the other hand, the Internet innovation platform can facilitate the production-marketing interface, which broadens the marketing channels of farmers and increases the sales of agricultural products [22]. In particular, the application of e-commerce has shortened the sales chain and greatly increased the market participation of farmers.

Furthermore, Internet use will enhance the factor allocation capacity of farmers and alleviate factor endowment constraints [23], thus optimizing farmers' marketing strategies related to agricultural products. The more farmers are in contact with outside information through the Internet, the more their sales thinking and approach will change, ultimately leading to changes in farmers' sales behavior. Generally, the more information a farmer has about the market, the more they expect to sell the product at a higher price. Internet use reduces the cost of trading agricultural products and expands trade channels. Therefore, when faced with price fluctuations, farmers with high Internet use will likely be reluctant to sell. Therefore, we propose the following hypothesis:

H2: *Farmers are more likely to be reluctant to sell their produce if they have a high level of Internet use.*

Chinese farmers have long had a weak position in the sales market, with intermediaries forming a monopoly market for small-scale farmers [24]. This is mainly because farmers know very little about market prices compared to intermediaries. However, Internet use can reduce the market power of intermediaries to some extent, improve the bargaining power of farmers, and thus increase the selling price of agricultural products [25]. Theoretically, Internet use mitigates the degree of risk aversion among farmers to a certain extent. The positive influence on the risk attitude of farmers who use the Internet more frequently is more significant [26,27].

Specifically, first, the change in information access channels brought about through the popularization of Internet technology in rural areas mitigates the degree of risk aversion of farmers through the effects of information [27]. Second, farmers' mastery of Internet technology can spill over to the level of knowledge network and social network. Better use of Internet technology can be internalized into farmers' knowledge endowment and social capital, improving farmers' ability to resist risks. Third, the Internet has improved farmers' access to credit [28]. Internet use can reduce farmers' liquidity constraints, mitigate the financial vulnerability of rural households, and encourage farmers to be more likely to engage in risky behavior.

In summary, the impact of Internet use on farmers' agricultural marketing behavior is in essence achieved by alleviating farmers' risk-averse attitudes, increasing farmers' risk resistance, and reducing rural households' liquidity constraints. The higher the risk appetite of farmers, the higher their resistance to risk, and the weaker their household liquidity constraints, the more likely they are to be reluctant to sell their produce. Given this, we propose the following hypothesis:

H3: *Internet use will mitigate the disincentive effect of risk aversion on farmers' reluctant selling behavior.*

3. Data

3.1. Data Collection

The research data were taken from a household survey of citrus growers in Hubei Province, China, conducted in July 2021. These survey areas were selected for two reasons: First, Yichang City, Hubei Province, as one of the important production areas of citrus in China, has rich reserves of varieties and a long and experienced history of cultivation. Second, as the most developed citrus industry in Yichang [29], Zigui County can basically reflect the current situation of citrus development in Yichang, and the study of its farmers' behavior is also generalizable to other production areas. Therefore, selecting the sample of citrus growers in Hubei Province is not only scientifically representative, but also has important practical value for the development of the citrus industry.

The survey first identified Zigui County, Yichang City, Hubei Province, as a sample area, and through a typical sampling method, selected two better citrus-producing towns, Guojiaba Town and Shuitianba Township. Secondly, the method of stratified random sampling was adopted, and the administrative villages were randomly selected according to the total annual output of citrus. A total of seven sample villages were formed. Finally, 60 citrus growers were randomly selected from each sample village for investigation. It is worth mentioning that the list of villagers provided by village cadres helps us better adapt to random selection. In each sample village, we ranked the citrus size from largest to smallest, and each sample farmer was selected to be distinguished by the same number of non-sample farmers. Finally, we carefully reviewed the survey data according to the integrity, logic, and authenticity of the questionnaire, obtaining 406 pieces of valid survey data for empirical analysis.

The interviewers consisted of doctoral and master's students from the research team, who had received advanced training. The interviewees were the main laborers or the heads of households responsible for citrus production and operation. Based on a randomly selected list, the interviewers entered the farmers' homes one by one for face-to-face communication. Then, the interviewers asked questions and filled out the questionnaire accurately according to the interviewees' answers. The main contents of the questionnaire included the input and output of citrus production, production and management decisions, and basic family and personal information.

3.2. Basic Characterization of the Sample

Table 1 reports the basic characteristics of the samples. Citrus marketing methods can be divided into two categories: only selling through intermediaries, and selling through intermediaries while also selling on their own (hereinafter referred to as "simultaneous self-selling"). The survey found that most farmers in the survey area rely on the sales method of 'farmers + middlemen', which is consistent with the research conclusions of Song and Qi [29]. However, while relying on intermediaries for sales, farmers also use other methods to sell on their own. Among all the survey samples, 141 households sell through online social networking platforms, accounting for 34.73% of the total sample. It can be seen that the Internet sales model based on social networking platforms is gradually being integrated into the farmers' sales process.

Table 1. The distribution of the sample.

Variable	Description	Observation	Percentage	Variable	Description	Observation	Percentage
Gender	Male	227	44.09	Education	Primary and below	204	50.25
	Female	179	55.91		Junior high	147	36.21
Age	<45	64	15.76		Senior High School	46	11.33
	45~60	224	55.17		Junior college	7	1.72
	>60	118	29.06		Bachelor and above	2	0.49
Orchard area (mu)	<4	120	29.56	Sales methods	Intermediaries	237	58.37
	4~8	207	50.99		Multiple channels	169	41.63
	>8	79	19.46	Multiple channels	E-commerce platforms	23	5.67
Citrus sales revenue	<50,000	223	54.93		Social platform	141	34.73
	50,000~10,0000	137	33.74		Short video platform	11	2.71
	100,000~150,000	33	8.13		Supply to supermarkets	6	1.48
	≥150,000	13	3.2		Sell offline to customers	36	8.87

Note: While relying on intermediaries for sales, farmers also use other methods to sell on their own; the way mainly includes 5 kinds: e-commerce platform, social platform, short video platform, supply to supermarkets and sell offline to customers. 1 mu = 1/15 hectare.

4. Empirical Model and Descriptive Statistics

4.1. Empirical Model

We construct a binary Probit model of citrus growers' sales behavior choice for analysis. The expression is as follows:

$$Y = \ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1\varphi + \beta_2\eta + \beta_3 X + \mu \tag{5}$$

where p represents the probability that citrus growers adopt reluctant selling behavior; $1-p$ represents the probability that farmers sell normally. φ and η represent the degree of risk aversion and the level of Internet use of farmers, respectively. β_1 and β_2 are their estimated coefficients, respectively. X is the control variable vector that affects the decision-making processes of farmers' sales behavior, and β_3 is its estimated coefficient vector. β_0 is a constant term and μ is a random error term.

In order to further explore whether the level of Internet use of farmers will alleviate the inhibitory effect of risk aversion on farmers' reluctance to sell, we add the interaction term of φ and η on the basis of Equation (5):

$$Y = \ln\left(\frac{p}{1-p}\right) = c_0 + c_1\varphi + c_2\eta + c_3(\varphi \times \eta) + c_4 X + \omega \tag{6}$$

In Equation (6), $\varphi \times \eta$ is the interaction term between farmers' risk aversion and Internet use level, and c_3 is its estimated coefficient. c_1 and c_2 are the estimated coefficients of φ and η, respectively. X is the vector of control variables, and c_4 is its estimated coefficient. c_0 is a constant term, and ω is a random error term.

4.2. Key Variables and Descriptive Statistics

In order to estimate the coefficients mentioned earlier, we need to define the variables. For the dependent variable, we selected 'whether citrus growers take reluctant selling behavior' in the questionnaire item to identify Y. Additionally, this study included two key independent variables. One of them is risk aversion. As the more risk-averse farmers tend to delay the adoption of new technologies [30,31], we refer to the research of Wang et al. [32], through the following question: 'Are you willing to try the new citrus planting technology' for identification. This is measured using a scale of 1 to 5, with lower values indicating

that farmers are more risk-averse and higher values indicating that farmers show a greater preference for risk.

The other is Internet use. We measure the Internet use level of citrus growers from five levels: learning, work, social, entertainment and business activities. These five categories of indicators are assigned from 1 to 7 according to the frequency of Internet use. In ascending order of fetching value, they represent seven levels: never, once every few months, once a month, 2–3 times a month, 1–2 times a week, 3–4 times a week, and almost every day. We use the mean score of these indicators to identify the Internet use of citrus growers. A higher score for farmers represents a higher level of Internet use. It is worth mentioning that compared with previous studies, we pay more attention to the farmer's Internet skills acquisition rather than simply measuring whether farmers can use the Internet.

Of course, we also controlled for the impacts of other factors on farmers' citrus sales behavior in this study. On the one hand, drawing on previous studies, we controlled the personal, family and production characteristic variables of citrus growers. Personal characteristics include gender, age, and education; family characteristics include cooperative membership, labor force and economic status; and production characteristics include planting scale, yield, planting years, the proportion of sales revenue and cooperative relationships. On the other hand, the transportation condition and market distance at the village level are controlled. The definition and characteristic statistical results of each variable in the model are shown in Table 2.

Table 2. Variable definitions and descriptive statistics.

Variables	Definition and Assignment	Mean	Standard Deviation
	Dependent variable		
Citrus sales behavior	1 if the farmer is reluctant to sell, otherwise 0	0.320	0.467
	Key independent variables		
Risk aversion	New technology adoption intention: Likert 1–5 points, 1 = very unwilling, 5 = very willing	2.773	1.032
Internet use	Means of 5 categories of indicators	3.607	1.340
Gender	1 = Male, 0 = Female	0.559	0.497
Age	Citrus growers' actual age(years)	54.892	10.589
Education	1 = Primary and below; 2 = Junior high; 3 = Senior high school; 4 = Junior college; 5 = Bachelor and above	1.660	0.784
Cooperative membership	1 if farmer is a cooperative member,0 otherwise	0.197	0.398
Labor force	Total household labor force (person)	3.032	1.094
Economic status	1 = Very poor, 2 = Poor, 3 = Medium, 4 = Good, 5 = Very good	2.640	1.030
Planting scale	Actual citrus planting area (mu)	7.142	24.847
Yield	Average yield per mu (kg), taking the natural logarithm	7.958	0.417
Planting years	Citrus planting duration(years)	27.744	10.060
Proportion of sales revenue	Total revenue from sales of citrus as a percentage of total family revenue (%)	81.344	28.055
Cooperative relationship.	1 = Very poor, 2 = Poor, 3 = Medium, 4 = Good, 5 = Very good	3.155	1.119
	Village characteristics		
Transportation condition	1 = Poor; 2 = General; 3 = Better	2.037	0.835
Market distance	Distance to the nearest agricultural trading market in the village (km)	7.850	9.539

Note: 1 mu = 1/15 hectare.

To check the suitability of the Internet use survey scales, the Kaiser–Meyer–Olkin (KMO) test and Bartlett's sphericity test are used. The Kaiser–Meyer–Olkin measure of sampling adequacy is 0.696, and the Bartlett test of sphericity is 718.745 (p = 0.000), indicating that the survey scales are suitable for factor analysis. The results of the factor analysis show that the Internal consistency (Cronbach's α) and composite reliability (CR) are greater than 0.7, and the average variance extracted (AVE) is greater than 0.5, indicating that the scale has good reliability and validity. The specific results are shown in Table 3.

Table 3. Description of Internet use.

Variable	Subject	Mean	Std.	Standard Factor Loadings	Cronbach's α	CR	AVE
Internet use	Learning	2.022	1.417	0.724	0.778	0.853	0.538
	Working	2.163	1.635	0.777			
	Social	5.293	1.873	0.715			
	Entertainment	5.488	2.027	0.678			
	Business	3.069	2.159	0.769			

Note: We use a 7-point Likert scale to measure Internet use, with scores of: 1 = never; 2 = once every few months; 3 = once a month; 4 = 2–3 times a month; 5 = 1–2 times a week; 6 = 3–4 times a week; 7 = almost every day.

In addition, Table 4 illustrates that 130 households out of the total sample of farmers exhibit reluctant selling behavior, accounting for 32.02% of the total sample. Among the sample farmers who adopt the reluctant sale behavior, the proportion of high level of Internet use is greater. The Pearson correlation coefficient between Internet use and sales behavior is statistically significant at the 1% level, indicating a significant positive relationship.

Table 4. Farmers' sales behavior under the difference of Internet use level.

Variable	Sales Behavior			
	No Reluctant Selling		Reluctant Selling	
	Observation	Percentage (%)	Observation	Percentage (%)
High level of Internet use	146	76.40%	45	23.60%
Low level of Internet use	130	60.50%	85	39.50%
Pearson correlation coefficient	0.171 ***			

Note: *** is significant at the 1% level.

5. Estimation Results and Robustness Test

5.1. Estimation Results

Table 5 reports the results of the benchmark regressions on the effects of risk aversion and Internet use on citrus growers' selling behavior decisions. Model 1 is the result of considering only the control variables. Model 2 and Model 3 are the results of risk aversion and Internet use each affecting farmers' marketing behavior decisions. Model 4 is the result of adding the interaction term of risk aversion and Internet use.

First, considering only the control variables, Model 1 shows that planting scale, yield, and proportion of sales revenue share significantly positively affect farmers' reluctant selling behavior. In contrast, the village transportation development and market distance have a significant negative effect. The possible reasons are as follows: First, farmers with larger citrus planting areas, higher yields and larger proportions of citrus sales revenue have a higher dependence on citrus sales revenue. They expect to sell at a higher price, so their wait-and-see time is longer, and the possibility of being reluctant to sell is higher when the market price fluctuates. Second, the higher the level of transportation development, the farmers can choose more sales channels through various ways to sell agricultural products promptly. Moreover, the closer the farmers are to the market, to save transaction costs, it is easier to choose to sell nearby, and farmers are less likely to make reluctant sales.

Second, according to the estimation results shown in Model 2, citrus growers' risk aversion has a significant negative impact on reluctant selling behavior after controlling for other influencing factors. Thus, Hypothesis 1 is supported. This is due to reluctant selling behavior greatly increasing the risks and costs that farmers need to bear, meaning that they easily miss the best time to sell [33]. However, risk-averse farmers are usually more cautious when making decisions [23], so they are less likely to be reluctant to sell.

Table 5. Benchmark regression results.

Variable	Model 1	Model 2	Model 3	Model 4
Risk aversion	—	−0.223 *** (0.073)	—	−0.292 *** (0.078)
Internet use	—	—	0.168 ** (0.066)	0.202 *** (0.067)
Risk aversion × Internet use	—	—	—	0.144 *** (0.054)
Gender	−0.037 (0.144)	−0.011 (0.146)	−0.039 (0.147)	0.033 (0.152)
Age	0.001 (0.009)	0.002 (0.009)	0.008 (0.009)	0.009 (0.010)
Education	0.086 (0.103)	0.114 (0.105)	0.006 (0.107)	0.010 (0.111)
Cooperative membership	−0.040 (0.184)	−0.014 (0.187)	−0.110 (0.187)	−0.112 (0.194)
Labor force	−0.101 (0.067)	−0.108 (0.068)	−0.109 (0.067)	−0.104 (0.068)
Economic status	0.027 (0.072)	0.082 (0.075)	0.009 (0.071)	0.071 (0.075)
Planting scale	0.043 ** (0.019)	0.050 ** (0.021)	0.035 * (0.019)	0.039 * (0.020)
Yield	0.447 ** (0.178)	0.435 ** (0.182)	0.408 ** (0.178)	0.407 ** (0.182)
Planting years	0.006 (0.008)	0.004 (0.008)	0.004 (0.008)	0.002 (0.008)
Proportion of sales revenue	0.010 *** (0.003)	0.010 *** (0.003)	0.010 *** (0.003)	0.010 *** (0.003)
Cooperative relationship.	−0.028 (0.065)	−0.038 (0.065)	−0.018 (0.064)	−0.051 (0.066)
Transportation development	−0.542 *** (0.098)	−0.535 *** (0.099)	−0.558 *** (0.100)	−0.546 *** (0.102)
Market distance	−0.068 *** (0.010)	−0.070 *** (0.011)	−0.070 *** (0.010)	−0.071 *** (0.011)
Constant	−3.591 ** (1.619)	−3.039 * (1.641)	−3.987 ** (1.645)	−3.445 ** (1.677)
Observations	406	406	406	406
Wald chi2	78.930 ***	80.000 ***	81.230 ***	89.330 ***
Pseudo r-squared	0.199	0.216	0.211	0.242

Note: ***, ** and * are significant at the 1, 5 and 10% levels, respectively; standard errors are in parentheses.

Third, the estimation results in Model 3 show that Internet use significantly positively affects citrus growers' reluctant selling behavior. Hypothesis 2 has been verified. This suggests that even though farmers use the Internet to gain access to a wealth of market information, they choose to wait and see in terms of prices in order to maximize profits based on a full weighing of external information. Farmers tend to be reluctant to sell, consistent with the judgment that farmers demonstrate 'bounded rationality' in the prospect theory [34].

Finally, the results of Model 4 show that the estimated coefficient of risk aversion is negative, the estimated coefficient of Internet use is positive, and the estimated coefficient of the interaction between risk aversion and Internet use is positive, and both are significant at the level of 1%. This shows that Internet use can weaken the inhibitory effect of risk aversion on farmers' reluctance to sell, which verifies Hypothesis 3. The reason is that the higher the level of Internet use of farmers, the stronger the ability to obtain information, which helps to compensate for their information asymmetry in the market and reduces uncertainty in the sales process of agricultural products [19]. Whether farmers are reluctant to sell citrus is a typical uncertainty decision. Effective information acquisition reduces farmers' uncertainty perception [35], and then promotes them to adopt reluctant selling behavior.

5.2. Robustness Test

In the baseline regression model, we control for many variables that affect farmers' selling behavior. Additionally, there is also a lack of evidence for the theory that the risk attitude of farmers is affected by their sales behavior. Therefore, the possibility of endogenous problems caused by risk aversion and farmers' reluctant selling behavior in the model is not great. Even so, there may still be endogeneity problems due to omitted variables, and there may still be some unobservable variables that can have an impact on farmers' selling decisions. To overcome potential endogeneity problems, this study re-estimates the model by replacing the regression model, limiting the sample, and re-measuring the key variables.

Specifically, the Logit model is first used for re-estimation. Meanwhile, considering that the risk attitude of the elderly in rural areas is less likely to be changed by external factors, we refer to the study of [27], excluding the sample of farmers aged 60 and above

and then substituting the processed data into the original model for regression. Further, in order to verify the impact of key variables from multiple perspectives, this study also draws on Cai et al. [36] by assigning the first three options of the risk-aversion measure to 0 for "no" and the last two options to 1 for "yes", redefining it as "risk aversion".

Finally, "farmers' ability to grasp and receive Internet information" is used to characterize farmers' Internet use, with 1~5 representing "very poor, poor, medium, good and very good", respectively. The stronger the ability of farmers to grasp and receive Internet information, the higher the level of Internet use. Table 6 shows the results of various robustness testing methods. After controlling for endogeneity problems, the estimation results of the key variables are consistent with those shown in Table 5, indicating that the results are robust and credible.

Table 6. Robustness test results.

Variables	Replacing the Regression Model		Limiting the Sample		Re-Measuring the Key Variables	
Risk aversion	−0.406 *** (0.131)	−0.502 *** (0.140)	−0.240 *** (0.091)	−0.347 *** (0.100)	−0.751 *** (0.233)	−1.167 *** (0.354)
Internet use	0.306 *** (0.115)	0.341 *** (0.119)	0.198 ** (0.084)	0.235 *** (0.086)	0.314 *** (0.088)	0.356 *** (0.093)
Risk aversion × Internet use	—	0.237 ** (0.096)	—	0.164 ** (0.068)	—	0.515 ** (0.229)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	406	406	272	272	272	272
Wald chi2	74.150 ***	78.208 ***	71.610 ***	75.140 ***	76.080 ***	73.370 ***
Pseudo r-squared	0.233	0.244	0.254	0.268	0.276	0.289

Note: ***, ** are significant at the 1 and 5 levels, respectively; standard errors are in parentheses.

6. Conclusions, Policy Implications and Limitations

Determining the best time to sell fresh fruit is the most important economic decision for citrus growers. Based on the survey data of 406 citrus growers in China's major citrus-producing areas, we empirically analyzed the impact of risk aversion and Internet use on farmers' reluctance to sell. We used various methods to test the robustness to address the potential endogenous problems, and the estimated results were still valid.

Our study shows that: First, citrus growers generally have a reluctant selling mentality. Farmers reluctant to sell account for about one-third of the total number of the sample, most of whom have a high level of Internet use. Second, risk aversion and Internet use significantly impact citrus growers' reluctant selling behavior. The higher the risk aversion of farmers, the lower the possibility of being reluctant to sell, and Internet use can significantly increase farmers' reluctance to sell. Third, Internet use can weaken the disincentive effect of risk aversion on citrus growers' reluctance to sell.

Our findings also inform agricultural development in China and other developing countries. First, governments should gradually establish significant agricultural production, supply and demand, price, monitoring and an early warning system. It is necessary to use Internet technology fully, build an information platform, collect feedback in a timely manner, and convey agricultural production and management information. In particular, analyzing the impact of significant events on the market provides farmers with reliable information security, improving their ability to judge future market trends.

Second, governments should strengthen agricultural industrialization and create a community of interest. Considering the fragmented nature of the smallholder economy, governments should support and regulate the development of agricultural organizations such as cooperatives and associations to bring together the scattered smallholders. At the same time, the government should vigorously develop contract agriculture, establish effective market docking, improve the market competitiveness of farmers, and reduce their income risks.

Third, governments should improve the agricultural insurance system, build high-quality storage facilities and logistics systems, and establish a corresponding agricultural insurance protection mechanism for farmers according to their needs and enhance their risk-coping ability. At the same time, storage facilities should be established to reduce the loss of agricultural products.

Fourth, the important role of the Internet should be given full play in helping agricultural production and operation. Internet knowledge and skills training should be provided to farmers, and personalized training courses for farmers with different educational levels should be carried out to enhance the initiative of farmers to use Internet technology to optimize agricultural production and management decisions.

However, this study also has some limitations. Firstly, although our study area, Hubei Province, is the main citrus-producing area, other producing areas remain. Secondly, the sample size of our study is small, which will affect the robustness of the results to some extent. Finally, our study sample is limited to citrus growers, and there may be differences in the factors affecting the marketing of other types of agricultural products. Therefore, more future studies could be conducted in other citrus-producing areas in China, and the sample size could be expanded. Attention should also be paid to the factors influencing the reluctant selling behavior of other agricultural products.

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Article

Monitoring System for *Leucoptera malifoliella* (O. Costa, 1836) and Its Damage Based on Artificial Neural Networks

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Abstract: The pear leaf blister moth is a significant pest in apple orchards. It causes damage to apple leaves by forming circular mines. Its control depends on monitoring two events: the flight of the first generation and the development of mines up to 2 mm in size. Therefore, the aim of this study was to develop two models using artificial neural networks (ANNs) and two monitoring devices with cameras for the early detection of *L. malifoliella* (Pest Monitoring Device) and its mines on apple leaves (Vegetation Monitoring Device). To train the ANNs, 400 photos were collected and processed. There were 4700 annotations of *L. malifoliella* and 1880 annotations of mines. The results were processed using a confusion matrix. The accuracy of the model for the Pest Monitoring Device (camera in trap) was more than 98%, while the accuracy of the model for the Vegetation Monitoring Device (camera for damage) was more than 94%, all other parameters of the model were also satisfactory. The use of this comprehensive system allows reliable monitoring of pests and their damage in real-time, leading to targeted pest control, reduction in pesticide residues, and a lower ecological footprint. Furthermore, it could be adopted for monitoring other Lepidopteran pests in crop production.

Keywords: apple pests; automatic monitoring systems; deep learning models; site-specific crop management; sustainable agriculture

1. Introduction

The pear leaf blister moth (*Leucoptera malifoliella* (O. Costa, 1836)) (Lepidoptera: Lyonetiidae) is one of the most important economic pests in apple production [1]. It occurs in orchards in Europe and Asia [2]. It is a multivoltine species [3], and due to climate change, it is becoming more common and with larger populations [4]. *L. malifoliella* is a typical physiological pest, whose larvae penetrate the leaf and feed on the mesophyll of the leaf tissue, leaving the epidermis untouched, forming circular mines. One mine has an average size of 0.88–1.04 cm^2 and represents a loss of 3.4–4.6% of the leaf surface. A higher number of mines (more than 40 per leaf) causes premature defoliation during August or early September [1]. Early defoliation has a negative effect on bud differentiation, while a severe infection on the leaves directly affects the size, yield, and quality of apple fruits [5]. Namely, the overwintering population is noticed too late due to the small dimensions of this pest and its hiding behavior, which is mostly why the damage in apple orchards is not

noticed in time [6]. Chemical treatments that are applied too late can only lead to worse results [5].

For successful control of *L. malifoliella*, monitoring of the first-generation flight and the beginning of its oviposition need to be conducted, as well as monitoring of the embryonic development of larvae, their perforation in the leaf and the initial development of mines up to 2 mm in diameter [5]. Synthetic pheromones have proven useful for monitoring *L. malifoliella* [4]. The most favorable time for insecticide treatment is the occurrence of mines of the first generation. It is considered that the critical number of mines per leaf is two to three. Such an infection enables the further development of *L. malifoliella* leading to damage of an economically significant scale [7,8]. Considering that mines are difficult to notice due to their small dimensions, it is necessary to use more precise and faster monitoring methods, in order to react in time and prevent the occurrence of significant damage.

Decision thresholds based on pest capture are the basis of integrated pest management (IPM) and are used to optimize the timing of insecticide treatment. However, IPM requires frequent visits to inaccessible orchards and checking traps on a weekly basis can lead to late interventions and ineffective control [9]. Due to climate change, agricultural systems are exposed to increasing pressures, and significant changes have been recorded in pest phenology [10]. Changes in air temperature directly affect the population dynamics, the relationship with natural enemies, and creates an increase in pest reproduction, which results in the occurrence of a greater number of generations and, consequently, greater damage. Considering the unpredictability of pest occurrence and the impracticality of existing monitoring methods, it is crucial to develop more sophisticated monitoring methods [11]. Therefore, automatic pest monitoring systems have recently been intensively developed [12,13]. The need to use automatic systems for pest monitoring is particularly important in crops that are grown on large areas, such as apples.

Apple (*Malus domestica* Borkh., 1803) is one of the most economically important fruit crops worldwide, whose fruits are consumed fresh or processed throughout the year [14]. It is grown on an area of 4.6 million hectares, and the global production in 2020 was 86.4 million tons [15]. The apple is the most commonly consumed fruit in Croatia and occupies 36% of the total fruit production [16]. Despite its importance, pest management, as well as early pest monitoring methods in apple production are mostly outdated and unreliable. Therefore, scientists developed automatic systems for monitoring apple pests [17,18], mostly for monitoring the most dangerous apple pest, codling moth (*Cydia pomonella* (Linnaeus, 1758)) (Lepidoptera: Tortricidae) [19,20]. *L. malifoliella* is a significant apple pest as well, and due to its morphology (small dimensions of all developmental stages), its detection is difficult using classical monitoring methods. Therefore, there is a need to develop and deploy automatic systems for monitoring this pest as well.

The use of deep learning for automatic pest detection from photos is increasingly being used to detect insect pests in a timely manner [21]. These works can serve as a basis for developing automatic systems to monitor other important pests and their damage. For example, Sabanci et al. [22] used two different deep learning architectures for detecting sunn pest-damaged wheat grains and achieved high classification success, with a classification accuracy of 98.50% and 99.50%. Zhong et al. [23] used neural networks to detect flying insects, and the detection accuracy was over 92%. Moreover, Sütő [24] developed a smart trap using a deep learning-based method for insect counting and proposed solutions to problems such as "lack of data" and "false insect detection". El Massi et al. [25] used a neural network and a support vector machine as a classifier for classifying and detecting damage caused by leaf miners, with more than 91% accuracy. Grünig et al. [26] presented a deep learning-based system for monitoring damage by *L. malifoliella*. The used neural network showed good results in categorizing different damage classes from 52,322 leaf photos taken under standardized conditions as well as in the field. However, for the above system to be fully effective in the timely detection of pests, it is critical that the system monitors the number of adult individuals in addition to leaf damage, as this will allow for earlier response and damage prevention.

In addition, Ding and Taylor [19] used deep learning techniques to develop a fully automated codling moth monitoring system. Namely, artificial neural networks were trained to recognize adult codling moths based on 177 collected red-green-blue (RGB) photos. The model was effective, but for the system to be even more reliable and successful in detection, a larger data set needs to be collected. Albanese et al. [27] developed a smart trap for monitoring codling moth using various deep learning algorithms. The advantage of this system is that photo processing is performed in the trap where big data is limited to a small message. In this case, only the detection results are sent to the external server, and the limited energy available in the field is used optimally. However, there is a need to develop these types of systems for monitoring *L. malifoliella* as well, so that they can be practically used under field conditions.

Most deep learning models are based on artificial neural networks (ANNs) [28,29], which have recently been applied in various fields, including agriculture [30]. In light of this, many researchers have adopted ANN-based detection methods for pest monitoring in agriculture [21,31]. Besides insect detection, artificial neural networks and their variants have been shown to be the most effective method for object detection and recognition [32].

Considering that there are no particularly effective ecological friendly control measures for *L. malifoliella* and that its management relies mostly on chemical control [2], it is extremely important to use as precise monitoring methods as possible, in order to limit chemical insecticides to only targeted and thus effective applications.

Therefore, this paper makes two main contributions. Firstly, the development of the model using artificial neural networks for early detection of *L. malifoliella* and its damage on apple leaves that is accurate, precise, fast, and requires minimal pre-processing of data. Secondly, the development of a Pest Monitoring Device (PMD) for monitoring *L. malifoliella* individuals and a Vegetation Monitoring Device (VMD) for detecting its damages. This system is based on detecting pests and their damage from photos taken with a monitoring device in the field. In these devices, data processing is performed on-the-node, which enables lower energy consumption, and thus a longer lifetime of the entire system, as well as less need for human intervention. Automatic pest monitoring is still in its infancy, and this system is an innovative solution for faster and more reliable pest monitoring.

The hypothesis of this study is that artificial neural networks and the proposed monitoring devices are a reliable tool for monitoring the pear leaf blister moth individuals and their damage if the detection accuracy is more than 90% compared to visual inspection by an expert entomologist.

2. Materials and Methods

The study is divided into four phases, which are shown in Figure 1. The first phase involves photo acquisition for the purpose of learning the ANN. In the second phase, data were processed, and the photos labelled. In the third phase, the learning (or training) ANNs were provided, in order to build an analytical model for automatic detection of *L. malifoliella* and its damage. In the final, fourth phase, monitoring devices were built to implement the developed model for monitoring pests and damage (Figure 1).

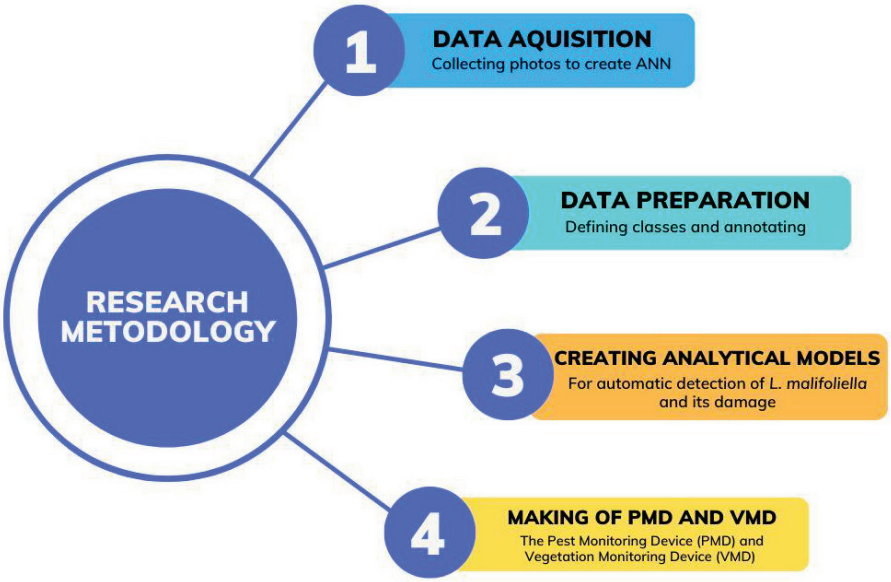

Figure 1. The methodology of the study.

2.1. Data Acquisition

The collection of photos was set up and structured so that it might be possible to obtain enough photos for all classes of defined observations. This was performed so that two EfficientDet Object identification (ANN) models could be trained [33]. No more than two ANN models were used in this work. Each of the two ANN models was used to identify a separate class. The two classes were: 1. the pest, *L. malifoliella*; and 2. the damage caused by this pest (leaf mines). The number of classes that can be seen is dependent on the quality of the photos taken, the accuracy of the detection methods, and the economic significance of the classes. How the characteristics of each class could be seen under different weather conditions was examined. This was done before the decision was made to observe a certain class.

In the period between April and September 2022, 400 photos for each model (photos of adhesive pads with adult *L. malifoliella* and photos of mines on the apple leaves) were taken in apple orchards in Zagreb County, Croatia (Petrovina Turopoljska, Mičevec, and Staro Čiče). Petrovina Turopoljska and Mičevec are orchards that use IPM strategies, whereas Staro Čiče is an orchard with organic production. Adults of *L. malifoliella* were caught on adhesive pads with traditional Delta traps, and pheromone lures (Csalomon®) were made for this species. Traps were inspected, adhesive pads were changed, and photos were taken on a weekly basis.

RGB camera was mounted in the polycarbonate housing, which mimics the housing of the Pest Monitoring Device (PMD), and used for data acquisition, in order to achieve similar shooting conditions as those taken later by the PMD. The adhesive pads were transferred from the Delta traps to the housing. Photos of adult *L. malifoliella* and apple leaves were taken manually in the field in a real production situation under different lighting conditions (sunny, cloudy, etc.) in order to create the model for automatic pest detection. The RGB cameras for both models were connected to the SBC (single board computer) of the Raspberry Pi 4 foundation, from where the camera is controlled. Photos of adult *L. malifoliella* from the Delta pheromone trap were taken in parallel with the collection of photos of vegetation. The data were collected on a weekly basis using an RGB camera. Photos of the central part of the apple tree were taken from a distance of 50 cm to detect mines on the leaves.

2.2. Data Preparation

The collected photos, both of the adhesive pads with pests, and of vegetation, were processed with the program LabelImg. Entomological experts were used to detect *L. malifoliella* adults (Figure 2) and their damage on apple leaves (Figure 3), which were marked manually with bounding boxes.

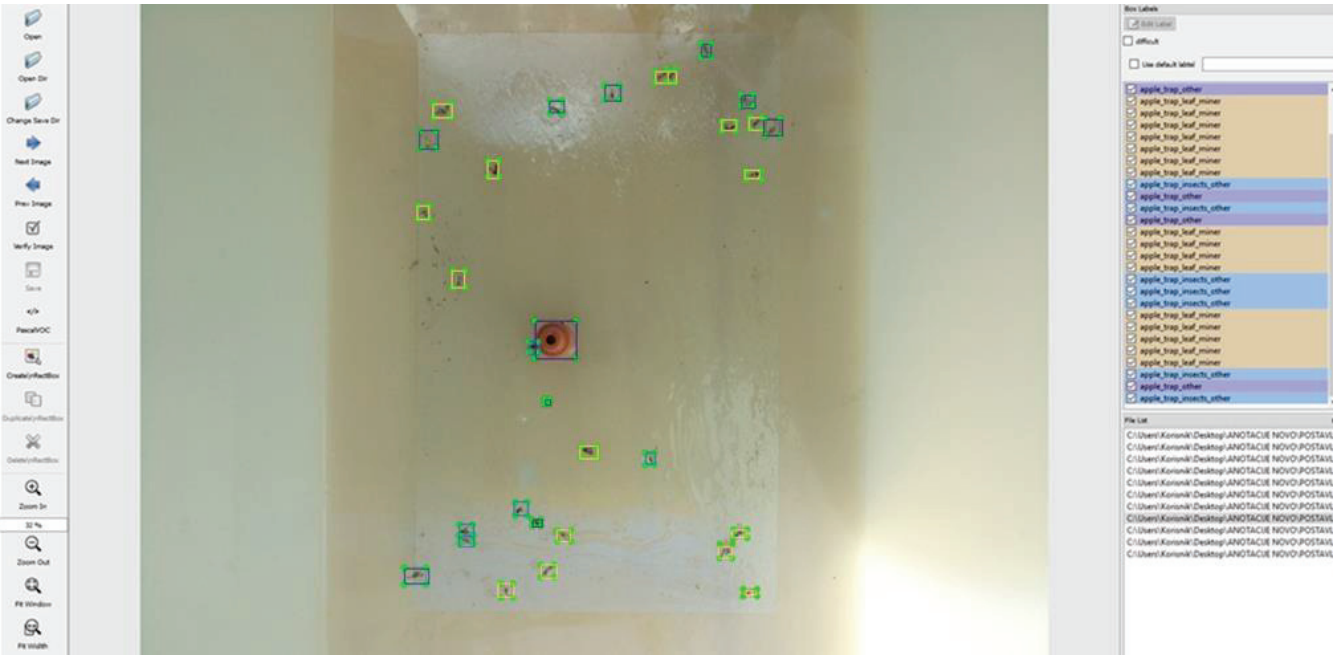

Figure 2. Annotated class MINES (*L. malifoliella* adults)—marked with yellow bounding boxes, class *OTHER* (other objects) marked with purple bounding boxes, class INSECTS (other insects) marked with blue bounding boxes in the LabelImg program from images of adhesive pads.

Figure 3. Annotated class MINES (damage caused by *L. malifoliella*)—marked with pink bounding boxes, class OTHER (other objects, healthy leaves, etc.) marked with light blue bounding boxes in the LabelImg program from images of vegetation.

For establishing a model for detecting *L. malifoliella* adults in the PMD, three classes were defined and annotated: MINER i.e., *L. malifoliella* adults, INSECT i.e., other insects and OTHER i.e., other objects (e.g., remains of leaves, branches, etc.). To make a model for detecting mines on apple leaves, two classes: MINES i.e., damage caused by *L. malifoliella*, and OTHER i.e., other objects (e.g., healthy leaves, nutrient deficiency on leaves, fruit coloration, etc.), were taken out of the 32-class model that is still under development. There are several less important subclasses for the development of both models, all of which have been set as class OTHER to better distinguish them from the important classes listed above. The 1880 annotations of the class MINES (damage) and 4700 annotations of the class MINER (pests) were used for the learning ANNs. The annotation format is PascalVOC, an XML structure. Thus, the images from the PMD consist of the segments shown in Figure 4, while the images from the VMD consist of the segments shown in Figure 5.

Figure 4. Examples of typical pest trap image segments with sizes of 55 × 90 pixels and 90 × 90 pixels include *L. malifoliella* adults (**a**,**b**); other insects (**c**); pheromone lure for *L. malifoliella* (**d**); other objects on adhesive pads (dirt, remains of leaves, branches, etc.) (**e**).

Figure 5. Examples of typical vegetation image segments with sizes of 200 × 200 pixels including damage caused by *L. malifoliella* (**a**–**c**); other objects (**d**).

2.3. Creating Analytical Models for Automatic Detection of L. malifoliella and Its Damage

Automatic object detection was performed by an artificial intelligence algorithm. The annotated images were used to create two ANNs. The ANNs are computer processing systems that are based on biological nervous systems. They are mostly made up of a large number of connected computing nodes called neurons, which work together in a distributed way to learn from inputs and improve the final output [32].

Learning (or training) ANNs to make an analytical model starts with raw images, extracting important features, such as edges and blobs, and bounding boxes of the objects (*L. malifoliella* adults and their damage) for the data set. During image processing, they were changed to fit the purpose by applying annotations and modeling concepts. A data set of 400 images was used for learning each ANN. Images were rotated by 0, 90, 180, and 270°, and copies were made that were mirrored on the horizontal and vertical axes. In the end, 12 images were taken from each original image. Then, the original image (size 4000 × 3900) was cut into smaller images (size 640 × 640), and 30 images were obtained from each of these 12 images. This gave 144,000 images for training ANN for pest detection and 144,000 images for training ANN for damage detection.

The images were randomly divided into three sets: the training set, the validation set, and the test set. For training, 80–95% of the images were used, while 20–5% of the images

were used for validation. The validation of the model is the first step of the model's quality examination, which is carried out during the model's creation [34]. For the validation phase, various basic statistical elements that define the precision of object detection were used. Namely, Average Recall (AR) and Average Precision (AP), as well as statistical indicators, which refer to indicators during the model's creation and validation at the end of each epoch, and final statistical indicators of the entire model and the classes included in the model.

Checking the accuracy of the validation during training allows for early termination and avoidance of overfitting [35]. Learning loss is a measure of how well a deep learning model fits the training data. Namely, it evaluates the error of the model on the training set. The training set is a portion of the data set used to initially train the model. The learning loss was calculated using the sum of the errors for each training sample [36]. Validation loss is a metric used to evaluate how well a deep learning model performs on the validation set. The validation set is a subset of the data set used to evaluate the performance of the model. Similar to the learning loss, the validation loss was calculated by accumulating the errors for each validation set [36].

For the test data set, it was important to select the most complicated images that the model had never seen before and test the model on this data set. The test results were statistically evaluated using the confusion matrix. Confusion matrices represent the number of predicted and actual values and indicate the accuracy of the model. The confusion matrix consists of 4 categories (TP—"true positive", TN—"true negative", FP—"false positive", and FN—"false negative") [37]. The confusion matrix was used to calculate the data on accuracy, precision, sensitivity (recall) and F1 score. The F1 score is the harmonic mean of Precision and Recall. Recall indicates the number of miners correctly identified as positive relative to the total number of miners in the image [38]. All of the aforementioned metrics were calculated using the equations of Aslan et al. [39]. The equation for each metric was defined from Equations (1)–(4). All metrics were calculated using correspondences across the entire data set and do not represent averages across individual images [19].

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{FP} + \text{TN} + \text{FN}} \times 100 \tag{1}$$

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}} \tag{2}$$

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}} \tag{3}$$

$$\text{F1 score} = \frac{2\text{TP}}{2\text{TP} + \text{FP} + \text{FN}} \tag{4}$$

The analytical models, themselves, were made through a series of algorithm tests and parameter changes to obtain the best performance for the model's intended use. The Python 3.6 programming language was chosen to run the program using the TensorFlow artificial intelligence library. Python makes it easy to write scripts quickly [40], and TensorFlow has all the functions needed to make models already built in. For the production application, the TensorFlow Lite platform was used. This means that the analytical models that were built can be used on ''end" devices with less power consumption, such as SBC [41]. Taking into account the use of analytical models on "end" devices with the TensorFlow Lite application, the quality of detection was tested on different concepts of analytical models, such as SSD (Single-Shot Detector) MobileNet in different versions, SSD ResNet in different versions, and EfficientDet-Lite in different versions. Finally, the network structure of EfficientDet-Lite 4 showed the best detection quality. EfficientDet is a new family of object detectors that are more accurate and use fewer resources than the current state-of-the-art [42].

Emerging technologies, such as computer vision, require accurate object identification but have limited processing resources. These requirements are not met by many high-accuracy detectors. Real-world object detection solutions use different platforms and

resources. "Scalable and Efficient Object Detection" (EfficientDet), an accurate object detector that uses few resources, was made by the authors in [33]. EfficientDet is nine times smaller and uses less computation than preceding state-of-the-art detectors. For its backbone for image feature extraction, it uses EfficientNet (Figure 6) [33]. The weighted bi-directional feature pyramid network (BiFPN) gives the input features more weight based on their resolution. This helps the network understand how important they are. In the next step, the feature network takes multiple levels of features from the input and sends out fused features that show the most important aspects of the image. All regular convolutions are replaced with depth-wise separable convolutions. Finally, a class or box network uses fused features to predict the class and location of each object. The EfficientDet neural network architecture can have a different number of layers in BiFPN and class or box networks based on how much processing power is available [43].

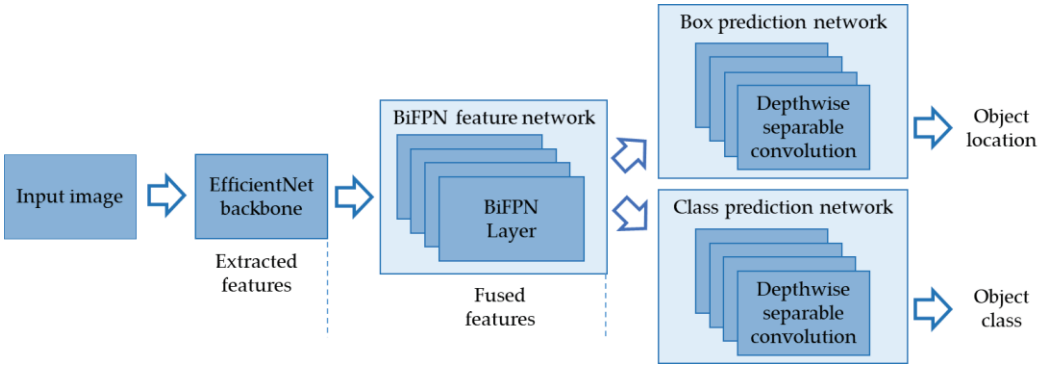

Figure 6. The structure of the EfficientDet neural network, where the number of layers changes depending on how much processing power is available [33].

Two separate ANNs were trained to identify *L. malifoliella* (MINER) and mines caused by this pest (MINES). Objects in RGB images (adult *L. malifoliella* and mines on leaves) were used to create analytical models based on what was seen and the structure of the corresponding object detection classes. The analytical models were divided into groups depending on what they are used for. For example, the PMD has an analytical model for insects (*L. malifoliella*) and the VMD has an analytical model for mines. Different concepts of algorithms have been used to develop analytical models depending on their intended use (e.g., the quality of detection, the speed of detection required, the amount of energy required for detection, etc.).

Once a model is created, each one must be tested and adjusted, and production parameters must be changed. Analytical models are constantly being improved. Regardless of the purpose or version of the camera control server, a way has been found to automatically update the analytical models. Computers specifically set up for this purpose have been used for storing data and to create analytical models. A computer with a special hardware configuration was acquired to ensure that models requiring more processing power could be created. A separate virtual server was set up for the appropriate storage of image material.

2.4. The Pest Monitoring Device (PMD) and Vegetation Monitoring Device (VMD)

The Pest Monitoring Device (PMD) for pest monitoring (Figure 7a) was housed in a milky-white polycarbonate shell. The housing contains an RGB camera, a temperature sensor for the battery and electronics, an adhesive pad, a pheromone lure, and a power supply system with a battery and a solar panel. On the other hand, in the Vegetation Monitoring Device (VMD), the RGB camera was placed in a separate housing (Figure 7b). The software for both cameras allows users to use a remote monitoring service with image transmission and processing. One PMD is sufficient for use on 1 to 3 ha of the orchard. The

devices (including the associated models) have been designed to be used throughout the vegetation and are resistant to weather conditions thanks to an external structure.

(**a**) (**b**)

Figure 7. Pest Monitoring Device (**a**); Vegetation Monitoring Device (**b**).

2.4.1. Trap Housing

During the building process, a lot of thought was put into how to protect the house from things like rain and sunlight. Because the devices were attached to the stakes in the orchard, special mounting stands had to be made. The trap, which was made specifically for several sorts of insects, also protects the camera within. The rectangular-shaped trap features two entrances on its two opposing sides. The openings are 16 cm wide and 10 cm high, while the house is 25 cm long, 24 cm high, and 16 cm broad. The antenna for the 4G and 5G networks is on top of the housing, along with the solar panel.

2.4.2. Camera

When making the camera, the features of the orchard, especially during the growing season, as well as how it would be used and the conditions in which it would work, were taken into account. The cameras were built around single-board computers (SBCs) from the Raspberry Pi Foundation. The cameras have an Rpi HQ sensor, which allows different M12 lenses to be used depending on what the camera is going to be used for. Lens specifications for the PMD are 75° HFOV, 1/23″, and 3.9 mm, while those for the VMD are 28° HFOV, 1/25″, and 12 mm. The resolution utilized was 12.5 megapixels, or 4056 × 3040 pixels. A SIM card was included in each camera to enable 4G network communication. The temperature of the battery and electronics can be observed from the temperature sensors.

2.4.3. Battery

The power supply system was made up of three Panasonic NCR18650B rechargeable lithium-ion batteries connected in series. These batteries have a 3350 mAh capacity, a 5 A maximum current capacity, and a 10.8 to 12.6 V voltage range. The Battery Management System (BMS) is in charge of making sure that charging and discharging work well so that the battery lasts as long as possible. The system is autonomous and has a long lifespan without assistance from people. The batteries were recharged using solar panels. A solar panel charges the battery system during the day so that it can run on its own.

3. Results

Two artificial neural networks or analytical models were established, one for the automatic detection of *L. malifoliella* adults within the developed PMD and one for the automatic detection of mines on apple leaves within the VMD.

3.1. Validation Phase

The validation parameters and final statistical indicators of the models and included classes are shown in Table 1. The Average Precision (AP) for the class MINER was 0.69 in the model for the PMD, while AP for the class MINES was 0.62 in the model for the VMD (Table 1). The AP of the whole model for the VMD was quite a bit lower than the AP of the MINES class, due to other classes in the model that were still in the training process.

Table 1. Validation parameters of the models for the PMD and VMD.

Parameter	Model for PMD	Model for VMD
AP	0.6630534	0.467365
AP50	0.9308306	0.6163057
AP75	0.79948294	0.538607
Aps	0.41702107	0.38043988
Apm	0.64587986	0.3874695
Apl	0.57356155	0.50087154
Armax1	0.3027751	0.5197058
Armax10	0.70718616	0.6650187
Armax100	0.75332874	0.6722461
Ars	0.5896679	0.68923765
Arm	0.73534316	0.57283384
Arl	0.6281324	0.6942948
AP_MINER	0.69061697	/
AP_MINES	/	0.62485766

* 'AP'—% AP at IoU = 0.50:0.05:0.95 (primary challenge metric); 'AP50'—% AP at IoU = 0.50 (PASCAL VOC metric); 'AP75'—% AP at IoU = 0.75 (strict metric); 'Aps'—% AP for small objects: area < 322; 'Apm'—% AP for medium objects: 32^2 < area < 96^2; 'Apl'—% AP for large objects: area > 96^2; 'Armax1'—% AR given 1 detection per image; 'Armax10'—% AR given 10 detections per image; 'Armax100'—% AR given 100 detections per image; 'Ars'—% AR for small objects: area < 32^2; 'Arm'—% AR for medium objects: 32^2 < area < 96^2; 'Arl'—% AR for large objects: area > 96^2; 'AP_/apple_trap_leaf_miner'—average precision of the class 'MINER'; 'AP_/apple_leaf_miner'—average precision of the class 'MINES' [44].

Statistical indicators during the model's creation and validation at the end of each epoch are shown in Figure 8. The EfficientDet-Lite model uses 50 epochs by default (Figure 8), which means it went through the training data set 50 times. Additionally, validation loss was measured after each epoch (Figure 8). This indicates whether the model requires additional adjustments.

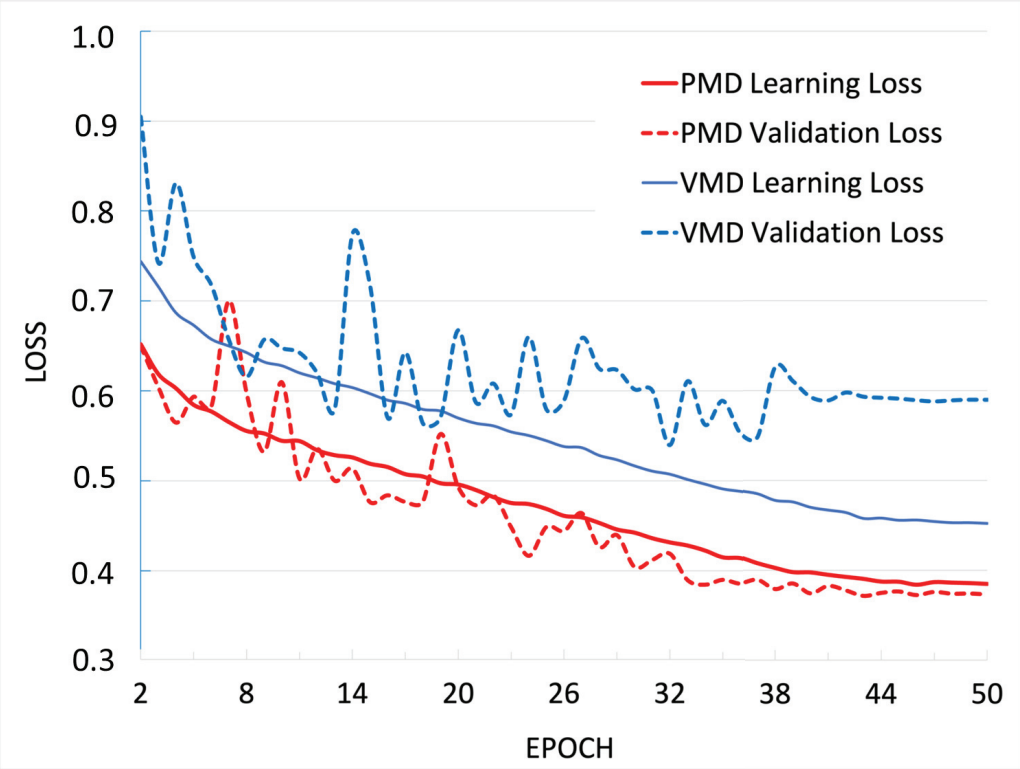

Figure 8. Process of learning and validation of the models through epochs (PMD – Pest Monitoring Device, VMD – Vegetation Monitoring Device).

In the case of the model for the VMD, the validation loss was greater than the learning loss (Figure 8), indicating underfitting of the model. Underfitting occurs when the model cannot accurately model the learning data and, therefore, produces large errors [45]. This result suggests that the model for the VMD needs to be improved with a larger data set for future use of the other classes (not mentioned in this paper), but our focus was on the class MINES. For the model for the PMD, both the learning and validation losses decreased and stabilized at a certain point (Figure 8), indicating an optimal fit (without overfitting or underfitting), so no further adjustments to the model are needed.

3.2. Test Phase

Due to the importance of the model's work in practice, the model was tested, i.e., its quality was checked after the overall creation. The data set used for model testing consisted of the 30 most complicated photos for each ANN. These photos were not used to train or validate the proposed two ANNs. The examples of automatic counts on the test photos (results of the model) are shown in Figures 9 and 10.

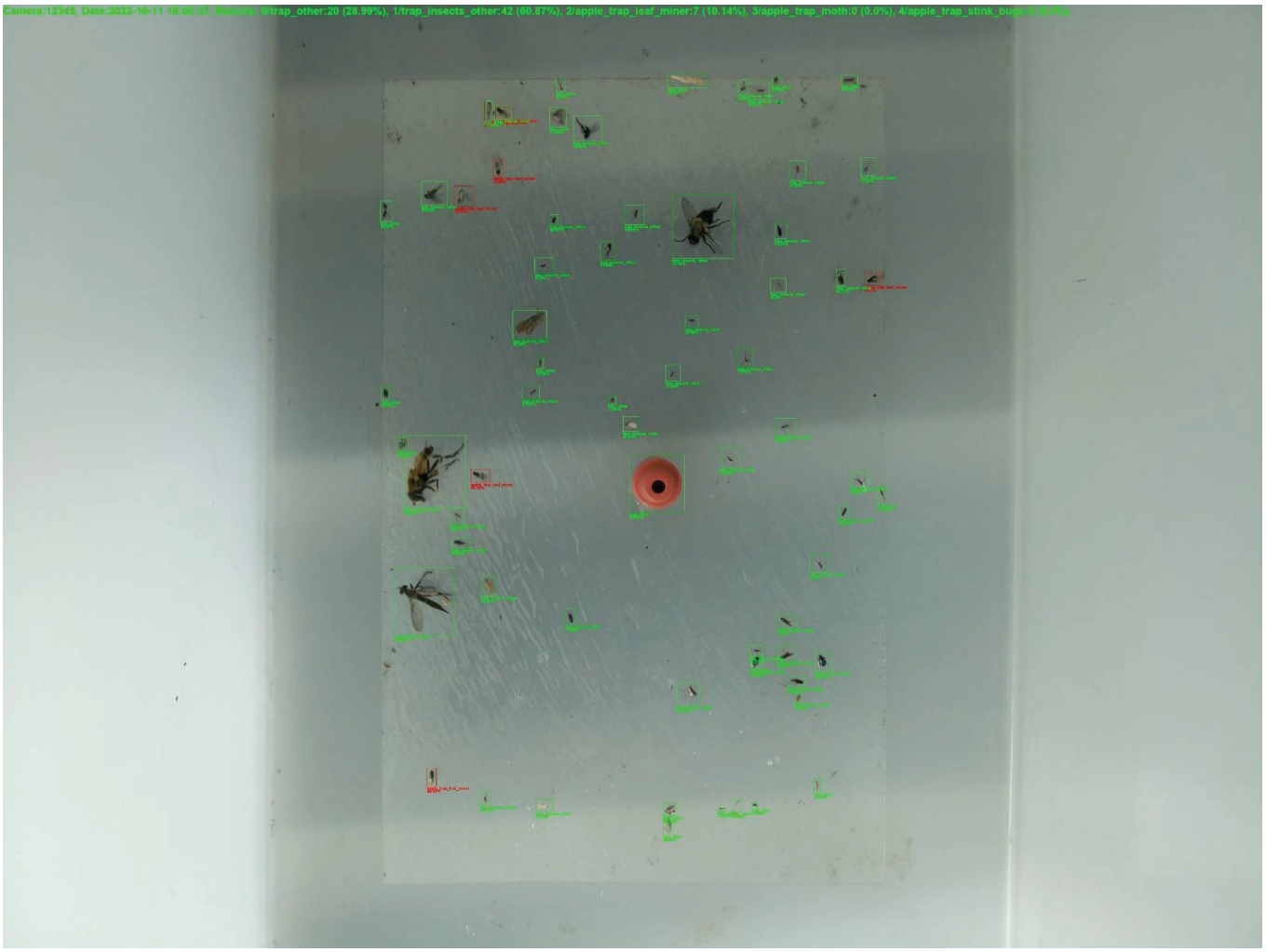

Figure 9. Example of the automatic counts of the model for the Pest Monitoring Device (PMD). Red bounding boxes – detected class MINER (*L. malifoliella* adults), green bounding boxes – detected classes OTHER (other objects) and INSECT (other insects).

The model was tested by comparing the automatic counts (Figures 9 and 10) to counts provided by an expert entomologist. The results were processed and shown using a confusion matrix (Figures 11 and 12).

In this case, the automatic counts given by the proposed detection algorithm were similar to the manual counts given by an expert entomologist. In Figure 11, which represents the confusion matrix of the model for the PMD, it can be seen that the number of class INSECT and class OTHER was high (>400).

Figure 10. Example of the automatic counts of the model for the Vegetation Monitoring Device (VMD). Green bounding boxes – detected classes (MINES, OTHER).

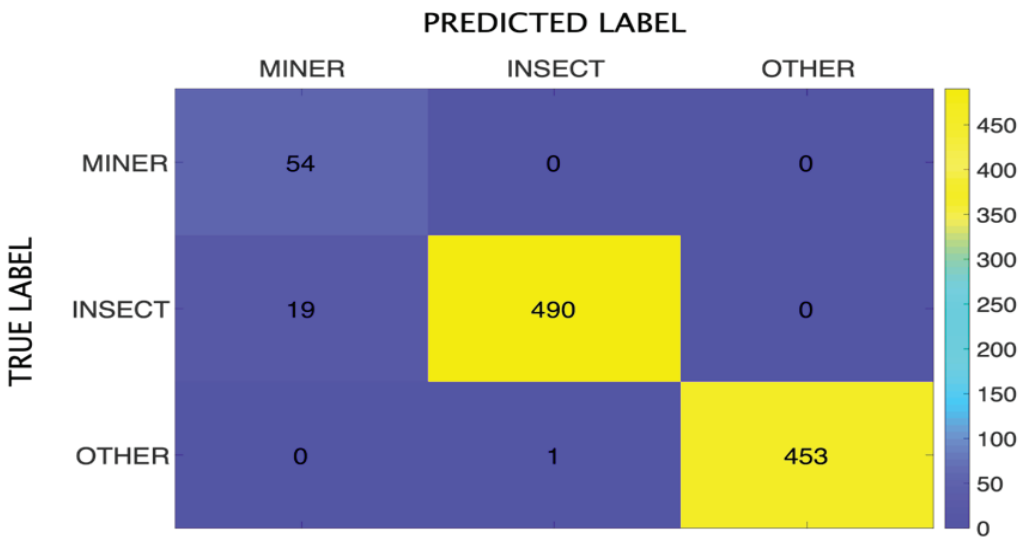

Figure 11. Confusion matrix of the detection algorithm for the Pest Monitoring Device (PMD).

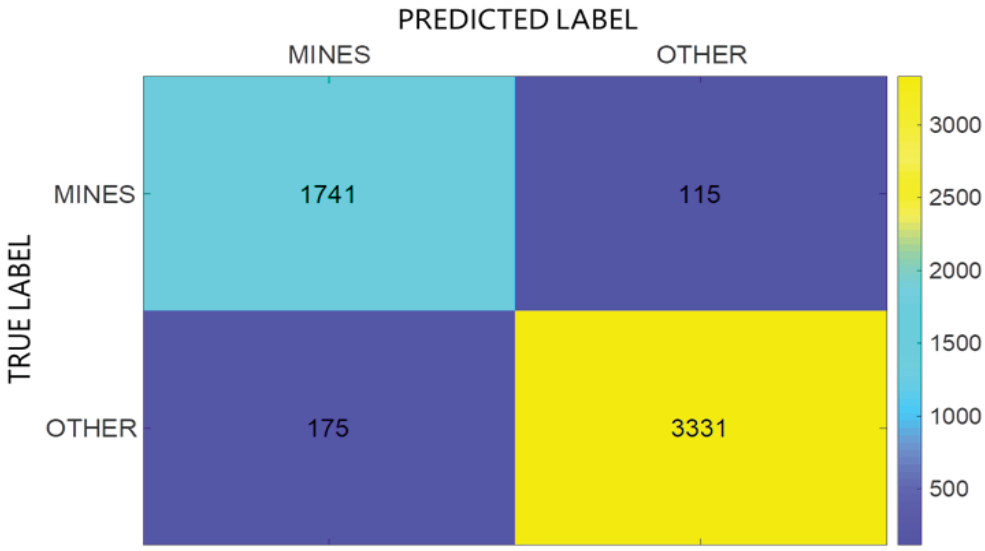

Figure 12. Confusion matrix of the detection algorithm for the Vegetation Monitoring Device (VMD).

However, there were no false positive (FP) detections, which points to the high precision of the model for the PMD (1.0) (Table 2), while the data set was big enough to build a model with a high level of accuracy (1.0) (Table 2). A high number of true positives (TP) were detected (54) and 19 objects were marked as false negatives (FN) (Figure 11). The overall model accuracy was 98.03%, and the detection accuracy of the MINER class was 98.13% (Table 2).

Table 2. Metrics per class in the model for the Pest Monitoring Device (PMD).

Class	(n) Truth	(n) Classified	Accuracy	Precision	Recall	F1 Score
MINER	73	54	98.13%	1.0	0.74	0.85
INSECT	491	509	98.03%	0.96	1.0	0.98
OTHER	453	454	99.9%	1.0	1.0	1.0

In the case of the model for the PMD, the precision value was 1.0, which indicates a completely precise model for detecting *L. malifoliella* (Table 2); while in the model for the VMD, the precision value was 0.94 (Table 3). The recall in the model for the PMD was 0.74 and 0.91 for the VMD. For detecting *L. malifoliella* adults in the PMD model, the F1 score was 0.85 (Table 2), and 0.92 in the model for the VMD (Table 3). All aforementioned metrics (accuracy, precision, recall and F1 score) were calculated and the values are shown in Tables 2 and 3.

Table 3. Metrics per class in the model for the Vegetation Monitoring Device (VMD).

Class	(n) Truth	(n) Classified	Accuracy	Precision	Recall	F1 Score
MINES	1916	1856	94.59%	0.94	0.91	0.92
OTHER	3446	3506	94.59%	0.95	0.97	0.96

In the model for the VMD, 115 FP detections were recorded (Figure 12), while the number of FN detections was 175. However, there was a high number of annotations and TP detections (1741 mines) (Figure 12). Finally, the overall accuracy of the model was 94.59%, as was the detection accuracy for the class MINES (Table 3).

The detection algorithm (model) started working as soon as an image was captured. On-site data processing was performed with a storage limit of 15 MB. The execution of the proposed method takes six minutes on average. Due to the built-in on-site detection mechanism, the detection result is sent with as few bytes as possible, which makes it

suitable for rural areas. Larger models require more storage space and more time to run, making them difficult to use. The optimization phase aims to reduce the model size while minimizing the loss of accuracy or performance to find the optimum. This allows faster evaluation while minimizing accuracy loss. The proposed implementation applies optimization both during the training phase and before the evaluation of the training model.

4. Discussion

In this study, while testing the model for the PMD, there were no false positive (FP) detections, which points to the high precision of the model. In contrast, Preti et al. [20] developed a smart trap for monitoring the codling moth (*C. pomonella*) (Lepidoptera: Tortricidae), which had a high number of FP detections, accounting for 90.7% of the automatic counts. The majority of FP detections were represented by shadows on the adhesive pads, lures, and flies. The low precision was caused by the high number of FP detections, suggesting that adjustments to the detection algorithm are required. They point out that the reason is a small data set, and Du et al. [46] proved this with a theoretical calculation that the error in the ANN algorithms class is correlated to the data set size.

Moreover, in the model for the PMD, several detected objects were marked as false negatives (FN), mostly due to the change in color and decomposition of the insects over time. Ding and Taylor [19] analyzed errors caused by different factors and emphasized that many errors are related to time. Hence, the same insect pest could have different wing poses and decay conditions over time. Moreover, decaying insects could make the originally transparent adhesive pad become dirty and reduce the contrast between the insects and the background. Errors caused by time-related factors could be largely avoided in real production systems if adhesive pads in the smart trap are changed approximately once in every ten days, in order to avoid insect decomposition and dirt accumulation, and thus, a higher number of misdetections.

The difference between counts detected by an algorithm and counts detected manually by an entomologist is called detection accuracy. An accuracy equal to 100% means that the number of objects marked and counted automatically by the ANN matches the number of *L. malifoliella* adults on the adhesive pad. An accuracy lower than 100% means that there were *L. malifoliella* adults that were not recognized by the model. An accuracy greater than 100% represents counting non-target insects or other items as the miner; thus, the automatic identification overestimated the true occurrence of miners, which was the case in Preti et al. [20]. In our case, there were no FP detections in the model for the PMD, whereas in the case of the model for the VMD's accuracy, this was not impacted by FP detections, due to the similar number of FN detections (Table 3). The precision parameter can range between 0 and 1. Values of precision close to 1 mean that the occurrence of false positives is very low, and therefore, the total automatic detection corresponded to the correct detections of *L. malifoliella* adults (showing that the algorithm is precise and does not mark non-target insects or other items) [20].

In the model for the VMD, several FP and FN detections were recorded (Figure 12). The reason for more FP detections is that the mines on leaves were misidentified as part of a branch or dry leaf. Most of these missed detections happened at the edges of the picture, where the mines were not fully shown and were, therefore, not seen. Even though there were more FP and FN than in the PMD model, and the overall accuracy, as well as the other parameters (Table 3) were slightly lower, the results are oddly satisfying, and the model is usable in practice, because there was a high number of annotations and TP detections.

When compared to other successful works concerning detecting Lepidopteran apple pests using ANNs, both models demonstrated the potential to work in practice. The accuracy of the considered models is higher than 90% [27,47], as well as in this work. Therefore, one can consider the models proposed in this work efficient for practical use. Suárez et al. [47] used the TensorFlow library and the programming language Python to make a model for detecting codling moths. The overall accuracy of the developed model was 94.8%. Similar results were obtained by Albanese et al. [27]. By using different deep

learning algorithms in their trap, they achieved an accuracy of 95.1–97.9% in detecting codling moths. Grünig et al. [26] created an image classification model for detecting damage on apple leaves, using neural networks to achieve good results in categorizing different damage classes from photos of leaves taken under standardized and field conditions. The model was 93.1% accurate at detecting damage caused by *L. malifoliella*. This means that the model is good for automatic damage detection. However, there is no available model for the automatic detection of this pest in a trap, nor the developed automatic system, and works by Grünig et al. [26] and El Massi et al. [25] only classify damage caused by this pest. For the above-mentioned system to be fully effective in controlling pests in a timely manner, it is critical that the system monitors the number of adult individuals, in addition to leaf damage, so that it can intervene earlier and prevent damage (mines) from occurring.

The proposed model is accurate, precise, fast, and requires minimal preprocessing of data. In addition, the Pest Monitoring Device (PMD) for monitoring *L. malifoliella* adults and Vegetation Monitoring Device (VMD) for detecting its damages on apple leaves are both portable, independent devices that require no additional infrastructure installation. Most of the time, they are operating in sleep mode. This means that they use less energy, last longer, and have less need for human intervention. This system is specific, because the output of each device is the number of objects of a certain class that it detects (not the whole image). Due to the fact that the output is represented as a small amount of data, it is sent quickly over a mobile network. The results of detection are sent to the web portal, which is where all further analysis and reporting are performed. Several smart traps for monitoring apple pests are available on the market [48,49], but there is no available trap, nor comprehensive system for automatic monitoring of *L. malifoliella* or its damage.

Therefore, in this work, a comprehensive system consisting of two object detection models and accompanying devices for pest and vegetation damage monitoring (the PMD and VMD) was developed to obtain complete information in the orchard about *L. malifoliella* occurrence, to react in a timely manner, and prevent the occurrence of economically important damage. This proposed system contributes to the improvement of automatic pest monitoring and, thus, to its wider application. The use of this system allows for targeted pest control, thus reducing the use of pesticides, decreasing the negative impact on the environment, and ultimately allowing for higher quality and more profitable apple production.

5. Conclusions

The developed models showed high accuracy in detecting *L. malifoliella* (>98%) and its damage (>94%), compared to visual inspection by an expert entomologist. Therefore, the hypothesis established is accepted and the proposed system is an effective and reliable tool for monitoring the pear leaf blister moths and their damage. The system is also operative in field conditions. Automatic monitoring systems are still in their infancy, and to date, there are no research results on automatic monitoring of *L. malifoliella* individuals. The proposed solution can provide comprehensive detection results (pest and damage monitoring) directly from apple orchards to enable site-specific management and sustainable apple production. Further research is recommended to extend this system for the detection of other important apple pests as well as other Lepidoptera pests in crop production. In precision agriculture, innovative solutions, such as automatic monitoring systems, are a key element of decision support systems. Therefore, they are expected to be used as the gold standard for pest monitoring in the future.

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Sustainable Bioconversion of Wetland Plant Biomass for *Pleurotus ostreatus* var. *florida* Cultivation: Studies on Proximate and Biochemical Characterization

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Abstract: The abundant biomass growth of aquatic macrophytes in wetlands is one of the major concerns affecting their residing biota. Moreover, the biomass degenerates within the wetlands, thereby causing a remixing of nutrients and emission of greenhouse gases. Therefore, it is crucial to find sustainable methods to utilize the biomass of aquatic macrophytes devoid of environmental concerns. The present study investigates the utilization of the biomass of three aquatic macrophytes, including the lake sedge (CL: *Carex lacustris* Willd.), water hyacinth (EC: *Eichhornia crassipes* Mart. Solms), and sacred lotus (NL: *Nelumbo nucifera* Gaertn.) to produce oyster (*Pleurotus ostreatus* var. *florida*) mushrooms. For this purpose, different combinations of wheat straw (WS: as control) and macrophyte's biomass (WH) such as control (100% WH), CL50 (50% WH + 50% CL), CL100 (100% CL), EC50 (50% WH + 50% EC), EC100 (100% EC), NL50 (50% WH + 50% NL), and NL100 (100% NL) were used for *P. florida* cultivation under controlled laboratory conditions. The results showed that all selected combinations of wheat straw and macrophyte biomass supported the spawning and growth of *P. florida*. In particular, the maximum significant ($p < 0.05$) growth, yield, bioefficiency, proximate, and biochemical parameters were reported using the WH substrate followed by CL, NL, and EC biomass, which corresponds to the reduction efficiency of the substrate parameters. Therefore, the findings of this study reveal that the biomass of selected aquatic macrophytes can be effectively utilized for sustainable mushroom cultivation while minimizing the risk associated with their self-degeneration.

Keywords: waste management; sustainable agriculture; mushroom cultivation; super foods; pollution reduction

1. Introduction

Wetland ecosystems have been regarded as a significant contributor to global greenhouse gas emissions [1]. Wetland vegetation serves as a major sink of carbon and CH_4 emissions, which consumes nutrients from the water and sediments. However, CH_4 release flux largely varies depending on the type of wetland plant, nutrient availability, the interaction of the root–shoot system, and the plant's biochemical composition [2]. Moreover, wetlands have a very high capacity to store atmospheric carbon dioxide in their soils and vegetation, which counteracts the greenhouse effect and slows the rate of global warming [3]. A wide variety of aquatic and semi-aquatic plants are some of the keystone species of the wetland ecosystem that regulate its functionality. However, wetland plant biomass contributes to environmental pollution in several ways due to its rapid growth, thus causing the death of other organisms above and below the water surface [4].

Moreover, when wetland plants die, their decomposing tissues release harmful greenhouse gases and nutrients (such as nitrogen and phosphorus) that pollute both the atmosphere and nearby water bodies [5]. The released nutrients from the decayed wetland plants can re-enter the water, which promotes the growth of harmful algae blooms, thereby reducing the amount of oxygen in the water and consequently causing harmful effects on fish and other aquatic animals [6,7]. Similarly, large amounts of CO_2 and other toxic gases are released into the atmosphere if the wetland plant biomass is burnt. Therefore, it has become necessary to find sustainable methods for managing wetland plant biomass [8]. However, wetland plant biomass is rich in several nutrients and mineral elements and can be utilized for several purposes, such as biofuel and mushroom production. Several studies have reported that aquatic plants harvested from wetlands could be a renewable resource for sustainable biofuel and essential raw materials for horticulture industries [9,10].

Unlike conventional horticulture crops, mushroom cultivation has become a fast-growing agri-business that provides good income without the need for large fields. In recent years, mushroom cultivation has expanded significantly in India [11]. After China, India is currently the second-largest mushroom producer worldwide. Oyster mushrooms are India's most commonly grown mushrooms, followed by button and shiitake mushrooms [12]. In India, approximately 0.23 million tons of mushrooms are produced annually [12]. Several small- and medium-sized businesses have recently been established to cultivate edible and medicinal mushrooms [13]. Currently, there are about 1500 mushroom farmers, of whom 60% have less than 1 hectare of land under cultivation to meet the market demands [14]. The remaining growers fall into two categories: medium and large growers, with 1–5 and 5–10 hectares of land under cultivation, respectively, which are responsible for international exports. Out of several mushroom species cultivated in India, oyster mushrooms make up about 17% of the total, followed by button and shiitake mushrooms [15].

Mushroom cultivation is very beneficial for managing plant waste. Growing mushrooms can aid in lowering greenhouse gas emissions caused by the natural decomposition of plant waste. Moreover, growing mushrooms can help recycle plant materials and lessen the amount of organic waste that would otherwise end up in landfills, which significantly contributes to plant waste management [16]. Therefore, the mushroom cultivation sector plays a significant role in the biological management of plant residues for generating foods [17]. Recent studies have shown that mushrooms can be grown using wetland waste as a substrate [9]. The wetland biomass comprises lignin, cellulose, hemicellulose, and other mineral elements [18]. Thus, these wastes can be inoculated with mushroom spawn to produce high-quality fruiting bodies.

Previously, limited studies have assessed the feasibility of wetland plant wastes for mushroom cultivation. Considering the environmental concern associated with using biomass, the efficient management of wetland plant biomass is necessary to reduce its environmental impacts. Keeping this in mind, the proposed study focused on utilizing the biomass of three wetland plants for the sustainable cultivation of oyster (*Pleurotus ostreatus* var. *florida*) mushrooms. These species were chosen for their high abundance in Haridwar wetlands. Further, the formulated mushroom substrates and harvested

fruiting bodies of *P. florida* were characterized in terms of physicochemical, proximate, and biochemical properties.

2. Materials and Methods

2.1. Collection of Wetland Plant Biomass and Mushroom Spawn

For the present study, fresh biomass of selected wetland plants such as lake sedge (CL: *Carex lacustris* Willd. 1805), water hyacinth (EC: *Eichhornia crassipes* Mart. Solms), and sacred lotus (NL: *Nelumbo nucifera* Gaertn) was collected from the local water bodies of Haridwar district, Uttarakhand, India (29.8876° N and 78.0195° E). Similarly, wheat straw (*Triticum aestivum* L.) was obtained from the local agricultural fields of Haridwar city. All wastes were collected in 10 kg capacity packaging-grade plastic bags and immediately transported to the laboratory for further processing. The collected wastes were sun-dried for one week and chopped into small pieces (2–3 cm) using a mechanical cutter. The freshly prepared grain spawn of oyster (*Pleurotus ostreatus* var. *florida*) mushroom was procured from Prakriti Mushroom and Spawn Lab located in Kaulagarh, Dehradun, Uttarakhand, India. One of the study's authors supervised the preparation of grain spawn at the aforementioned locations to ensure an adequate process. The grain spawn was stored at 4 °C until its final mixing with the substrate.

2.2. Experimental Design and Conditions

A total of seven treatments (having different ratios of selected wastes), such as control (100% WS.), CL50 (50% WH + 50% CL), CL100 (100% CL), EC50 (50% WH + 50% EC), EC100 (100% EC), NL50 (50% WH + 50% NL), and NL100 (100% NL), were prepared as substrates for the cultivation of *P. florida* mushrooms (Figure 1). The mixtures' proportions were chosen based on a previous pilot study performed (data not shown). All experiments were performed using five identical replicates. For this, the proportional weight of selected wastes was placed individually in plastic tubs of 25 L capacity (pre-sterilized using 10% formalin solution and sun-dried) for all treatments [19]. The wastes were moistened and chemically sterilized by dipping in the tubs containing 20 L tap water mixed with 20 mL formalin solution, 2 g carbendazim, and 50 g calcium carbonate for a period of 12 h [19]. Subsequently, the substrate was removed and placed on a plastic rack for rinsing the excess water and achieving optimum moisture content (≈65%) [19]. Further, the substrate was placed in an aluminum container and then pasteurized at 60 °C for 4 h using an autoclave (7421PAD Equitron, Medica Instruments, Mumbai, India) [20].

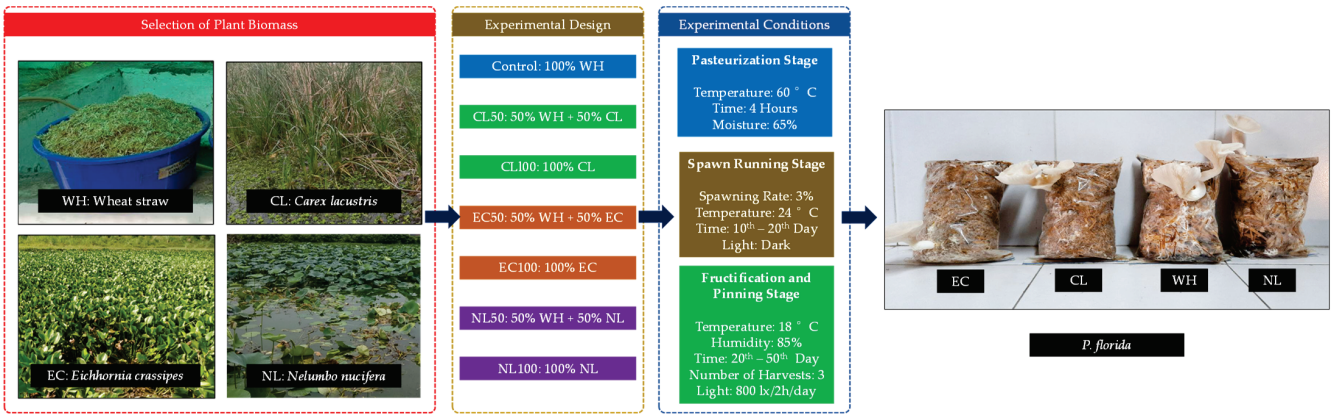

Figure 1. Study layout for plant biomass selection, experimental design, and conditions for cultivating *P. florida*.

After cooling, 2 kg substrate was filled in the breathable polypropylene bags (3 kg capacity), and 3% *w*/*w* grain spawn was aseptically mixed [21]. The spawned bags were then placed on a cultivation rack inside the mushroom cultivation room of the Agro-ecology and Pollution Research Laboratory, Department of Zoology and Environmental

Science, Gurukula Kangri (deemed to be a university), Haridwar, India. Spawn running was allowed at a room temperature of 24 °C in dark conditions. The room was opened for 2 h (daily) for efficient fresh air exchange (FAE). Once spawn running was completed, the room conditions were adjusted to 18 °C temperature, 85% relative humidity, and 800 lx of light intensity (2 h/day), respectively [22]. The substrate bags were pierced using sterile needles to make holes for efficient pin-head formation. The fruiting bodies of *P. florida* were carefully harvested (cut with a knife) once they reached marketable size and color. In this experiment, the *P. florida* crop was harvested in three subsequent flushes.

2.3. Analytical Methods

The mushroom substrates prepared from selected wastes were analyzed for selected physicochemical and proximate parameters before and after the cultivation of *P. florida*. Specifically, standard methods of chemical analyses were adopted as prescribed by AOAC [23] and used by Kumar et al. [24]. The pH and electrical conductivity (EC: dS/m) were measured using the pre-calibrated meter (ESICO 1611, Parwanoo, India). The contents of carbon and nitrogen in the substrate were determined with the methods of Walkley and Black [25] and Kjeldahl [26]. The proximate parameters such as ash, cellulose, hemicellulose, and Klason-lignin contents in the mushroom substrate were assessed using techniques previously reported by Gessner [27]. The harvested *P. florida* mushroom bodies were characterized for selected parameters such as moisture (%), protein (%), lipids (%), carbohydrates (%), ash (%), ascorbic acid (μg/100 g), carotenoids (μg/100 g), and total phenol (mg/100 g) contents. The moisture content of *P. florida* mushrooms was estimated using the oven-drying method by placing the fresh fruiting bodies at 60 °C until a constant weight was achieved. Similarly, the protein content was determined by the Kjeldahl method [28]. Total lipids and carbohydrate contents were determined using modified methods as previously adopted by Alam et al. [29]. Ash, ascorbic acid, carotenoids, and total phenol contents were analyzed following the methodology described by Kumar et al. [30]. Briefly, ash content was determined using a muffle furnace at 550 °C for 1 h. The ascorbic acid content was ascertained (absorbance peak 245 nm) using a 5% metaphosphoric acid solution as an extraction reagent. Similarly, carotenoids were determined by extracting them with petroleum ether and measuring the absorbance at 450 nm. Total phenol content was determined using the acetone extraction method (adding sodium carbonate and Folin–Ciocalteau reagent) and spectrophotometric analysis at 725 nm (Cary 60, UV-Vis, Agilent, Santa Clara, CA, USA).

2.4. Data Analysis

In this study, the obtained data were tested using analysis of variance (ANOVA) and Tukey's multiple range test based on Prob. (p) < F value of 0.05. The changes in the mushroom substrate properties were presented using the percent reduction efficiency (BE) tool [24]. The following Equation (1) was used for RE (%) calculation:

$$\text{Reduction Efficiency} = [(\text{IV} - \text{FV})/\text{IV}] \times 100 \quad (1)$$

where IV and FV are the initial and final (after cultivation) parameter values of the *P. florida* mushroom substrate. Moreover, the biological efficiency (BE: %) of selected waste substrates for *P. florida* production was also calculated in order to understand their cultivation suitability [31]. The following model (Equation (2)) was used for the calculation of BE:

$$\text{Biological Efficiency (\%)} = [(\text{FM}/\text{DW})] \times 100 \quad (2)$$

where FM refers to the total fresh weight of mushrooms (g) harvested from mushroom bag treatment having DW, i.e., initial dry weight of substrate (g), respectively. The interactive effects of different waste materials and their properties on growth, yield, and biochemical constituents of harvested *P. florida* mushrooms were studied using Pearson correlation analysis. This tool measures the strength of the linear relationship between variables with

−1 and +1 representing the respective values of total negative and positive correlations and a neutral (0) value corresponding to no correlation. Further, a hierarchical cluster analysis tool tested the similarities among different treatment groups and different properties of *P. florida* mushroom. The latter consists of agglomerative nesting that uses single-element clusters for each group to develop similarity. As a result, a combined tree is developed, and a heatmap showing similarities between participating groups is obtained.

2.5. Software and Tools

The obtained data were analyzed and processed using Microsoft Excel 2021 (Microsoft, Redmond, WA, USA) and OriginPro 2022b (OriginLab, Northampton, MA, USA) software packages.

3. Results and Discussion

3.1. Changes in Substrate Properties before and after P. florida Cultivation

The mushroom substrate prepared from different combinations of wetland plant biomass and wheat straw was analyzed for selected properties to evaluate its efficiency in *P. florida* cultivation. The changes in the physicochemical and proximate characteristics of the substrate before and after *P. florida* mushroom cultivation are presented in Table 1. The results showed that the initial characteristics of the mushroom substrate were significantly ($p < 0.05$) reduced after the termination of experiments. Specifically, it was observed that the pH and EC of the mushroom substrates in all treatments were maximally reduced in the control and CL50 treatment, while the minimum value was observed in the EC100 treatment. Similarly, the contents of C and N were also significantly ($p < 0.05$) reduced as a result of mycelial action on the substrate and utilizing them as a primary energy source. Other proximate parameters of the substrate also declined significantly ($p < 0.05$). Based on the reduction efficiency index, the highest reductions in C (38.88%), N (9.16%), ash (13.21%), hemicellulose (51.32%), cellulose (64.27%), and lignin (38.70%) were observed in control treatment followed by CL50, NL50, EC50, CL100, NL100, and EC100, respectively (Figure 2). Overall, a 50% blend of wetland plant biomass with 50% wheat straw waste showed better reduction than their absolute treatments (CL100, EC100, and NL100). Mycelia produces acidic enzymes that help in the breakdown of β-galactoside bonds inside cellulose thereby reducing the pH of substrate rapidly in the colonization stage; however, it becomes stationary during the fructification stage [32]. It is reported that mushrooms require greater contents of C to grow and reproduce efficiently than N, which might be the reason behind their rapid reduction [33]. In this study, the C/N ratio ranged from 23.45 to 36.72, which is the ideal range as previous studies have shown that a substrate having a C/N ratio of 7–40 is considered optimum for mushroom cultivation [34].

Previously, limited studies have assessed the feasibility of wetland plant wastes for mushroom cultivation. Hultberg et al. [9] utilized the residues of the common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) plant for *P. ostreatus* (M2140) mushroom cultivation. They reported that wetlands produced significant biomass in two subsequent years (2016–2017) having a C/N ratio of 24 ± 5. A significant reduction in common-reed-based mushroom substrate was reported, producing high-quality fruiting bodies of *P. ostreatus*. Similarly, Mukhopadhyay et al. [10] also evaluated the potential of water hyacinth (*E. crassipes*) biomass in combination with wheat straw for the cultivation of selected *Pleurotus* spp. They found that water hyacinth biomass had sufficient energy sources and nutrient loads to support *Pleurotus* spp. growth.

Table 1. Changes in properties (mean ± SD of five replicates) of wetland plant biomass-based substrates before and after *P. florida* cultivation.

Treatment		Mushroom Substrate Properties								
		pH	EC (dS/m)	C (%)	N (%)	C/N	Ash (%)	H.C.L. (%)	CL (%)	L (%)
Control	Before	7.01 ± 0.01 a	3.01 ± 0.03 a	48.10 ± 1.90 a	1.31 ± 0.01 a	36.72	2.12 ± 0.03 a	24.20 ± 0.56 a	45.37 ± 2.74 a	9.07 ± 0.03 a
	After	5.10 ± 0.03 b	2.07 ± 0.05 b	29.40 ± 2.02 b	1.19 ± 0.03 b	24.71	1.84 ± 0.04 b	11.78 ± 1.78 b	16.21 ± 3.06 b	5.56 ± 0.09 b
CL50	Before	6.96 ± 0.03 a	2.79 ± 0.06 a	47.23 ± 0.95 a	1.30 ± 0.02 a	36.33	2.08 ± 0.02 a	22.99 ± 1.05 a	43.69 ± 1.59 a	8.74 ± 0.12 a
	After	5.13 ± 0.02 b	2.09 ± 0.10 b	30.15 ± 1.64 b	1.20 ± 0.01 b	25.13	1.93 ± 0.03 b	12.50 ± 2.66 b	19.32 ± 2.20 b	6.10 ± 0.07 b
CL100	Before	6.90 ± 0.03 a	2.56 ± 0.05 a	46.35 ± 1.31 a	1.29 ± 0.02 a	35.93	2.04 ± 0.01 a	21.78 ± 0.97 a	42.01 ± 1.11 a	8.40 ± 0.05 a
	After	5.87 ± 0.04 b	2.12 ± 0.09 b	35.09 ± 1.05 b	1.21 ± 0.01 b	29.00	1.93 ± 0.02 b	14.02 ± 1.32 b	23.58 ± 3.01 b	6.25 ± 0.19 b
EC50	Before	6.76 ± 0.01 a	2.91 ± 0.08 a	38.59 ± 2.10 a	1.28 ± 0.01 a	30.27	1.96 ± 0.04 a	21.62 ± 0.63 a	38.97 ± 2.48 a	8.99 ± 0.08 a
	After	5.49 ± 0.02 b	2.25 ± 0.03 b	28.09 ± 1.47 b	1.19 ± 0.02 b	23.61	1.84 ± 0.03 b	12.95 ± 1.70 b	19.81 ± 0.97 b	6.84 ± 0.10 b
EC100	Before	6.50 ± 0.03 a	2.81 ± 0.04 a	29.08 ± 0.89 a	1.24 ± 0.02 a	23.45	1.80 ± 0.02 a	19.03 ± 1.07 a	32.57 ± 1.76 a	8.91 ± 0.04 a
	After	5.75 ± 0.05 b	2.34 ± 0.07 b	22.47 ± 0.52 b	1.20 ± 0.01 b	18.73	1.74 ± 0.02 b	13.66 ± 0.81 b	18.82 ± 2.55 b	6.96 ± 0.11 b
NL50	Before	6.92 ± 0.02 a	2.87 ± 0.10 a	41.02 ± 1.73 a	1.26 ± 0.01 a	32.56	1.85 ± 0.01 a	23.75 ± 1.25 a	41.25 ± 2.02 a	8.80 ± 0.09 a
	After	5.12 ± 0.01 b	2.18 ± 0.05 b	27.09 ± 0.86 b	1.18 ± 0.03 b	22.96	1.75 ± 0.02 b	13.59 ± 2.04 b	20.06 ± 1.17 b	6.37 ± 0.03 b
NL100	Before	6.82 ± 0.04 a	2.73 ± 0.04 a	33.94 ± 1.24 a	1.21 ± 0.02 a	28.05	1.58 ± 0.03 a	23.29 ± 1.42 a	37.13 ± 2.35 a	8.52 ± 0.10 a
	After	5.78 ± 0.03 b	2.22 ± 0.06 b	25.09 ± 0.92 b	1.16 ± 0.02 b	21.63	1.50 ± 0.01 b	15.91 ± 0.63 b	21.09 ± 1.60 b	6.43 ± 0.04 b

The same letters (a,b) indicate no significant difference in substrate properties before and after *P. florida* cultivation; CL: *Carex lacustris*; EC: *Eichhornia crassipes*; NL: *Nelumbo nucifera*; EC: electrical conductivity; C: carbon; N: nitrogen; C/N: carbon to nitrogen ratio; HCL: hemicellulose; CL: cellulose; L: lignin.

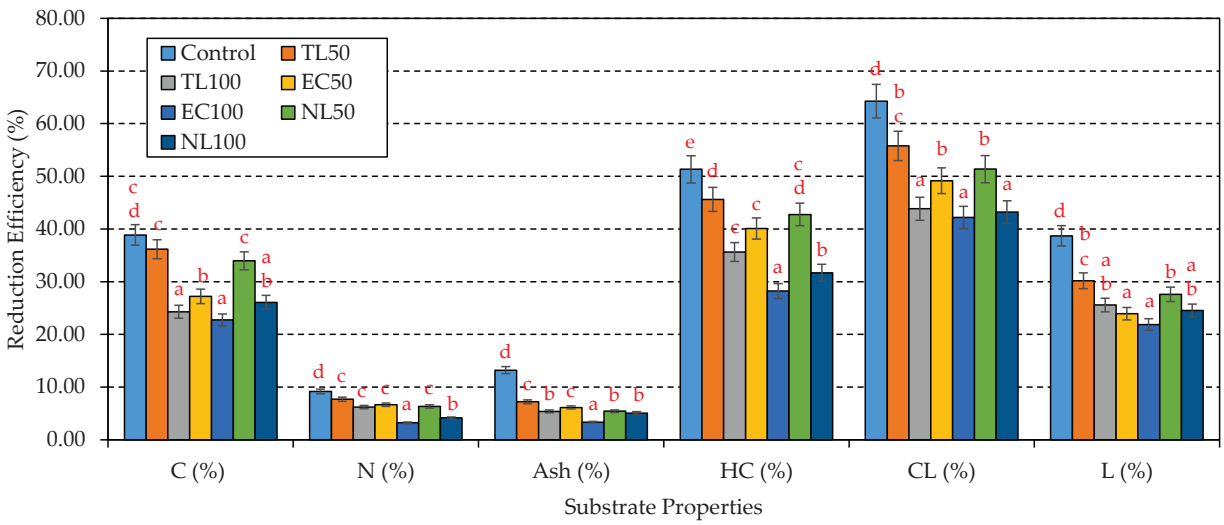

Figure 2. Reduction efficiency (%) of mushroom substrate properties before and after *P. florida* cultivation (The same letters (a–e) indicate no significant difference between treatment group values; TL: *Typha latifolia*; EC: *Eichhornia crassipes*; NL: *Nelumbo nucifera*; EC: electrical conductivity; C: carbon; N: nitrogen; HCL: hemicellulose; CL: cellulose; L: lignin).

3.2. Effect of Wetland Plant Biomass on Growth and Yield of P. florida

The fastest colonization of *P. florida* for substrates was detected with the control and CL50 as 12.0 ± 1.0 and 13.0 ± 1.0 days, respectively (Table 2). The growth of *P. florida* on plant extracts cultivated on Petri dishes at a 25 °C incubation showed fast colonization, thus, corroborating with the current field findings [35]. Moreover, the high cellulose content in these substrates promotes the mycelial colonization of *Pleurotus* spp., as previously outlined by Sassine et al. [36]. In the first flush, the highest yield was observed with the control followed by CL50 with 115.46 ± 4.08 and 95.10 ± 3.57 g/kg, respectively ($p < 0.05$). A similar trend was observed in the second and third flushes, with 93.55 ± 2.77 and 86.81 ± 4.23 g/kg, and 45.05 ± 1.50 and 42.18 ± 2.74 g/kg, respectively. Consequently, the total yield was also the highest in those two treatments, with 254.06 ± 6.82 and 224.17 ± 8.10 g/kg, respectively. The lowest yields and BEs were observed when *P. florida* mushrooms were grown on substrates fully based on wetland biomass. This could be explained by the fact that these biomasses had a lower C/N ratio than other treatments;

mycelial growth and development are normally associated with a high C/N ratio [31]. Lower cellulose content in such substrates may have contributed to the delay of substrate colonization and the reduction in yield and BE; this component acts as the main source of energy for the mycelium [37]. It is worth noting that mushroom yields decrease as the growing cycle proceeds; i.e., subsequent flushes outline decreased yields [22]. The BE is an important parameter for mushroom substrate selection. Although no substrate reached 80% BE—the economically feasible BE for mushroom cultivation [38]—the control and CL50 treatments (72.59 ± 0.80 and 64.05 ± 1.47%, respectively) showed significantly higher ($p < 0.05$) BEs compared to the remaining substrates, as depicted in Table 2. Figure 3a outlines a strong correlation between wheat straw on the one hand and yield and BE on the other hand, which explains the highest yield and BE observed with the control. A previous study outlined the use of the wetland common reed (*Phragmites australis*) in the production of *P. ostreatus* [9]. The results delineated a 140% BE, which is 2.2–3.7 times higher than the values obtained with wetland plant biomass in this study. Incorporating other plant biomass, e.g., alfalfa pulp, also resulted in 166.3% BE [39]. These authors referred to the increase in BE in the protein content of the used substrate. This corroborates the strong correlation between these two parameters, as shown by Pearson's correlation (Figure 3a).

Table 2. Effect of wetland plant biomass on growth and yield properties (mean ± SD of five replicates) of *P. florida*.

Treatment	Colonization (Days)	Yield (g/kg Fresh Substrate)				Biological Efficiency (%)	Pileus Diameter (cm)	Stipe Length (cm)
		First Flush	Second Flush	Third Flush	Total			
Control	12.00 ± 1.00 a	115.46 ± 4.08 e	93.55 ± 2.77 e	45.05 ± 1.50 d	254.06 ± 6.82 f	72.59 ± 0.80 e	7.30 ± 0.04 f	6.39 ± 0.07 e
CL50	13.00 ± 1.00 a	95.10 ± 3.57 d	86.81 ± 4.23 e	42.18 ± 2.74 d	224.17 ± 8.10 e	64.05 ± 1.47 d	6.79 ± 0.07 e	5.75 ± 0.05 d
CL100	18.00 ± 2.00 c	70.22 ± 5.16 a	56.63 ± 2.06 b	30.08 ± 0.98 a	156.96 ± 5.17 ab	44.85 ± 1.82 b	4.66 ± 0.03 b	4.22 ± 0.18 b
EC50	15.00 ± 1.00 b	77.36 ± 2.09 b	64.09 ± 3.42 c	34.10 ± 1.26 b	175.45 ± 7.32 c	50.13 ± 3.25 c	5.30 ± 0.10 c	4.42 ± 0.09 b
EC100	19.00 ± 2.00 c	61.09 ± 4.82 a	46.32 ± 1.85 a	24.67 ± 2.30 a	132.09 ± 9.51 a	37.74 ± 0.78 a	4.20 ± 0.18 a	3.46 ± 0.13 a
NL50	14.00 ± 1.00 b	82.24 ± 2.70 c	70.40 ± 2.57 d	39.30 ± 1.10 c	191.99 ± 4.08 d	54.85 ± 1.35 c	5.82 ± 0.05 d	4.75 ± 0.06 c
NL100	14.00 ± 1.00 b	67.02 ± 3.56 a	51.06 ± 3.14 a	26.50 ± 3.12 a	144.58 ± 8.66 a	41.31 ± 2.92 b	4.38 ± 0.12 a	3.64 ± 0.20 a

The same letters (a–f) indicate no significant difference among different substrate groups; CL: *Carex lacustris*; EC: *Eichhornia crassipes*; NL: *Nelumbo nucifera*; EC: electrical conductivity; C: carbon; N: nitrogen; HCL: hemicellulose; CL: cellulose; L: lignin.

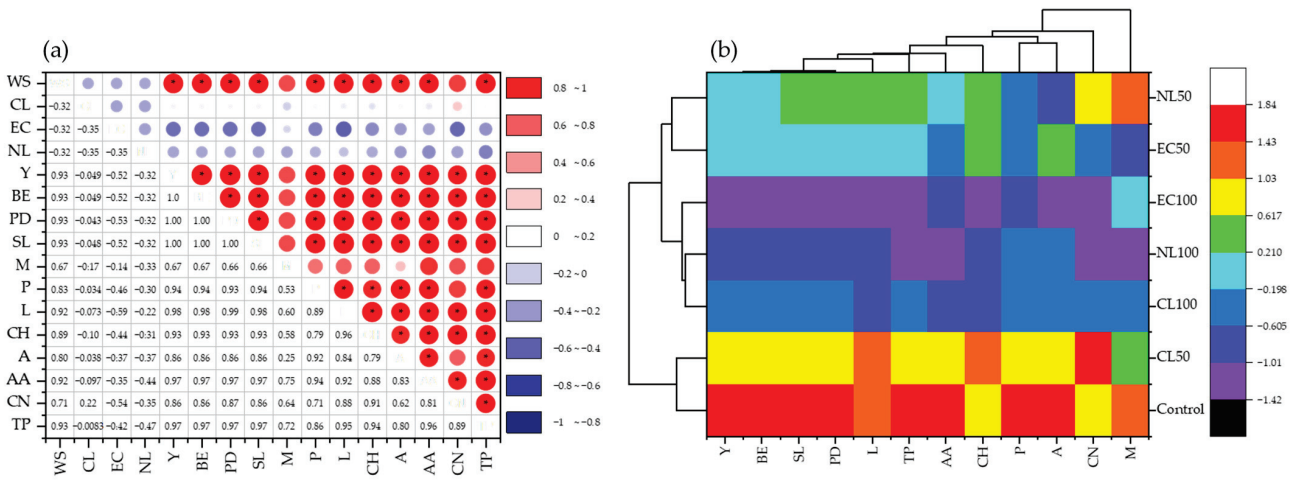

Figure 3. (**a**) Pearson correlation and (**b**) hierarchal cluster matrices showing the effect of different biomass treatments on growth, yield, and biochemical constituents of *P. florida* (TL: *Typha latifolia*; EC: *Eichhornia crassipes*; NL: *Nelumbo nucifera*; WS: wheat straw; Y: yield; BE: biological efficiency; PD: pileus diameter; SL: stipe length; M: moisture; P: protein; L: lipid; CH: carbohydrates; A: ash; AA: ascorbic acid; CN: carotenoids; TP: total phenols).

Commercially, mushrooms with large pilei and short stipes are the most preferred by consumers. The largest pileus (PD) and longest stipe (SL) were observed with the control and CL50 (7.30 ± 0.04 and 6.79 ± 0.07 cm, and 6.39 ± 0.07 and 5.75 ± 0.05 cm, respectively).

EC100 and NL100 had the shortest and most economically preferred stipes (3.46 ± 0.13 and 3.64 ± 0.20 cm, respectively). Therefore, CL50 showed the most economically feasible mushrooms in terms of pileus diameter, while EC100 and NL100 were the most suitable in terms of stipe length. A previous study indicated the close interrelationship between shorter oyster mushroom stipes and the inoculation of plant biomass residues in the growing substrate [37]. Strong correlations were observed between PD on the one hand, and yield and BE on the other hand (Figure 3a), which is obvious as caps generally weigh more than stipes. Increased PD and SL simulate increased protein, lipid, and carbohydrate contents in the substrate; those contents need further investigation. Similar findings were reported on *P. ostreatus* where PD and SL were closely related to substrate composition, especially in terms of protein and carbohydrates [37]. Hierarchical cluster analysis (HCA) is a descriptive classification that helps identify high similarities/dissimilarities between parameters or groups of parameters [24]. Herein, the similarities between groups of treatments were depicted in a heat-map-based cluster diagram (Figure 3b) in terms of the production and composition parameters of *P. florida* mushrooms. The minimum and maximum distances were −1.42 and 0.67, respectively, based on the nearest neighboring method of Euclidian clustering. The highest similarity was observed between the control and CL50, and dissimilarity between their grouping on the one hand and the remaining treatment group on the other hand. Although HCA effectively outlined the interactive effect of the composition parameters, no clear understanding of the effect of the production parameters of *P. florida* treatments was obtained.

3.3. Effect of Wetland Plant Biomass on Nutrient and Biochemical Composition of P. florida

The results of the proximate and biochemical constituents of *P. florida* grown on different wetland plant biomass spp. are presented in Table 3. Moisture, protein, lipid, carbohydrates, ash, ascorbic acid, carotenoids, and total phenol levels were significantly ($p < 0.05$) the highest in control and CL50 treatments (86.30 ± 2.10 and 85.66 ± 1.98%; 25.14 ± 0.22 and 24.42 ± 0.24%; 2.36 ± 0.05 and 2.35 ± 0.05%; 48.70 ± 0.40 and 49.02 ± 0.21%; 7.52 ± 0.04 and 7.48 ± 0.05%; 0.49 ± 0.01 and 0.47 ± 0.02 μg/100 g; 0.23 ± 0.01 and 0.24 μg/100 g; 6.12 ± 0.03 and 6.10 ± 0.04 μg/100 g, respectively) compared to the remaining treatments. Increased moisture content in mushrooms can hasten the deterioration process during the postharvest period leading to enzymatic browning [40]. Herein, the incorporation of wetland plant biomass decreased the moisture content in harvested *P. florida* mushrooms. Oyster mushrooms grown on alfalfa pulp showed slightly lower moisture content (83.13%) [39]. These authors also outlined a lower protein content in harvested mushrooms than those grown on wetland plant biomass in this study (lower by 2.54–4.82%). The observation of Figure 3a depicts a correlation between moisture content in *P. florida* mushroom and WS. This finding corroborates with Abou Fayssal et al. [37], who found a direct influence of WS in *P. ostreatus* growing substrate on the moisture content of harvested mushrooms. Moreover, lower protein and carbohydrate contents in mushrooms grown on substrates fully based on wetland biomass can be related to the lower C/N ratio of such substrates, as observed in Table 1. Furthermore, the lower lignin content found in mushrooms grown on these substrates compared to the control explains the fact that *P. florida* had a lower capability to degrade this component from the substrate and translocate it into the fruiting body. This finding corroborates a similar hypothesis lately raised on *P. ostreatus* [22].

Our findings outlined a strong positive correlation between protein content in the harvested mushrooms and WS in the growing substrate. This contradicts the findings of Piskov et al. [41] and Gao et al. [42] on wheat and rice straws in *P. ostreatus* and *L. edodes* cultivation, respectively. Moreover, the protein content was significantly correlated with increased yield, BE, PD, and SL (Figure 3a). Mushrooms are generally low in fat/lipid; the incorporation of different wetland plant biomass reduced this content, especially with CL100, EC100, and NL100 ($p < 0.05$). Therefore, mushrooms harvested from these treatments are healthier than those from the control and can help in the remediation

of cardiovascular problems [37]. CL50 increased the carbohydrate content in harvested mushrooms, which can present a promising additive to carbohydrate-rich diets. Wetland plant biomass-based substrates resulted in mushrooms with lower ash content. Overall, harvested mushrooms in this study were not very rich in ash; it may be returned to their freshness as, during storage or processing, mushrooms dry, and their ash content tends to increase accordingly [43]. Promising ascorbic acid contents (also known as vitamin C) were found in *P. florida* mushrooms grown on wetland plant biomass spp. This vitamin is essential for humans as a primary antioxidant found in plasma and cells [44]. CL50 mushrooms had a higher carotenoid content than the control ones; carotenoids play a crucial role in the non-enzymatic ROS defense mechanisms [45]. When wetland plant biomass was added to the growing substrate, good total phenol values were noted in harvested mushrooms. Phenolic compounds hold interesting redox properties, which are responsible for antioxidant activity [46].

Table 3. Effect of wetland plant biomass on proximate and biochemical constituents (mean ± SD of five replicates) of *P. florida*.

Treatment	Proximate Constituents (%)					Biochemical Constituents		
	Moisture	Protein	Lipid	Carbohydrates	Ash	Ascorbic Acid (μg/100 g)	Carotenoids (μg/100 g)	Total Phenol (mg/100 g)
Control	86.30 ± 2.10 ab	25.14 ± 0.22 c	2.36 ± 0.05 b	48.70 ± 0.40 cd	7.52 ± 0.04 b	0.49 ± 0.01 d	0.23 ± 0.01 b	6.12 ± 0.03 b
CL50	85.66 ± 1.98 a	24.42 ± 0.24 c	2.35 ± 0.05 b	49.02 ± 0.21 d	7.48 ± 0.05 b	0.47 ± 0.02 cd	0.24 ± 0.01 b	6.10 ± 0.04 b
CL100	85.10 ± 2.06 a	23.15 ± 0.17 b	2.30 ± 0.06 a	46.20 ± 0.19 b	7.38 ± 0.10 a	0.43 ± 0.02 b	0.22 ± 0.01 a	6.05 ± 0.01 a
EC50	84.90 ± 1.55 a	23.23 ± 0.30 b	2.32 ± 0.04 ab	47.81 ± 0.28 c	7.44 ± 0.05 ab	0.44 ± 0.01 c	0.22 ± 0.02 a	6.07 ± 0.04 ab
EC100	85.53 ± 2.91 a	22.90 ± 0.13 a	2.28 ± 0.06 a	45.75 ± 0.13 a	7.35 ± 0.07 a	0.43 ± 0.02 b	0.21 ± 0.01 a	6.03 ± 0.02 a
NL50	86.37 ± 1.72 ab	23.28 ± 0.25 b	2.33 ± 0.07 ab	47.94 ± 0.36 c	7.36 ± 0.03 a	0.45 ± 0.01 c	0.23 ± 0.01 ab	6.08 ± 0.04 ab
NL100	84.48 ± 1.05 a	23.20 ± 0.18 b	2.30 ± 0.04 a	46.09 ± 0.09 b	7.39 ± 0.06 a	0.42 ± 0.02 a	0.21 ± 0.01 a	6.02 ± 0.02 a

The same letters (a–d) indicate no significant difference among different substrate groups; CL: *Carex lacustris*; EC: *Eichhornia crassipes*; NL: *Nelumbo nucifera*; EC: electrical conductivity.

4. Conclusions

The findings of this study concluded that the biomass of selected wetland plants (TL: *Typha latifolia*; EC: *Eichhornia crassipes*; NL: *Nelumbo nucifera*) could be efficiently utilized in combination with wheat straw waste for the sustainable cultivation of oyster (*Pleurotus ostreatus* var. *florida*) mushrooms. Overall, a 50% blend of wetland plant biomass and wheat straw (WS) gave the highest *P. florida* yield with enhanced proximate and biochemical constituents. However, the use of absolute (100%) wetland plant biomass gave a relatively lesser yield than treatments carried out in combination with WS. The highest yield, growth, proximate, and biochemical properties of *P. florida* were reported using WS (100%) treatment followed by 50% blends of CL, NL, and EC, respectively. Therefore, this study suggests that the biomass of selected aquatic plants harvested from wetlands can be used as renewable substrate resources for *P. florida* mushroom cultivation to reduce the environmental risk associated with their self-degradation. Further studies on using other aquatic plants to cultivate *P. florida* and other mushroom species are highly recommended.

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