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Zero Hunger

Health, Production, Economics and Sustainability

Edited by
Richard John Roberts, José-María Montero, María del Carmen Valls Martínez,
Viviane Naimy and José Manuel Santos-Jaén

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About the Editors

Richard John Roberts

Richard J. Roberts is the Chief Scientific Officer at New England Biolabs, a Royal Society Fellow, and the 1993 Nobel Laureate in Physiology or Medicine. He obtained a B.Sc. in Chemistry (1965) and a Ph.D. in Organic Chemistry (1968) from the University of Sheffield. His postdoctoral research in Prof. J.L. Strominger's lab at Harvard focused on tRNAs involved in bacterial cell wall biosynthesis. From 1972-1992, he worked at Cold Spring Harbor Laboratory, becoming Assistant Director for Research under J.D. Watson. In 1972, he began work on Type II restriction enzymes; subsequently, over 100 such enzymes were discovered and characterized in his laboratory. His laboratory has cloned genes for several restriction enzymes and their cognate methylases, and studying them remains a major theme. He also studied Adenovirus-2 transcription, leading to the discovery of split genes and mRNA splicing in 1977. This was followed by deducing the Adenovirus-2 genome sequence (35,937 nucleotides). His laboratory pioneered computer applications in this area, and developing methods for protein and nucleic acid sequence analysis remains a major focus. DNA methyltransferases are also an area of active research interest, and crystal structures for HhaI methyltransferase (alone and with DNA) were obtained with Dr. X. Cheng. This complex is remarkable as the protein causes the target cytosine base to flip out of the helix, making it accessible for chemical reaction—an elegant, previously unseen distortion. He runs REBASE, a database of all known bacterial and archaeal restriction enzymes and DNA methylases. Current interests include semi-automatic identification of restriction enzyme and methylase genes within GenBank and developing rapid function assays. Several new specificities were found, revealing more restriction enzyme genes in Nature than previously suspected. PacBio sequencing now allows for determining complete methylomes for bacteria, leading to the discovery of many novel enzymes.

José-María Montero

José-María Montero is Professor of Applied Economics and Statistics at the University of Castilla-La Mancha (Spain) and Director of the International Academic Council of Exponential Education (since 2020), which includes, among its members, four Nobel Laureates. He currently serves as President of the International Association of Applied Economics-ASEPELT (since 2019) and as Vice President of the Supreme Executive Council of the International Association CESTIRA (since 2016). Professor Montero is also an advisor to the International Association for Sustainable Economics (IASE) and to the Social Sciences and Humanities Research Council of Canada (since 2014). He is a Research Fellow at the Athenian Policy Forum (York University, United Kingdom), a member of the External Committee of the Lawrence Klein University Institute, a former patron of the Philippe Cousteau Foundation (2014–2022), and an Honorary Life Member of the International Atlantic Economic Society (since 2014), among other academic and institutional roles. Professor Montero has delivered keynote lectures at major international conferences, collaborated in scientific programs with Nobel Laureates in Economics and Medicine, and taught at numerous universities worldwide. His academic output includes 32 books, 51 book chapters, and over one hundred articles published in journals indexed in Clarivate and Scopus. He has served as principal investigator for 42 research projects and acted as Editor-in-Chief of *CLM.Economy* and *the IEB International Journal of Finance*, and is currently a member of the editorial boards of 21 leading international journals. His h-index is 32, with a total of 4,818 citations. His research interests encompass data science, artificial intelligence, business analytics, spatial-temporal geostatistics, air pollution control, real estate prices, and income distribution.

María del Carmen Valls Martínez

María del Carmen Valls Martínez, Ph.D., is a Full Professor of Financial Economics and Accounting at the University of Almería (UAL), Spain. With over 30 years of academic experience, her research has evolved from financial mathematics toward sustainability, corporate social responsibility, and gender studies within the economic sphere. She is the founder and head of the research group "Ethics, Gender, and Sustainability". Dr. Valls Martínez has published extensively with prestigious academic publishers, including Springer, Dykinson, Pirámide, and McGraw-Hill. She is the author of numerous articles in high-impact scientific journals such as the *Journal of Cleaner Production*, *Corporate Social Responsibility and Environmental Management*, *European Research on Management and Business Economics*, *Women's Studies International Forum*, *Sustainable Development*, and *Oeconomia Copernicana*, among others. Beyond her research and teaching, she contributes significantly to the scientific community through her editorial work. She serves as an editor for *Mathematics*, *PLOS ONE*, and *Frontiers* in Public Health.

Viviane Naimy

Viviane Naimy is a Professor of Finance and Dean of the Faculty of Business Administration and Economics at Notre Dame University, Lebanon. A recognized expert in financial econometrics and risk management, she has an extensive publication record in top academic journals and has received several research awards for her contributions. As Dean, she successfully led AACSB accreditation. She also founded and serves as Managing Editor of the *Journal of Sustainable Economies*, in partnership with Northeastern University, providing a platform for research on poverty and hunger alleviation. Dr. Naimy has collaborated with a Nobel Laureate on research focused on poverty reduction. She is also the co-founder and president of the Sustainable Farming Technology Association (SFT), an initiative dedicated to improving agricultural solutions to combat hunger and improve livelihoods. Beyond academia, Dr. Naimy has served as a consultant in risk management across several Arab countries, advising on financial stability and economic resilience. In recognition of her leadership and research impact, she has been honored with the 2025 Beta Gamma Sigma Dean of the Year Award.

José Manuel Santos-Jaén

José Manuel Santos-Jaén, PhD, is an Associate Professor of Accounting and Finance at the University of Murcia, Spain. He is a graduate in Business Administration and Management, and a graduate in Law. He has completed three masters (MBA, Financial Management, and Auditing). He finished his PhD in 2011. He is currently teaching financial statement analysis, financial accounting, and corporate accounting. His research is focused on several aspects of Business and Management, such as Firm Performance, Innovation, Sustainability, and Corporate Social Responsibility, among others. He is strongly oriented to a quantitative, survey-based methodology, mainly Structural Equation Modeling (PLS-SEM). He has published in international journals, including *Journal of Cleaner Production*, *Corporate Social Responsibility and Environment*, *IEEE Transactions on Engineering Management*, *Sustainable Production and Consumption*, *The International Journal of Management Education*, and *Total Quality Management and Business Excellence*. He has also presented the progress of his research at national and international congresses.

Preface

Ending hunger is not only a question of producing more food; it is a systemic challenge that sits at the intersection of human health and nutrition, agricultural and aquaculture production, natural resource stewardship, market performance, and the governance of risk. In recent years, the fragility of these interconnections has become more visible: climate variability, geopolitical instability, price shocks, and disruptions in trade and logistics can rapidly translate into reduced access to safe and nutritious food—particularly for the most vulnerable communities. Against this backdrop, achieving Sustainable Development Goal 2 (Zero Hunger) requires integrated solutions that improve productivity and livelihoods while protecting ecosystems, reducing waste, and strengthening resilience from farm to fork.

The MDPI Topic "Zero Hunger: Health, Production, Economics and Sustainability" was conceived to provide a multidisciplinary forum where these interdependent dimensions can be examined together. Rather than treating food security as a single-sector problem, this Topic emphasizes cross-cutting evidence and methods that connect sustainable production practices, circular resource use, and value-chain and policy dynamics. Its objective is both practical and analytical: to identify interventions that can be implemented, measured, and scaled, and to highlight the tradeoffs and synergies that decision makers must navigate when designing strategies for food system transformation.

This reprint compiles twelve peer-reviewed articles published within the Topic across the MDPI journals. Collectively, the contributions span multiple levels of analysis—ranging from field and farm management to processing and product innovation, and from national value chains to broader scientific and policy landscapes. Taken together, they illustrate how progress toward Zero Hunger depends on combining technological and agronomic innovation with resource efficiency, behavioral and organizational change, and sound economic and policy design.

Several chapters focus on the prevention of food loss and waste and operational strategies that can improve both nutritional outcomes and system efficiency. Institutional settings, including school and early-childhood food services, provide an especially important point of intervention: reducing avoidable waste in these environments can generate immediate economic savings, lower environmental footprints, and reinforce healthy consumption patterns at formative stages of life. Complementing these demand- and operations-side perspectives, other contributions highlight circular approaches that recover value from residues and by-products—demonstrating how innovation in processing and product development can reduce waste while creating new economic opportunities.

A second thematic cluster addresses sustainable production and resource efficiency. These studies examine nutrient management under Good Agricultural Practices, the use of bio-based amendments and composts to improve soil fertility, and approaches to recycling nutrients and water under conditions of increasing scarcity. This Topic's scope intentionally includes emerging strategies for integrating recovered resources into agriculture—reflecting a broader shift toward circularity and the reduction in dependency on finite inputs. This cluster also extends to controlled-environment and specialty crop production, including research on edible mushrooms that evaluates growth performance and associated emissions, as well as work aimed at optimizing bioactive compound production. These contributions illustrate how sustainability in agriculture increasingly involves simultaneous optimization across yield, quality, and environmental impact metrics.

A third cluster foregrounds resilience, markets, and the economics of food systems under uncertainty. Food security outcomes are shaped not only by production potential but also by how shocks propagate along value chains, how prices adjust across market levels, and how policies and expectations influence investment and behavior. The volume therefore includes analyses of vertical price transmission and value-chain dynamics, empirical work on the impacts of external shocks on agri-food pricing, and broader evidence on the role of the digital economy in enhancing agricultural productivity. In addition, bibliometric and synthesis-oriented research helps map how scholarly attention is responding to geopolitical pressures and sustainability concerns—offering a structured view of evolving research priorities and knowledge gaps.

Across these themes, a common message emerges: progress toward Zero Hunger will be accelerated by approaches that are both integrated and evidence-based. Technological advances and improved agronomic practices matter, but they are most effective when paired with measures that reduce losses and waste, strengthen market functioning, support informed policymaking, and align incentives across stakeholders. Moreover, solutions must be context-sensitive. What is feasible and impactful depends on agroecological conditions, infrastructure, institutional capacity, and the distribution of risks and benefits along the food value chain.

We hope this collection serves as a useful reference for researchers seeking contemporary methods and empirical findings, for policymakers designing interventions that balance productivity with sustainability, and for practitioners and industry leaders implementing innovations in production, processing, and supply-chain management. By bringing together contributions that cut across health, production, economics, and sustainability, the reprint aims to support more coherent strategies—strategies capable of improving food availability, access, utilization, and stability in ways that are durable and equitable.

As Guest Editors, we are grateful to the authors for the rigor and relevance of their contributions, and to the reviewers for their careful evaluations and constructive recommendations, which strengthened the manuscripts substantially. We also thank the editorial and administrative teams at MDPI and the participating journals for their professional support throughout the development of the Topic and the preparation of this volume. We also extend special thanks to the Associate Publisher, Dr. Syna Mu, for their outstanding coordination, responsiveness, and guidance at every stage of the process, which were instrumental in bringing this project to completion.

Richard John Roberts, José-María Montero, María del Carmen Valls Martínez, Viviane Naimy, and José Manuel Santos-Jaén

Topic Editors

resources

Article

Developing Guidelines for *Azolla microphylla* Production as Compost for Sustainable Agriculture

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Abstract: *Azolla* is a substitute compost that has the potential to enhance nutrient cycling in agricultural systems for sustainable development. In this study, four experiments were conducted to compare the Department of Agriculture (DOA, Thailand)'s methodology for determining the suitable type and rate of animal manure and the optimal light intensity for the growth and yield of *Azolla* (*Azolla microphylla*). The results revealed that applying 100% pig manure gave the highest yield of *Azolla* compared to the other manures. However, there was no discernible ($p > 0.05$) difference in yield across the various doses (20.16, 30.16, and 40.16 gN m^{-2}) of pig manure treatments, for which the minimal pig manure dosage of 20.16 gN m^{-2} was chosen. For further experimentation in the optimal light intensity, the 40% shading gave the highest yield of *Azolla* compared to no shading or 20 and 60% shading ($p \leq 0.01$). When compared with the DOA Thailand methodology (1.27 kg m^{-2} of cow manure and covered with a size 32 mesh net), the findings indicated that the modified method (20.16 gN m^{-2} of pig manure + 40% shading) gave a 16% greater *Azolla* yield than that under the DOA Thailand methodology. The current finding method can produce a monthly fresh biomass of *A. microphylla* of 40.7 t ha^{-1} $year^{-1}$ with higher contents of total N (4.92%) and lower C:N ratio ($\leq$10:1) that could release minerals relatively rapidly. Its use can be encouraged by farmers to produce their own ecofriendly biofertilizer or soil amendment for sustainable agriculture.

Keywords: *Azolla*; manure; shading; nutrient content; fresh biomass yield

1. Introduction

Azolla (*Azolla* sp.) is an aquatic floating fern that can be grown in swampy areas of both temperate and tropical regions. It can be grown quickly in varied environments globally, and its proper soils are clay, sandy, and nutrient-rich, as well as stagnant water with little flow [1,2]. The genus *Azolla* sp. is an excellent biofertilizer due to its ability to harvest atmospheric nitrogen through a symbiotic association with cyanobacteria or blue-green algae (specifically *Anabaena azollae*), which resides in its dorsal leaves [3,4]. *Azolla* sp. is known for being a natural source of green manure and is composted for agricultural use in many areas [5,6]. Specifically, *Azolla* sp. has been widely utilized for nitrogen fertilization; this plant's nitrogen content has been observed to range from 3.3% to 5.4% dry weight [7,8]. *Azolla* also contains various macronutrients and micronutrients, such as Ca, Mg, Fe, Cu, and Zn, considered essential nutrients for plant growth. In addition, it is well established that *Azolla* releases the nutrients quickly, probably due to the comparatively low or narrow C:N ratio of *Azolla*. A study by Watanabe et al. [9] showed that around 50% of the N content in *Azolla* tissues is released within the first 6–8 weeks after soil application and entirely within 13 weeks. Widiastuti et al. [10] suggested that the optimal time to harvest these plants is 1–2 weeks after cultivation, which accounts for the most nutrients stored in its tissues. Nevertheless, some studies demonstrated that *Azolla* was equally effective as urea as a fertilizer for vegetable and crop production. For instance, Jama et al. [11] reported that *Azolla* produced spinach yields comparable to those of the urea treatment when administered at the same N rates, in line with the findings of Yang et al. [12], which has been demonstrated that *Azolla* cover on the floodwater surface of rice agriculture can significantly reduce the use of a 15–30% nitrogen fertilizer without reducing rice yield. Since the cost of chemical fertilizers has increased globally due to rising oil prices, the sustainability of chemical fertilization is now in question. Additionally, long-term usage of chemical fertilizers may have detrimental effects on crop yield, soil biodiversity, and the ecosystem [13]. The on-farm production of organic fertilizer, like *Azolla*, is thought to have numerous agronomic and environmental benefits [11]. To encourage the widespread adoption of on-farm *Azolla* production and use, the best conditions for *Azolla* production may be necessary to determine the maximum biomass production.

Abiotic characteristics, both structural habitat and physicochemical factors, influence the growth of *Azolla* [14]. Numerous studies have been conducted on the optimal water depth and conditions (e.g., temperature and pH) for *Azolla* growth. *Azolla* thrives in conditions of stagnant or gently flowing water, and the ideal water depth is between 10 and 30 cm [15] since shallow water depths might slow down *Azolla* growth and hence reduce its biomass production [16]. Furthermore, Serag et al. [17] reported that *Azolla* is capable of surviving in environments with pH values between 3.5 and 10, in which the growth rate is regulated by the interacting effect of temperature, light intensity, and the amount of nutrients [18,19]. According to Kathirvelan et al. [20] and Cary and Weerts [21], the optimum temperature for growing *Azolla* is 18–28 °C with a pH of 4.5–7.5. However, it has been discovered that the ideal pH range for *Azolla microphylla* is between 4.0 and 4.5 [22]. In addition, *Azolla* sp. generally requires 25–50% full sunlight for regular growth and multiplication, although a reduction in nitrogen fixation occurs when the light intensity was lower than 10,000–13,000 lux [23] and a considerable decrease in *Azolla* yield occurs when light intensity falls below 1500 lux [24]. Nevertheless, the nutrients directly impact *Azolla*'s development and increase sporulation-based multiplication. According to Costa et al. [25], if there is sufficient phosphorus in the aquatic environment, *Azolla* can grow without the need for a combined form of nitrogen, such as NH_4NO_3, as numerous studies have shown that phosphorus is a major limiting nutrient for *Azolla* growth and sporulation [26–28].

Several studies have revealed that organic fertilizer as a nutrition source was more efficient for *Azolla* sp. growth than inorganic fertilizer [2,29]. For instance, Azab and Soror [2] found that the growth and protein content of *Azolla* sp. was higher in the treatment of organic fertilizer used as poultry manure rather than that of inorganic fertilizer treatment (urea and pure phosphorus), which was attributed to the high contents of N and P in the tissues of *Azolla* sp. exposed to organic treatment. However, the supply of organic fertilizer made from animal manure generally affected the productivity of *Azolla* biomass, despite the stability and quality of the manure varying depending on animal species, diet composition, manure storage, type of bedding, and moisture content [30]. Some studies have reported the utilization of animal manure, such as cattle [31], poultry, goat, rabbit [32], sheep, vermicompost [33], as well as the wastewater from catfish pond [34] and piggery farm [35], for cultivating *Azolla* sp. However, cow, swine, and chicken manures are often the most readily available animal manures for *Azolla* production in the local region of Thailand, which would reduce the production cost of *Azolla* farming. It is evident that most nutrition supplies from animal manures are local and have varying nutrient concentrations.

Additionally, no research has been conducted on using open-farm animal manure, such as cow or pig manure, following organic farming regulations. The objectives of this study were to establish the types and rates of manure from livestock raised in non-confinement systems, including cow and pig manure, as well as the optimal shading for the growth and production of *A. microphylla*. This knowledge can be applied to *Azolla* cultivation, which has been extensively used for compost or soil amendment for organic plant production, a sustainable alternative protein source for animal feed, and medicinal supplements.

2. Materials and Methods

2.1. Experimental Layout and Treatments

A. microphylla, which is a high-potential fern in biomass productivity and tolerance to various environmental stresses, was selected in this study. It was obtained from the Agricultural Production Sciences Research and Development Division, Department of Agriculture, Bangkok, Thailand. Firstly, *A. microphylla* was vegetatively multiplied in plastic containers before being injected into the experiments at a small farm in Chai Nat province (Latitude: 14.913466, Longitude: 99.963741), Thailand, following the Department of Agriculture. In Brief, a 20 cm depth of soil was mixed with 1.27 kg m^{-2} of cow manure uniformly spread over, and the water depth from the soil layer was raised to 10 cm using tap water. Then, 100 g m^{-2} of *A. microphylla* was placed into plastic containers and shaded with a blue nylon net having 70% light transmittance, which was determined by comparing the light intensity under full sunlight with that under the blue nylon net. *A. microphylla* was harvested after ten days for use in setting up the studies.

Four experiments were conducted in concrete ponds, each with a volume of 0.105 m^3 (55 cm length, 55 cm width, 35 cm height). The purpose was to investigate the most suitable type and rate of animal manure and the optimal shading conditions to evaluate the maximum biomass growth and nutrient compositions of *A. microphylla*. This modified cultivation method was then compared with the conventional method the Department of Agriculture referenced. All the experimental designs and layouts were described as follows.

2.1.1. Effect of Different Manure Types on Growth Development and Chemical Compositions of *A. microphylla*

The experiment used a completely randomized design (CRD) with three replicates. The treatments were T1: control (no manure), T2: cow manure, T3: pig manure, T4: 25:75 v/v of cow manure and pig manure, T5: 50:50 v/v of cow manure and pig manure, and T6: 75:25 v/v of cow manure and pig manure. The identical amounts of manure per each concrete pond were 380 g (1.27 kg m^{-2}).

The chemical properties of the cow manure used in this experiment were as follows: pH 9.30, EC 6.63 dS m^{-1}, 41.63% organic matter, 1.16% total N, 0.34% total P, 3.31% total K, and a C:N ratio of 20.82. In addition, the chemical properties of pig manure were as follows: pH 7.50, EC 1.12 dS m^{-1}, 15.90% organic matter, 0.52% total N, 0.64% total P, 0.72% total K, and a C:N ratio of 17.73.

2.1.2. Effect of Different Manure Application Rates on Growth Development and Chemical Compositions of *A. microphylla*

The selected manure from the previous experiment (Section 2.1.1) was used to evaluate the appropriate rate for *A. microphylla* cultivation. A completely randomized design (CRD) with three replications (0.105 m^3 of concrete ponds) was conducted in this trial. The four treatments applying different rates consisted of T1: no manure (control); T2: 20.16 g N m^{-2}; T3: 30.16 g N m^{-2}; and T4: 40.16 g N m^{-2}.

2.1.3. Effect of Different Shading Levels on Growth Development and Chemical Compositions of *A. microphylla*

The selected manure type indicated in experiment Section 2.1.1 and the optimal manure rate discovered in experiment Section 2.1.2 were used to evaluate the appropriate shading levels for *A. microphylla* cultivation continuously. The experiment was laid out in a completely randomized design (CRD) with three replications (0.105 m^3 of concrete ponds). The four treatments consisted of T1: no shading (control), T2: 20% shading net, T3: 40% shading net, and T4: 60% shading net. The light transmittances of the three shading nets (20%, 40%, and 60% black shading nets, respectively) were 80%, 71%, and 50%, respectively, which was determined by comparing the light intensity under full sunlight with that under the shade nets.

2.1.4. Comparison Between the Developed Method and the Conventional Method

The developed method from the previous experiments (Sections 2.1.1–2.1.3) was used to compare the conventional method referenced by the Department of Agriculture, Thailand. The management of manure type, rate, and shading level of the traditional method consisted of 1.27 kg m^{-2} of cow manure shaded with the blue nylon net, with the light transmittance being 70%. The developed method was called 3.86 kg m^{-2} (20.16 g N m^{-2}) of pig manure and shaded with 40% black shading nets.

The entire set of experiments was designed to cultivate *A. microphylla* with a density of 100 g m^{-2}. Fertile soil was evenly distributed into the pits at a depth of 20 cm from the soil layer, and freshwater was added during the experimentation to a 10 cm depth from the soil layer, where the water's pH ranged from 7.13 to 7.57. Daily readings of the water's temperature (measured 10 cm depth from the water surface), air temperature (measured 20 cm above the canopy), and relative humidity were made.

The average temperature in the *Azolla* culture area (an open environment) ranged from 22.5 to 34.3 °C. The water temperature was slightly lower than the surrounding temperature and varied between 21.6 and 33.9 °C. The relative humidity in the air ranged from 60.19 to 76.09%. In addition, the water pH stayed between 7.03 and 7.85 during the experiment. The cultivation of *A. microphylla* in each experiment was uniformly set up using a 20 cm depth of soil, and the water depth from the soil layer was raised daily to 10 cm using tap water. Then, 30 g of *A. microphylla* was placed into the concrete ponds and harvested every ten days for the experiment (Figure 1).

(**a**) (**b**) (**c**)

Figure 1. The cultivation of *A. microphylla* in each experiment was uniformly set up using a 20 cm depth of soil (**a**), and the water depth from the soil layer was raised to 10 cm with tap water. Then, 30 g of *A. microphylla* was placed into the concrete ponds (**b**) and harvested every ten days (**c**).

2.2. Data Collection and Analysis

2.2.1. Growth Rate Analysis

Three samples of *A. microphylla* were harvested every ten days for each treatment (one sample from each concrete pond). They were then thoroughly washed with tap water to remove dirt particles and carefully blotted dry on a paper towel before weighing them to determine the fresh weight. They were dried in the oven at 50 °C for 72 h until a stable dry weight was achieved, and subsequently, their dry weight was determined. The total fresh and dry weight of harvested *A. microphylla* each month (three harvested per month) under different experimental treatments was also calculated. The relative growth rate and doubling time expressed as g g^{-1} per day and day, respectively, were calculated using the following formula [2,36,37].

$$RGR = (\ln W_2 - \ln W_1)/(t_2 - t_1) \quad (1)$$

where

W_1 and W_2 represent the plant fresh weight at times t_1 and t_2 of the sampling period.

$$\text{Doubling time} = t/r \quad (2)$$

where

t = the duration of *Azolla* growth; r = [log (Wt/Wo)]/0.301; Wt = weight of *Azolla* at time t; Wo = weight of initial inoculums.

For the determination of the dry matter from the fresh and dry weight of harvested *A. microphylla*, the equation below with the modification [38] was used:

$$\text{Dry matter (\%)} = 100 - \{[(\text{fresh weight} - \text{dry weight})/\text{fresh weight}] \times 100\} \quad (3)$$

2.2.2. Chemical Analysis of *A. microphylla*

The chemical analysis was performed on *A. microphylla* at the third harvesting (the end of each monthly sampling) from each experiment. The total N concentration was determined by using the Kjeldahl method. Briefly, one g of each sample was mixed with concentrated H_2SO_4 and a metal catalyst and then digested at 370–380 °C temperature. After the digestion was completed, the sample was diluted with water and transferred to the distillation unit, and then, the distillate NH_4^+ was analyzed by titration with standard NaOH solution. The levels of phosphorus (P) and potassium (K) in the samples were measured using a modified version of the standard protocol of the Association of Official Analytical Chemists [39]. In brief, each sample (1.0 g) was mixed with a solution of nitric-perchloric acid (HNO_3:$HClO_4$ in a ratio of 2:1 v/v) and digested. The digestion process was carried out in 15 mL of the solution. After digestion, the samples were diluted with distilled water to a final volume of 50 mL and stored in plastic tubes at room temperature. The determination of P in distilled samples was analyzed by using a spectrophotometer (UV-1280, Shimadzu, Kyoto, Japan) at 420 nm. The K concentration was analyzed with an atomic absorption spectrometer (PinAAcle900F, Perkin-Elmer, Waltham, MA, USA). The Walkley and Black [40] method quantified the organic carbon and organic matter. The ratio of C and N of each sample was then calculated.

The protein content was determined using the Kjeldahl method [39] for comparison between the developed method and the conventional method in experiment Section 2.1.4, which was calculated using the following formula:

$$\text{Protein (\%)} = \%\ \text{N} \times 6.25 \quad (4)$$

2.3. Statistical Analysis

The experimental treatment effects were analyzed using a completely randomized design (CRD) with three replications. Data were analyzed through a one-way analysis of variance (ANOVA). The means of different manure types and rates, as well as the different shading levels (Sections 2.1.1–2.1.3), were evaluated using Duncan's multiple range test ($p \leq 0.05$). For the comparison between the modified cultivated method and the conventional method (Section 2.1.4), the mean values were compared by using the Independent-Samples *t*-test using SPSS statistic, Version 26.0 software (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Effect of Different Manure Types on Growth Development and Chemical Compositions of A. microphylla

The growth responses of *A. microphylla* under the different manure treatments are presented in Table 1. The average relative growth rate of *A. microphylla* was much higher in the presence of manure than in the absence, ranging from 0.11 to 0.13 g g^{-1} day^{-1}. In terms of the doubling time, it was seen that all manure treatments quadrupled the amount of *A. microphylla*, with an average doubling time of 5.86 to 8.50 days, whereas the lack of manure necessitated 12.79 days for the amount to double. Meanwhile, treatment with pig manure revealed the highest relative growth rate and the shortest doubling time compared to the other fertilizer treatments (Table 1). Furthermore, compared to no manure or other manure treatments, the application of pig manure produced the highest fresh weight of *A. microphylla*, 360.16 g $month^{-1}$. The highest dry weight of *A. microphylla* was found under pig manure treatment (16.98 g month^{-1}), which did not significantly differ from the treatment of cow manure and 25:75 w/w of cow and pig manure (Table 1). Conversely, *A. microphylla* produced the least amount of dry matter (4.89%) when the pig manure was added, without any significant difference with the ratio of 25:75, 50:50, and 75:25 w/w of cow and pig manure (5.37%, 5.19%, and 5.48%, respectively) (Table 1).

Table 1. Growth responses of *A. microphylla* plants exposed to different cow and pig manure treatments.

Treatment	Relative Growth Rate (g g^{-1} day^{-1})	Doubling Time (day)	Fresh Weight (g month^{-1})	Dry Weight (g month^{-1})	Dry Matter (%)
T1: Control (no fertilizer)	0.09 b [1]	12.79 a	229.83 d	13.56 c	6.13 a
T2: Cow manure, 100%	0.11 a	7.61 b	301.65 c	16.06 ab	5.62 ab
T3: Pig manure, 100%	0.13 a	5.86 b	360.16 a	16.98 a	4.89 c
T4: Cow manure: Pig manure, 25:75% w/w	0.12 a	6.56 b	305.09 bc	16.02 ab	5.37 bc
T5: Cow manure: Pig manure, 50:50% w/w	0.12 a	7.83 b	312.71 b	15.48 b	5.19 bc
T6: Cow manure: Pig manure, 75:25% w/w	0.11 a	8.50 b	297.25 c	15.29 b	5.48 bc
Significance	**	**	**	**	**
C.V. (%)	9.58	18.91	1.58	3.97	5.88

[1] Means with different letters in the same column indicate a significant difference according to Duncan's multiple range test. ** refers to $p \leq 0.01$. Fresh and dry weights were calculated from the volume of each pond at 0.105 m^3.

The nutritional contents of *A. microphylla* with several kinds of manure use can be seen in Table 2. The different fertilizer treatments did not affect ($p > 0.05$) the total nitrogen and phosphorus content, ranging from 2.30–2.55% and 0.09–0.14%, respectively. Additionally, the organic matter content of *A. microphylla*, which was found to fluctuate between 59.32 and 61.94%, was unaffected by the presence or absence of manure. As a result, there was no significant ($p > 0.05$) difference in the carbon-to-nitrogen ratio (C:N ratio), with values ranging from 13.86 to 15.10 (Table 2). However, the significantly ($p \leq 0.01$) highest potassium content of *A. microphylla* occurred in the pig manure treatment (1.14%), which did not differ considerably from the 1.02% potassium content seen in the cow manure treatment. In this case, potassium content was increased by 44% and 29%, respectively, compared with the control treatment (no fertilizer).

As a result of this experiment, the pig manure was chosen to assess the appropriate rate in the following studies because, in comparison to the other treatments, it produced the highest fresh weight yield and relative growth rate, the shortest doubling time, and the highest potassium content in *A. microphylla* tissues ($p \leq 0.01$).

Table 2. The chemical properties of *A. microphylla* plants exposed to different cow and pig manure treatments.

Treatment	Total N (%)	Total P (%)	Total K (%)	Organic Matter (%)	C:N Ratio
T1: Control (no fertilizer)	2.30	0.09	0.79 b [1]	59.32	14.95
T2: Cow manure, 100%	2.55	0.10	1.02 a	60.37	13.86
T3: Pig manure, 100%	2.43	0.14	1.14 a	60.12	14.38
T4: Cow manure: Pig manure, 25:75% w/w	2.38	0.10	0.54 c	61.94	15.10
T5: Cow manure: Pig manure, 50:50% w/w	2.52	0.12	0.50 c	61.72	14.36
T6: Cow manure: Pig manure, 75:25% w/w	2.49	0.10	0.33 d	61.71	14.55
Significance	ns	ns	**	ns	ns
C.V. (%)	7.51	15.07	9.58	3.24	13.86

[1] Means with different letters in the same column indicate a significant difference according to Duncan's multiple range test. **, ns refer to $p \leq 0.01$ and non-significant, respectively.

3.2. Effect of Different Manure Application Rates on Growth Development and Chemical Compositions of *A. microphylla*

Based on the observation, the average growth rate of *A. microphylla* grown under the pig manure application at all rates was considerably greater than without, which showed an increment of 57% (Table 3). In contrast, all the rates of pig manure treatment resulted in almost two days shorter than that with no manure applied, varying from 3.10 to 3.22 days. Additionally, all rates of pig manure application led to noticeably greater fresh and dry weight increments for *A. microphylla* when compared to no manure treatment; these increments ($p \leq 0.01$) were enhanced by 2.1–2.3 and 1.6–1.7 times, respectively. Concerning fresh and dry weight, *A. microphylla* had the highest dry matter at 5.46% when no manure was applied. In contrast, all the rates of pig manure application had no statistical effect on *A. microphylla*'s dry matter, which was between 4.05 and 4.18% (Table 3).

Table 3. Growth responses of *A. microphylla* plants exposed to different rates of pig manure.

Treatment	Relative Growth Rate ($g\ g^{-1}\ day^{-1}$)	Doubling Time (day)	Fresh Weight ($g\ month^{-1}$)	Dry Weight ($g\ month^{-1}$)	Dry Matter (%)
T1: Control (no fertilizer)	0.14 b [1]	5.06 a	375.73 b	20.67 b	5.46 a
T2: Pig manure 20.16 gN m^{-2}	0.22 a	3.22 b	792.06 a	32.49 a	4.18 b
T3: Pig manure 30.16 gN m^{-2}	0.22 a	3.15 b	834.08 a	33.60 a	4.05 b
T4: Pig manure 40.16 gN m^{-2}	0.22 a	3.10 b	865.32 a	35.07 a	4.07 b
Significance	**	**	**	**	**
C.V. (%)	3.33	5.42	6.69	7.61	3.33

[1] Mean with different letters in the same column indicates a significant difference according to Duncan's multiple range test. ** refers to $p \leq 0.01$. Fresh and dry weights were calculated from the volume of each pond at 0.105 m^3.

Then, the nutrient content of *A. microphylla* cultivated with various amounts of pig manure was discovered to be significantly ($p \leq 0.01$) higher when compared to cultivation without pig manure, which contained total phosphorus and potassium between 0.84 and 1.01% and between 4.21 and 4.33%, respectively. In addition, *A. microphylla* tissue also had a 24–46% increase in total nitrogen content after the pig manure was exposed. However, there was no discernible ($p > 0.05$) difference between the pig manure treatment at a rate of 40.16 gN m^{-2} and the control group. In terms of organic matter, there was no significant ($p > 0.05$) difference between the treatments, with results falling between 55.05 and 57.85%. The control plants without N supply showed the highest C:N ratio, which was not significantly different from the pig manure treatment at a rate of 40.16 gN m^{-2}. The C:N ratio was only somewhat decreased by adding N from the pig manure at a rate of 20.16 to 30.16 gN m^{-2}, and this effect was not statistically significant (Table 4).

Therefore, considering the experiment results, pig manure applied at a rate of 20.16 gN m^{-2} was found to be the lowest rate of application for promoting *A. microphylla* growth, yield, and fresh and dry weight, and reducing doubling time. Even with the higher rates of pig manure application, the increase in *A. microphylla* tissue nutrients was not statistically different. For the next experiment, pig manure was selected at a rate of 20.16 gN m^{-2}.

Table 4. Chemical properties of *A. microphylla* plants exposed to different rates of pig manure.

Treatment	Total N (%)	Total P (%)	Total K (%)	Organic Matter (%)	C:N Ratio
T1: Control (no fertilizer)	2.67 b [1]	0.09 b	2.11 b	57.75	12.60 a
T2: Pig manure 20.16 gN m^{-2}	3.69 a	0.84 a	4.21 a	55.05	8.75 b
T3: Pig manure 30.16 gN m^{-2}	3.90 a	0.96 a	4.34 a	55.94	8.36 b
T4: Pig manure 40.16 gN m^{-2}	3.32 ab	1.01 a	4.33 a	57.85	10.31 ab
Significance	*	**	**	ns	*
C.V. (%)	11.26	19.74	5.62	17.20	13.07

[1] Means with different letters in the same column indicate a significant difference according to Duncan's multiple range test. **, *, ns refer to $p \leq 0.01$, 0.05, and non-significant, respectively.

3.3. Effect of Different Shading Levels on Growth Development and Chemical Compositions of *A. microphylla*

Although there was no difference in the relative growth rate of *A. microphylla* among the shading levels in a range of 0.22–0.23 g g^{-1} day^{-1}, different shading levels significantly ($p \leq 0.01$) influenced its doubling time. Among the *A. microphylla* grown in the control (no shading) and those under varying shading levels, the shortest doubling time was observed in the 40% shading treatment, which did not differ noticeably from the non-shading (control) and 20% shading treatments (Table 5).

The 40% shading and non-shading treatments observed the greatest fresh and dry weight. However, *A. microphylla* grown under 60% shading showed the significantly lowest fresh and dry weight, which decreased by 11% and 15%, respectively, compared to the control. In terms of dry matter, it was discovered that the different shading levels did not affect the dry matter of *A. microphylla,* which were in a range of 4.10–4.44% (Table 5).

Table 5. Growth responses of *A. microphylla* plants exposed to different shading conditions.

Treatment	Relative Growth Rate (g g^{-1} day^{-1})	Doubling Time (day)	Fresh Weight (g $month^{-1}$)	Dry Weight (g $month^{-1}$)	Dry Matter (%)
T1: Control (no shading)	0.23	3.12 ab [1]	903.80 ab	39.15 a	4.44 a
T2: Shading 20%	0.22	3.07 ab	890.47 b	36.63 b	4.14 b
T3: Shading 40%	0.23	3.00 b	922.13 a	37.51 ab	4.10 b
T4: Shading 60%	0.22	3.18 a	806.68 c	32.91 c	4.10 b
Significance	ns	*	**	**	**
C.V. (%)	2.86	1.98	1.58	2.66	2.10

[1] Means with different letters in the same column indicate a significant difference according to Duncan's multiple range test. **, *, ns refer to $p \leq 0.01$, 0.05, and non-significant, respectively. Fresh and dry weights were calculated from the volume of each pond at 0.105 m^3.

The nutrient contents in *A. microphylla* tissues varied across different shading treatments (Table 6). There were no significant differences among the shading treatments in the total nitrogen content and organic matter, which ranged from 3.27% to 3.81% and from 59.92% to 63.66%, respectively. However, the total phosphorus and potassium contents in *A. microphylla* tissues followed a similar trend, with the highest values observed under the 20% shading treatment. There were no discernible ($p > 0.05$) differences between the 20% and 40% shading treatments for total phosphorus content and between the 40% and 60% shading treatments for total potassium content. Specifically, the lowest total phosphorus and potassium contents were observed in *A. microphylla* tissues cultured with non-shading (control) treatment. In addition, the C:N ratio decreased with increasing levels of shading to 40% and 60%. Control plants without shading applied showed an increase in the C:N ratio to 11.09, without any significant difference with 20% shading plants (Table 6).

Table 6. Chemical properties of *A. microphylla* plants exposed to different shading conditions.

Treatment	Total N (%)	Total P (%)	Total K (%)	Organic Matter (%)	C:N Ratio
T1: Control (no shading)	3.27	0.30 c [1]	1.56 b	62.29	11.09 a
T2: Shading 20%	3.40	0.75 a	2.11 a	63.66	10.92 a
T3: Shading 40%	3.81	0.67 a	1.88 a	59.92	9.20 b
T4: Shading 60%	3.80	0.44 b	2.06 a	60.81	9.29 b
Significance	ns	**	**	ns	*
C.V. (%)	8.43	11.68	7.07	3.01	8.41

[1] Means with different letters in the same column indicate a significant difference according to Duncan's multiple range test. **, *, ns refer to $p \leq 0.01$, 0.05, and non-significant, respectively.

Based on the experimental outcomes, the growth development of *A. microphylla* was not statistically ($p > 0.05$) different, whether it was slightly shaded (20% and 40% shading) or not. However, this experiment revealed that 40% shading was considered as an optimal shading for promoting both *A. microphylla*'s development and the highest macronutrient content (3.81% N + 0.67% P + 1.88% K = 6.36% N + P + K). In addition to the observation under non-shaded situations, rainwater poured directly on *A. microphylla* can harm the plant by smashing and dispersing it. The 40% shading allows *A. microphylla* to be grown in all seasons, including rainy ones, under various environmental conditions. The results of the three experiments led to the conclusion that applying 20.16 gN m^{-2} of pig manure along with 40% shading was a suitable management method for *A. microphylla* culture. This resulted in *A. microphylla* having the shortest doubling time and the highest fresh weight yield, dry weight yield, and nutrient accumulation contents. Consequently, this developed method was selected for comparison with the approach advised by the Department of Agriculture, using 1.27 kg m^{-2} of cow manure (23.37 gN m^{-2}) and shaded with a blue nylon net (30% shading) to avoid insect infestation.

3.4. Comparison Between the Developed Method and the Conventional Method

The comparison between the conventional method advised by the Department of Agriculture, Thailand (using 23.37 gN m^{-2} of cow manure and shaded with a blue nylon net at 30% shading) and the developed method (using 20.16 gN m^{-2} of pig manure and shaded with the black shading net at 40% shading) for *A. microphylla* production is displayed in Figure 2.

Figure 2. Characteristics of *A. microphylla* cultivated by conventional (**a**) and developed (**b**) methods.

According to the study results, the developed method significantly ($p \leq 0.05$) increased the relative growth rate of *A. microphylla* from 0.24 to 0.25 g g^{-1} day^{-1}. In addition, it significantly ($p \leq 0.05$) reduced the doubling time from 2.95 to 2.77 days compared to the conventional method. Nevertheless, the modified method significantly ($p \leq 0.01$) enhanced the fresh weight of *A. microphylla* by almost 16% compared to the conventional method. More specifically, the developed method elicited an increment in the total nitrogen, total potassium, protein, and organic matter (0.61, 28.30, 0.46, and 6.85%) of *A. microphylla* tissues, without any significant difference ($p > 0.05$). However, its total phosphorus was 28.57% significantly lower ($p \leq 0.05$) in the developed method compared to the conventional method. Regarding the C:N ratio, it was discovered that the developed method provided a higher C:N ratio than the conventional method, which showed an increment of 6.13%, without significance ($p > 0.05$) (Table 7).

Table 7. Comparison of *A. microphylla* productivity between the conventional and developed methods.

Parameters	Conventional Method [1]	Developed Method	*t*-Test	Compared (%)
Relative growth rate (g g^{-1} day^{-1})	0.24 b [2]	0.25 a	*	+4.17
Doubling time (day)	2.95 a	2.77 b	*	−6.10
Fresh weight (g $month^{-1}$)	1589.94 b	1842.60 a	**	+15.89
Dry weight (g $month^{-1}$)	74.64	71.27	ns	−4.52
Dry matter (%)	4.65 a	3.87 b	**	−16.77
Total N (%)	4.89	4.92	ns	+0.61
Total P (%)	1.05 a	0.75 b	*	−28.57
Total K (%)	3.18	4.08	ns	+28.30
Protein (%)	30.58	30.72	ns	+0.46
Organic matter (%)	63.10	67.42	ns	+6.85
C:N ratio	7.50	7.96	ns	+6.13

[1] Conventional method referenced from the Department of Agriculture, Thailand. [2] Means with different letters in the same row indicate a significant difference according to the Independent-Samples T-test. **, *, ns refer to $p \leq 0.01$, 0.05, and non-significant, respectively.

4. Discussion

Azolla is one of the fastest-growing aquatic macrophytes globally [14]. Because of its broad distribution and quick biomass production, *Azolla* has excellent potential as a green manure and biofertilizer that could be used to replace part or all of the inorganic nitrogenous fertilizer required for plant production [29] and could encourage sustainable plant production, especially in the local farmers [41,42]. However, *Azolla*'s growth directly affects the optimal ecological systems, including temperature (air and water), relative humidity, water quality and availability, nutrition, and light intensity. To investigate the appropriate type and rate of animal manure as well as the ideal light intensity in this study, the temperature of the air (22.5–34.3 °C) and water (21.6–33.9 °C), as well as the relative humidity estimated at 60.19–76.09%, were observed to confirm that these ecological factors were optimized. Some studies reported that the suitable temperature should not exceed 35 °C [43], and the mean relative humidity for allowing *Azolla* growth was estimated at 55–83% [11]. Additionally, the water pH (7.03–7.85) during these experiments was within the optimal growth pH of *Azolla* species that various studies identified as a range of pH 5–8 [21,44]. Overall, the suitable environment (such as temperature, pH water, etc.) was controlled, along with the investigation of the appropriate type and rate of animal manure and the optimal light intensity for *A. microphylla* production. The results of this study showed that the developed method using 20.16 gN m^{-2} of pig manure and shaded with the black shading net at 40% shading displayed a significantly higher fresh weight yield of *A. microphylla* compared to the conventional method advised by the Department of Agriculture, Thailand (using 23.37 gN m^{-2} of cow manure and shaded with a blue nylon net at 30% shading).

From the research finding of the growth responses of *A. microphylla* plants exposed to different treatments of cow manure and pig manure, only the 100% pig manure treatment revealed the shortest doubling time (5.86 days), which was nearly that in the previous study, which was found in a range of 2–5 days [45]. In addition to the appearance of *A. microphylla* among the different manure treatments, the reddish-brown coloration was more observed in *A. microphylla* grown under the 100% cow manure treatment, compared to that grown under the 100% pig manure treatment (Figure 3). The presence of anthocyanin pigments shows that the *Azolla* plants were under stress, usually because of high light intensity or nutrient deficiency, especially phosphorus [14,44]. Furthermore, Temmink et al. [46] stated that the most crucial and frequently limiting component for *Azolla* growth is phosphorus, which is red, which could indicate its phosphorus deficiency. The current results are consistent with this general statement, reflecting the nutritional content of different manures, in which the phosphorus content in cow manure was two times less than in pig manure.

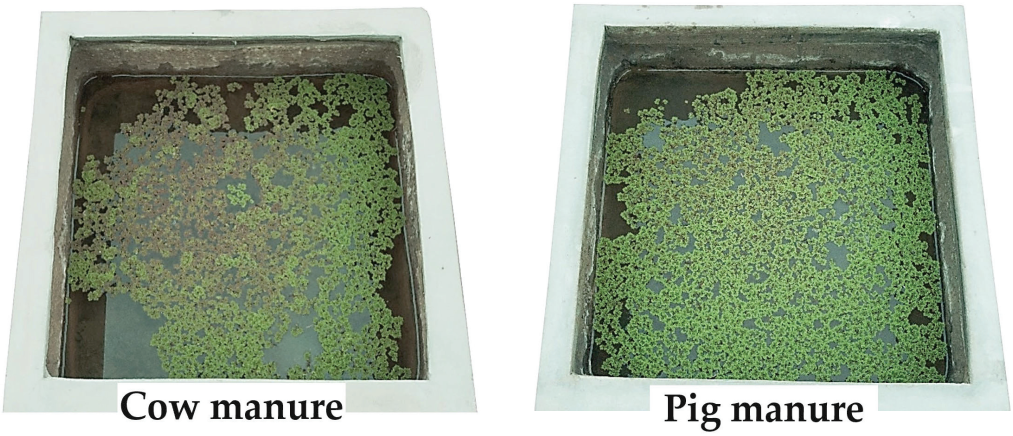

Figure 3. Morphology of *A. microphylla* in response to different cow and pig manure treatments.

Furthermore, previous research has shown that *Azolla* plants can rapidly grow during the early stages of development due to their ability to absorb phosphorus [47]. Phosphorus is important for increasing plants' dry weight, which helps them form the necessary pyrophosphate compounds, which serve as the primary energy source for plant growth and development [48]. Phosphorus is also a component of phospholipids, essential for the structure of cell membranes [32].

Although nitrogen is also an essential nutrient that *Azolla* needs in large amounts, it was found that the cyanobacteria (*Anabaena* sp.), which reside in the *Azolla*'s leaf sheaths, play a significant role in fixing nitrogen from the air and converting it into a form that plants can use [23]. Additionally, several researchers found that external N supply did not increase *Azolla* growth, and it can double its biomass within one week under N-free and P-rich conditions, entirely relying on the symbiosis with diazotrophs for its N supply [46,49]. Our results are consistent with this finding that supplying pig manure at different N rates had no positive or negative effects on the fresh weight of *A. microphylla*. Notably, *A. microphylla* tended to accumulate lower nitrogen when pig manure was treated at the highest rate. It seems likely that the negative impact of the high pig manure rate on nitrogen accumulation of *A. microphylla* was due to excessive salinity in the manure released into water, which agreed with Arora and Singh [50], who reported that salinity drastically decreased biomass production in all six *Azolla* species (*A. filiculoides*, *A. mexicana*, *A. microphylla*, *A. pinnata*, *A. rubra*, and *A. caroliniana*). Based on this observation, however, *A. microphylla* showed higher tolerance to salinity than other species, and our results concerning saline tolerance of this *Azolla* species may be similar to that previous report.

Light intensity has a direct effect on the leaf growth and fresh biomass yield of *Azolla* species, where previous studies with *A. pinnata* reported that the optimal average natural light varied from 47,500 to 75,000 lux [51–53]. Nevertheless, Effendi et al. [54] stated that the optimal growth rate of *A. microphylla* was found under the 30% shaded level, compared to the full sunlight (0% shade level) or the other shade levels (50%, 70%, and 100% shaded levels). In this study, the daily measured light intensity (12 p.m.) throughout the different shading studies was measured, where the average illuminations under different shading conditions from no shading, 20% shading, 40% shading, and 60% shading were 88,300–114,167 lux (Av = 114,167 lux), 82,567–112,200 lux (Av = 97,384 lux), 69,767–98,733 lux (Av = 84,250 lux), and 45,633–70,133 lux (Av = 57,883 lux), respectively. From the results, it seems that full sunlight caused *A. microphylla* to produce higher final biomass, which was not significantly different from that grown under 20% and 40% shading. However, 60% shading with the lowest intensity of sunlight, lower than 57,883 lux, affected the fresh and dry weights of *A. microphylla*. This finding agreed with previous reports, which stated that the light intensity had a strong correlation with the growth rate of *Azolla* species and usually required 25–50% full sunlight for regular growth. In addition, the increase would decrease quickly under heavy shade (more than 50% of full sunlight or the light intensity range of 1202 to 44,945 lux) by reducing photosynthesis [44,45,55].

In general, *Azolla* plants have long been used in agriculture as a green manure or soil amendment product because they contain a lot of plant nutrients, such as nitrogen (N), phosphorus (P), and magnesium (Mg), as well as high organic matter, thereby improving the soil chemical properties and increasing the crop yield [45,56]. An increase in crop yield has been found for a variety of crops, including rice [57], maize [58], and beans [59]. Using *Azolla* compost in agriculture is also considered a sustainable environmental practice because it reduces methane emissions and slows global warming [60]. To confirm the potential of *A. microphylla* plants that could be used as compost for crop production, some selected chemical properties of its dry sample were measured to compare with the compost specifications of Thai Agricultural Standard [61], Thailand, as shown in Table 8. It was evident that the level of organic matter, as well as the macronutrients (N, P, and K) in *A. microphylla* tissues were in accordance with the compost quality standards according to TAS 9503–2005, in which the organic matter, total N, total P and total K were 67.42% (≥30.0%), 4.92% (≥1.0%), 0.75% (≥0.5%), and 4.08% (≥0.5%), respectively. Nevertheless, the total N content in *A. microphylla* was higher in this study than in previous studies using chicken compost (2.10%), rabbit fecal compost (4.05%), goat fecal compost (3.67%) [33], or even piggery wastewater (2.40%) under ideal surface area and harvesting time conditions [62]. Additionally, the C:N ratio of *A. microphylla* tissues (7.96) was less than 20:1, indicating the decomposition process ran ideally [63]. Furthermore, several reports have demonstrated that *Azolla* species with a low C:N could mineralize within 2–5 days, and about 40–60% of available N and P were released by 20–40 days after application [5,64,65]. Notably, the addition of *Azolla* compost led to the enhancement of the soil organic matter and soil microbial activity and thus can improve nutrient recycling in treated soil, as well as the formation of both macro and micro aggregates [66,67]. Some studies also demonstrated that *Azolla* is a cost-effective organic fertilizer that replaces urea fertilizer application without affecting crop yield [11]. Based on the previously mentioned advantages of *Azolla* compost and the current results of the chemical composition of *A. microphylla* tissues compared to Thai Agricultural Standard, *A. microphylla* can be used as a compost with a beneficially natural source of nutrients for crop production.

Table 8. The chemical properties of *A. microphylla* are compared with Thailand's organic fertilizer standard.

Parameters	*A. microphylla*	Compost Specifications of Thai Agricultural Standard: Compost (TAS 9503-2005), Thailand
Organic matter (%)	67.42	≥30.0
C:N ratio	7.96	≤20:1
Total Nitrogen (%)	4.92	≥1.0
Total Phosphorus (%)	0.75	≥0.5
Total Potassium (%)	4.08	≥0.5

Since *Azolla* can be cultivated in small catchments and can float into fields, it requires relatively little capital to cultivate [45]. To encourage farmers to grow *Azolla*, it can be grown in nursery ponds as described above and harvested in about 10 days to be mixed into the soil at the rate of 500–1000 kg ha^{-1} of green *Azolla* as a dual crop in rice fields [68] or 4.69 t ha^{-1} dried *Azolla* for vegetable crops [11]. *Azolla* production was, however, severely hampered by a few pests, including snails and insect pests (e.g., *Coleoptera* and *Diptera*). Furthermore, a number of insecticides (e.g., cypermethrin and chlorpyrifos) are thought to be detrimental to its growth. Therefore, the cultivated area should be regularly inspected or treated with a biopesticide, such as *Bacillus thuringiensis* for insect control [69]. The primary determinants of biomass yield using multiranked culture methods for the production of *Azolla* were also further investigated.

5. Conclusions

Managing the right fertilizer (types and rates) and the optimal light intensity significantly influenced the yield production of *A. microphylla*. The results reported here demonstrated that the developed method, indicating 20.16 gN m^{-2} of pig manure application with 40% shading by the black shading net, can significantly increase the relative growth rate (4.17%) and fresh biomass (15.89%), as well as significantly decrease the doubling time (6.10%), compared to the conventional method advised by the Department of Agriculture, Thailand (using 23.37 gN m^{-2} of cow manure and shaded with the blue nylon net at 30% shading). The current finding method can produce a monthly fresh biomass of 3.7 kg m^{-2} projected as 40.7 t ha^{-1} $year^{-1}$, with two rest days after fertilizer application and harvesting every ten days (three harvesting per month). Nonetheless, the currently developed method for producing *A. microphylla*, which has a relatively higher total N content (4.92%) and exhibits the advantage of rapid mineralization due to its low C:N ratio (7.96), can be a good substitute for farmers managing compost production on their farm in order to lower crop production costs and support sustainable agriculture.

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Transforming Agriculture: Empirical Insights into How the Digital Economy Elevates Agricultural Productivity in China

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Abstract: The United Nations Sustainable Development Goals (SDGs) emphasize enhancing agricultural productivity sustainably and strengthening the resilience of agricultural systems amidst rising economic uncertainties, escalating climate change risks, and geopolitical tensions. Amidst these challenges, the relentless progress of digital and information technologies heralds the digital economy as a potential game-changer for agricultural productivity. In 2023, the scale of China's digital economy reached 7.64 trillion US dollars, accounting for 42.8% of China's GDP, with the contribution of digital economy growth to GDP growth reaching 66.45%. As a nascent yet formidable force in the global economy, the digital economy is reshaping industries worldwide, particularly the agricultural sector. Food security and sustainability could potentially be affected by the digital economy, while agricultural productivity is a crucial element of food security and sustainability. The primary objective of this study is to investigate the extent to which the digital economy (DE) contributes to agricultural technical efficiency (ATE) in the context of China and to explore the mechanisms through which this impact is mediated and the implications for regional disparities. This study delves into the Chinese context, examining the empirical evidence of how the DE bolsters ATE utilizing provincial panel data. Key findings reveal the following: (1) DE exerts a significant and positive impact on ATE, demonstrating robust effects. (2) Marketization acts as a pivotal mediation mechanism in transmitting the positive influence of DE on ATE. (3) DE fosters convergence in ATE, narrowing regional disparities. Based on these insights, we propose strategic recommendations to mitigate agricultural production risks in agricultural productivity and propel food security and sustainability in China.

Keywords: food security and sustainability; digital economy; agricultural technical efficiency; convergence; mediating mechanism

1. Introduction

The digital economy is a new driver of the global economy that is profoundly affecting many industries, especially in the agricultural sector. The United Nations Sustainable Development Goals (SDGs) encompass the "Zero Hunger" goal (SDG 2) [1], emphasizing the promotion of sustainable agricultural production and the enhancement of agricultural systems' resilience to guarantee sufficient nutrition and food for all individuals. The digital economy holds a pivotal role in facilitating the attainment of this objective. In the face of global challenges, prioritizing food security and sustainability is more important than ever; from a global perspective, the challenges of agricultural production are rising sharply due to rising economic uncertainty, the growing risk of climate change, and the instability of geopolitical conflicts. In recent years, digital and information technology has advanced continuously, and the advancement of the digital economy could serve as the driving force to address the present challenges related to food security and sustainability.

China offers rich material for our study. China's agriculture has long been challenged by low productivity, such as fragmented land, low mechanization, an aging and feminized rural labor force, etc., which have constrained China's agricultural development. Chinese policymakers view digital technology as a crucial means to drive the high-quality advancement of agriculture. Certain research suggests that the digital economy can facilitate the circulation of elements and optimize resource allocation [2–4]. Focusing on the effect of the digital economy on the productivity of agriculture is valuable, as it contributes practical implications for the global sustainable development goals (SDGs) and theoretical development for the study related to agricultural productivity.

As the new generation of information technology continues to evolve, the digital economy is increasingly characterized by new technologies such as the Internet, big data, and artificial intelligence, which has shaped new economic formats and promoted the digital transformation of traditional formats. Based on research conducted by the China Academy of Information and Communications Technology, the annual penetration of the digital economy in China's primary industry is steadily rising, and the penetration rate will exceed 35% by 2023. By shaping the economy, digital technologies optimize the allocation of industrial elements and strengthen the accumulation of human capital by digital means. The combination of digital technology and agriculture has great potential for the improvement of agricultural total factor productivity in China.

At present, few studies have concentrated on the relationship between the digital economy and agricultural productivity. Most studies still focus on the effects of agricultural factors on overall agricultural performance, including the participation of agricultural cooperatives [5,6], urban distance [7], interpersonal trust [8], arable land transfer [9,10], off-farm work [11] on agricultural production performance. From the perspective of total factor productivity (TFP), most academic studies have empirically shown that the digital economy can promote macroeconomic growth by optimizing element allocation and improving total factor productivity levels: firstly, the development of DE can significantly improve the allocation of data elements by integrating them with especially production elements such as labor and capital, thereby enhancing production efficiency and fostering economic growth. Second, upgrading industrial structures and technological innovation are critical mechanisms through which DE improves total factor productivity [9]. Therefore, we draw attention to the relationship between the digital economy and agricultural productivity as an area of significant concern for further research.

Hence, the primary objective of this study is to investigate the extent to which the DE contributes to ATE in the context of China and to explore the mechanisms through which this impact is mediated and the implications for regional disparities. Three main marginal contributions: (1) Based on overcoming endogeneity, we construct a digital economy index covering digital infrastructure, Internet development, and the information industry and select historical data on energy consumption in the production of electronic communications equipment and chips as instrumental variables. Through comparative analysis of the technical efficiency of agriculture at different scales and in northern or southern provinces of China, our findings indicate that the effect of the digital economy on agricultural technical efficiency is both significant and stable; (2) through theoretical analysis and empirical models, we examined the mechanism of the marketization of agricultural elements in the digital economy on the improvement of agricultural technical efficiency, and creatively measured the degree of marketization by agricultural farming structure, off-farm work, and arable land transfer, expanding the content of the examination of the improvement mechanism of agricultural technical efficiency driven by the digital economy. (3) Based on the "super efficiency" DEA and the methods of absolute β convergence and spatial conditional β convergence, we found that the digital economy significantly promotes the convergence growth rate of China's agricultural technical efficiency.

2. Literature Review

2.1. Digital Economy and Agricultural Technical Efficiency

Many studies have found that the digital economy (DE) can improve the level of total factor productivity (TFP) by optimizing the allocation of elements to promote macroeconomic growth. TFP is similar to agricultural technical efficiency (ATE), which measures the efficiency of economic growth and mainly evaluates the input–output effect of all production elements in the production process, including labor, capital, energy, and raw materials. ATE is a measure of the capacity of decision-making units (DMU). Standard evaluation produces a certain amount of output with as little input as possible, which can be used to evaluate agricultural production performance, covering agricultural issues such as land fragmentation [12], irrigation shortages [13], agricultural skills deficiencies [14], and industrial air pollution [15]. The literature on the impact of the digital economy on TFP has concluded important mechanism findings: the development of the digital economy can significantly improve the allocation of elements by integrating data elements with elements such as labor and capital, thereby enhancing production efficiency and achieving economic growth [16,17]. Industrial structure upgrading and technological innovation are two major mediation impact mechanisms for the digital economy to improve TFP. For example, studies have determined that the digital economy (DE) has markedly enhanced China's green total factor productivity (GTFP) by advancing the industrial structure, utilizing methodologies such as quantile regression analysis, Tobit, and mediation effect models [15,18]. The study indicates that DE stimulates an innovation-driven enhancement in China's TFP, contributing to the broad and sustainable expansion of TFP. [19].

Agricultural production is an essential part of the economy, and optimizing the allocation of production elements is an important path to improve agricultural productivity. According to the study of the digital economy on issues related to TFP, this paper focuses on agricultural technical efficiency (ATE). ATE represents the development of agricultural productivity and will also be affected by DE. Optimizing the allocation of agricultural factors in the digital economy will also improve the efficiency of agricultural technology. Therefore, hypothesis 1 of this study is that the digital economy can promote the efficiency of agricultural technology.

Due to differences in China's economic development level, social and cultural environment, etc., the impact of the digital economy on agricultural technical efficiency may, therefore, vary across regions of China. The improvement gradually weakens from east to west, while a significant inhibitory effect is observed in the west [20]. The impact of digital finance on agricultural total factor productivity varies across regions. Among them, the impact of digital finance on total factor productivity in the central region is the strongest compared to the eastern and western regions [21]. In the central and western regions of China, the impact of the digital economy on total factor productivity in agriculture is greater than in the eastern part of the country. At the same time, taking into account the decomposition effect of total factor productivity in agriculture, the impact of the digital economy on technological progress and efficiency is also greater in the central and western regions of China than in the eastern part of the country [22]. The contribution of the digital economy to total factor productivity in agriculture in China is mainly reflected in the following: it has played both a positive and a negative role in southwest and northern China, respectively [23]. This paper focuses on the North–South divide in China and argues that this difference in agricultural production patterns may decisively influence the impact of DE on ATE. Therefore, based on Hypothesis 1, this paper further proposes Hypothesis 1a: The effect of DE on ATE varies significantly across regions.

2.2. Marketization of Agricultural Elements

The development of digital technology has promoted the marketization level and improved the element distortion of the rural labor market and capital market. As a result, TFP has increased [24]. DE optimizes the allocation of agricultural resources through marketization, improves efficiency, and transforms farmers' production from "relying on the weather" to systematic input and output based on digital technology [25]. The marketization of agriculture promotes the progress of agricultural productivity, the upgrading and optimization of the agricultural industrial structure, and the increased mobility of factors of agricultural production. In this way, producers can participate more efficiently in the production process, and ATE can be improved. Therefore, Hypothesis 2 of this study is as follows: DE promotes the enhancement of ATE by facilitating agricultural marketization.

2.3. The Impact of Digital Economy on the Convergence of Agricultural Technical Efficiency

Related research has concentrated on the convergence of TFP. Some research has discussed the convergence of agricultural TFP in China and found that there is an absolute β convergence of TFP in China [26,27]. Similarly, some research found that agricultural GTFP showed an absolute σ convergence trend [28]. Based on information and communication technology, the digital economy promotes the growth of agricultural productivity [29,30] and guides traditional enterprises to move towards digitalization by forming a virtuous circle between the supply of information products and the demand of other industries [31,32]. With e-commerce platforms, digital consumption and transactions have changed the mode of distribution of agricultural products. The third hypothesis of our study is as follows: DE promotes the convergence of ATE.

3. Materials and Methods

3.1. Digital Economy

The Australian government defines the digital economy (DE) as the integration of global economic and social networks facilitated by information and communication technologies, including the Internet, mobile phones, and sensor networks. DE is also defined as taking digital information as the core element of production, information technology as the support, modern information network as the main carrier, and digital technology to provide products or services. It is a new economic form of technology integration, industrial integration, producer and consumer integration [33,34]. This paper summarizes the connotation of the digital economy into three aspects: the development of information, the development of the Internet, and the development of digital transactions. For the measurement, we refer to existing studies [35,36], which contain 8 secondary indicators: information infrastructure, information communication, Internet terminal equipment, mobile phone, fixed telephone, mobile network impact, information industry infrastructure, and information industry. Detailed indicators are shown in Table A1. The original data can be sourced from the China Statistical Yearbook and the China Information Industry Yearbook. Through the improved entropy method [37], the above eight indicators are grouped into groups to reduce the dimension after data standardization, and the comprehensive development index of the digital economy is obtained, which is recorded as DE.

Figure 1 illustrates the trend of the digital economy (DE) across different years. The DE index in Figure 1 shows the great differences in the digital economy across provinces of China, which reflects the imbalance in China's internal economic development. The Appendix A Tables A3 and A4 contain detailed maps of the spatial distribution of China's digital economy from 2013 to 2019.

As shown in Figure 1, a clear distribution feature of the DE indicator within the observation period (2013~2019) can be found: there is a significant gap between the DE of the eastern provinces of China and that of the other provinces. However, during the period from 2013 to 2019, China's DE has risen rapidly—in 2013, the central and western provinces were basically in the low range (0.07~0.12), but in 2019, the DE of these provinces was close to 0.2. The most significant increases were in Shaanxi, Sichuan, Hubei, Chongqing, and Anhui, all of which increased by more than 0.1.

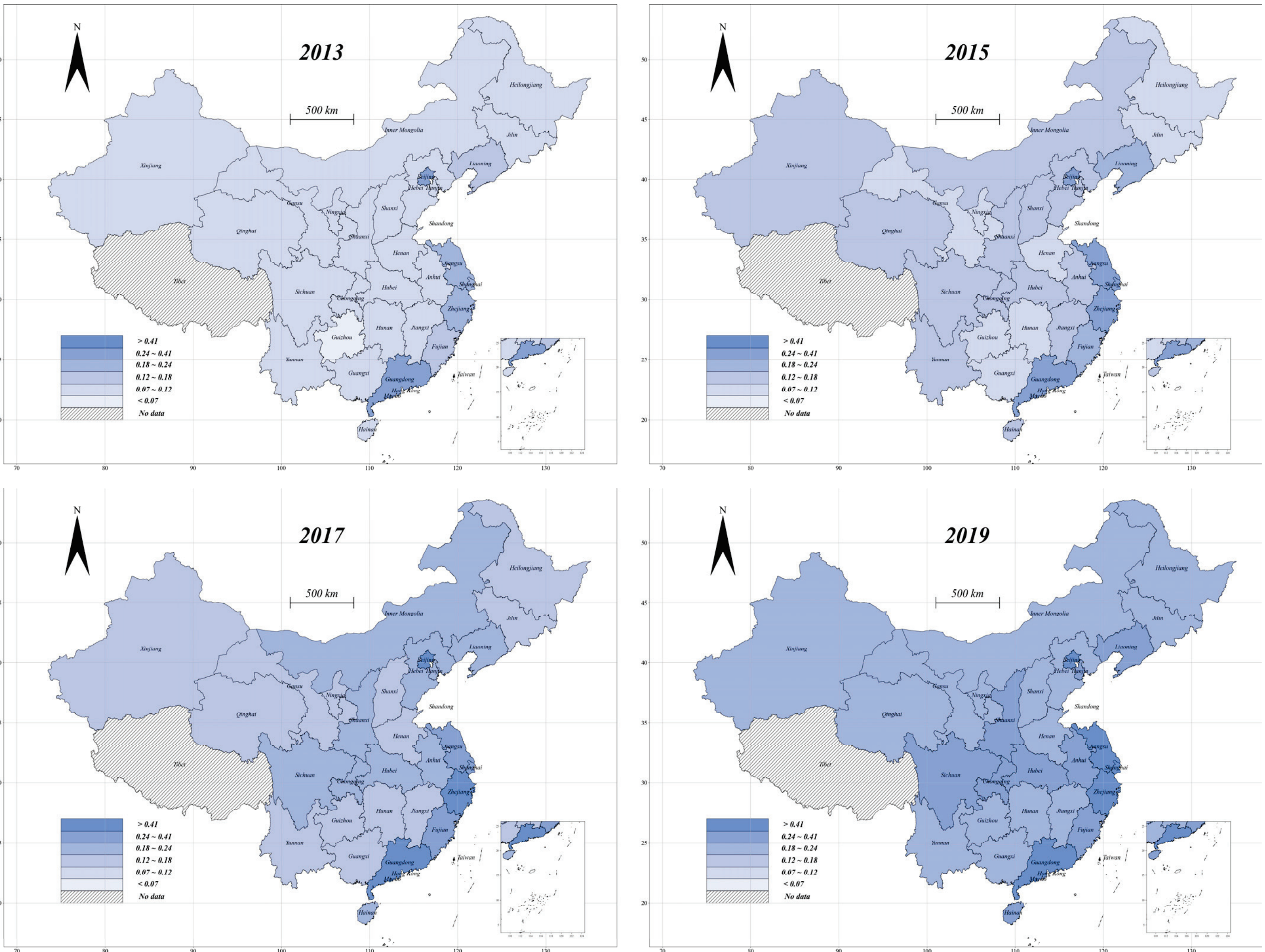


Figure 1. Geographical distribution of China's DE over the specified period (horizontal axis: longitude, vertical axis: latitude; same below).

3.2. Calculation of Agricultural Technical Efficiency Based on the DEA

Currently, Data Envelopment Analysis (DEA) is commonly employed for measurement purposes. DEA models include the CCR and BCC approaches [38]. The CCR model operates under the assumption of constant returns to scale, whereas the BCC model assumes increasing or decreasing returns to scale. The efficiency, as defined by DEA, encompasses three dimensions: overall technical efficiency (CCR), pure technical efficiency (BCC), and scale efficiency [33]. In this study, ATE is assessed as overall technical efficiency (based on the CCR), which assesses the ability to produce a given output using the least amount of inputs. Therefore, the input-oriented CCR model is utilized.

Since DEA gives every efficient decision-making unit (DMU) a score of 1, it complicates the task of establishing a hierarchy among them. As a result, the effectiveness of DEA as a framework system for measuring efficiency is undermined because only inefficient DMUs can be ranked. Some studies have introduced the concept of 'super efficiency' as a means to create a hierarchy among decision-making units [39].

The fundamental principle of the super-efficiency evaluation technique is to exclude the effective evaluation unit from the dataset and conduct a re-evaluation. This method retains the original assessment of non-effective values, enabling comparison when the initial effective value exceeds 1. To measure agricultural technical efficiency (ATE), we utilize a super-efficiency DEA model. Assuming there are n decision-making units, m input indicators, and q output indicators, the following model is employed to determine ATE:

$$min\left(\theta-\varepsilon\left(\sum_{i=1}^{m}s_i^-+\sum_{j=1}^{q}s_j^+\right)\right)$$
$$s.t.\begin{cases}\sum_{k=1}^{n}\lambda_k x_{ik}+s_i^-=\theta x_i\ ;\ i\ =\ 1,\ 2,\ \ldots,\ m\ ;\ k\neq j\\ \sum_{k=1}^{n}\lambda_k y_{jk}-s_j^+=y_j\ ;\ j=1,\ 2,\ \ldots,\ q\ ;\ k\neq j\\ \lambda_k\geq 0,\ k=1,\ \ldots,\ n\\ s_i^-\geq 0,\ s_j^+\geq 0\end{cases} \tag{1}$$

For the kth DMU, x_{ik} denotes the ith input indicator, y_{jk} represents the jth output indicator. and s_i^- and s_j^+ are input and output slack variables, respectively. λ_k denotes the weight coefficient. An elevated θ value serves as an indicator of increased ATE.

Additionally, the variables incorporated into the DEA model are defined as follows: fertilizer input is measured by the amount of nitrogen and phosphate fertilizer applied to agricultural production; pesticide input is quantified based on the amount of pesticides used; diesel consumption in agricultural production is utilized as an indicator of energy input; total agricultural water use is employed to represent water input; the total area sown acts as a proxy for land input; and the yield value of the agricultural planting industry is used as an indicator of output value. To account for inflation, output values are deflated using 2013 as the base year.

In Figure 2, the average of ATE increased from 0.51 in 2013 to 0.74 in 2019. This is an increase of nearly 45.09%. Similar to DE, ATE shows a clear spatial distribution feature. However, the trend of imbalance is declining, which means that the ATE in different regions of China is experiencing balanced growth.

3.3. Econometric Model

We investigate the impact of the digital economy on agricultural technical efficiency, where the digital economy (DE) serves as the key independent variable and agricultural technical efficiency (ATE) is the dependent variable. Dynamic panel methods are employed to analyze the potential lagged effects on ATE. The basic model is formulated as follows:

$$LnATE_{it}=\alpha+\beta_0 LnATE_{i,t-1}+\beta_1 LnDE_{it}+\beta_2 X_{it}+\varepsilon_{it} \tag{2}$$

In Equation (2), i represents the province, and t represents the corresponding year for each variable. The intercept term is represented by α. ε_{it} represents the stochastic error term. While β_i represents the coefficients for the regress. The agricultural technical efficiency of the province is denoted by $LnATE_{it}$, and DE_{it} represents the digital economy. A vector of control variables is denoted by X. From the perspective of agricultural production, existing research on the factors influencing agricultural production efficiency can be categorized into several angles: first, the fundamental elements of agricultural production, such as water resources [40]; second, uncertain factors like climate and natural disasters [41,42]; and third, agricultural energy efficiency, environmental regulation intensity, and other policy functions [43,44].

In addition, agricultural energy efficiency (AEE) is calculated as fiscal agricultural expenditure divided by total fiscal expenditure. Water resource adequacy (WRA) is evaluated by dividing regional water resources (in 100 million m^3) by the area sown to crops (in 1000 hectares). Environmental regulation intensity (ERI) is determined by the share of industrial pollution control investments completed in the secondary sector. The measure for natural disasters (ND) is the ratio of the affected area relative to the cultivated area. Table A2 shows the descriptive statistics.

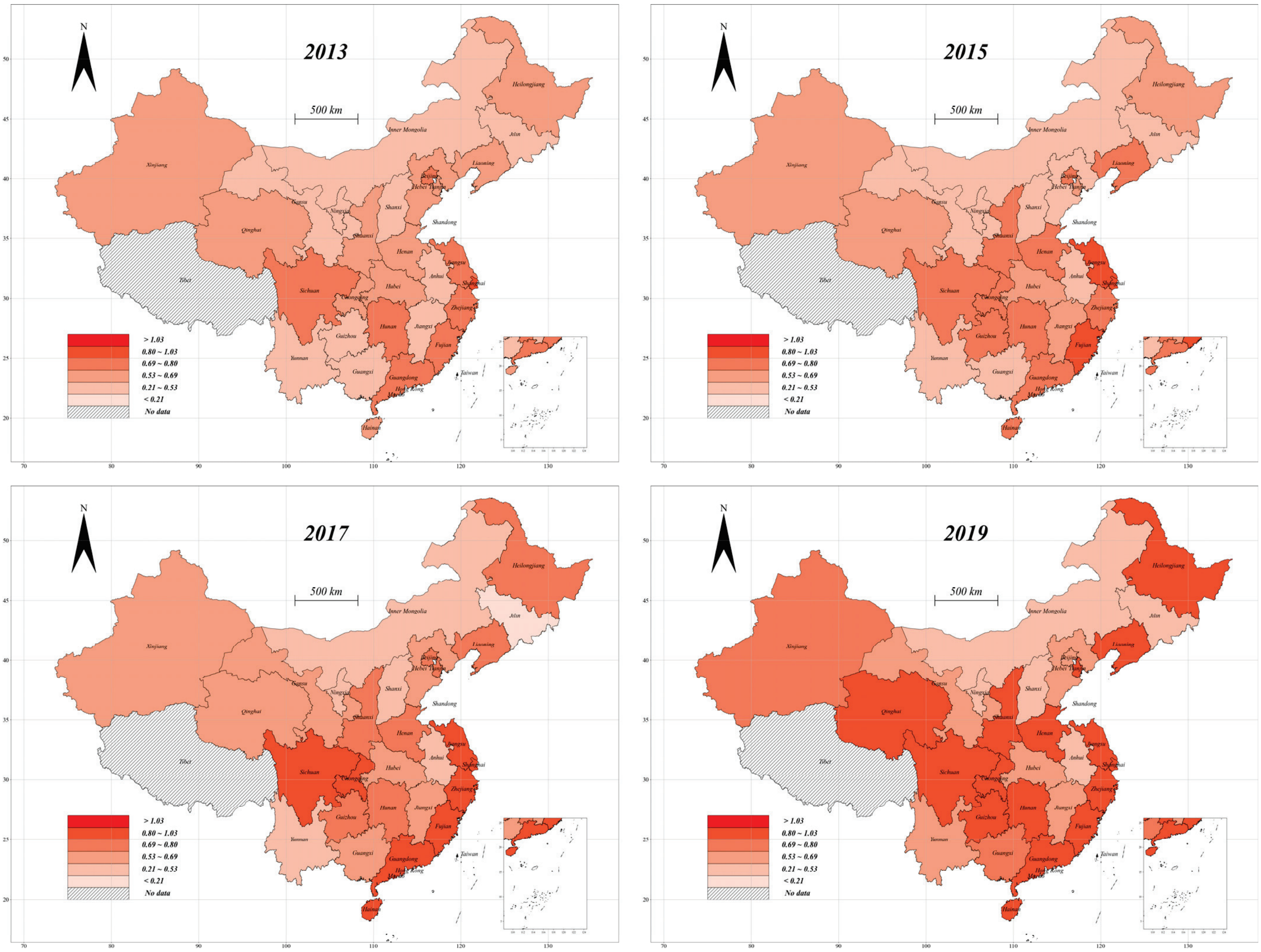


Figure 2. Geographical distribution of China's agricultural technical efficiency over the specified period.

3.4. Data Sources

Constrained by the availability of data, this research period is limited to 2013–2020. For this study, all data were sourced exclusively from the public database of the National Bureau of Statistics (https://data.stats.gov.cn/, accessed on 10 March 2024), particularly the China Statistical Yearbook, the China Agriculture Yearbook, the China Rural Statistical Yearbook, and the China Population and Employment Statistics Yearbook. We refer to the selection of relevant studies [45,46] and the issues of concern to this study and conduct the screening and collection of yearbook data. All data in this study are public data and can be used free of charge. Table 1 displays the descriptive statistics of our key variables.

Table 1. Descriptive statistics of key variables.

Variables	Observations	Mean	Standard Deviation	Min	Max
LnATE	240	−0.424	0.351	−1.544	0.222
LnDE	240	−1.633	0.501	−2.617	−0.264
LnWRA	240	−2.146	1.202	−4.923	0.571
LnAEE	240	3.196	1.279	0.583	5.939
LnND	240	−2.294	1.036	−7.169	0.964
LnERI	240	−6.200	0.914	−10.022	−3.709

4. Results

This study employs several key empirical estimation methodologies. First, the Pesaran cross-sectional dependence (CD) test and the Lagrange Multiplier (LM) test are conducted in Section 4.1 to determine the existence of cross-sectional dependence. Then, panel unit root tests are performed in Section 4.2 to assess the stationarity of each variable. Lastly, in Section 4.3, the ordinary least squares (OLS), generalized least squares (GLS), random effects (RE), and fixed effects (FE) methods are applied to estimate the impact.

4.1. Examination of Cross-Sectional Dependency

Before conducting a valid econometric analysis, it is essential to check for cross-sectional dependency in panel data. Neglecting cross-sectional independence often leads to unreliability and inconsistencies [47]. To address this, the analysis incorporates several assessments to determine the presence of cross-sectional interdependence: the Pesaran CD test [48], the Breusch–Pagan LM test [49], the Frees test [50], and the Friedman test [51].

Table 2 provides the findings of the four tests of cross-sectional dependency. Except for the Friedman test, all *p*-values for cross-sectional dependence checks were greater than 1%. As a result, the analysis disproves the null hypothesis, which posits the absence of cross-sectional dependency. The result indicates that the cross-sectional components of the research are not independent. Therefore, the presence of cross-sectional dependence must be considered in the subsequent empirical analysis.

Table 2. Tests for cross-sectional dependency.

	Statistics	Probability
Frees test	3.307 ***	0.0001
Friedman test	40.956 *	0.0695
Breusch–Pagan LM test	604.41 ***	0.0001
Pesaran CD test	10.532 ***	0.0001

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

4.2. Verifying the Stationarity of Panel Data

Testing stationarity is essential for avoiding biased regression results. Notably, the reliability of first-generation panel unit root tests, such as the Phillips–Perron test and the LLC test, is diminished in the presence of cross-sectional dependence [52]. Consequently, second-generation panel unit root tests, which account for cross-sectional dependence, are recommended by Pesaran [52]. In this study, both the Levin–Lin–Chu (LLC) and Phillips–Perron (PP) panel unit root tests are applied in Table 2.

Each of the indicators analyzed in this study possesses a first-order integration, denoted as I (1). The unit root tests emphasize two distinct forms: one with intercept only and another with both intercept and trend components. Table 3 presents evidence suggesting that, with the exception of ATE and ERI, the original data series is non-stationary, irrespective of the presence of a trend component. Subsequently, first-order differentiation is applied to the raw data, resulting in statistically significant *p*-values ($p < 0.01$) for the transformed first-order series. Therefore, the raw data are not stationary.

Table 3. Outcomes of verifying panel stationarity.

	Level		Difference of the First Order		Integration
	I	I + T	I	I + T	
	LLC test				
LnATE	−0.31842 ***	−0.86594 ***	−1.24207 ***	−1.32299 ***	I (1)
LnDE	−0.35841	−0.94970	−1.30371 ***	−1.36913 ***	I (1)
LnWRA	−0.93447	−1.11783	−1.32972 ***	−1.42627 ***	I (1)
LnND	−0.57860	−0.85285	−1.19507 ***	−1.38679 ***	I (1)
LnAEE	−0.19917	−0.64242	−0.91364 ***	−1.13099 ***	I (1)
LnERI	−0.79274 *	−1.22233 *	−1.50375 ***	−1.62972 ***	I (1)

Table 3. *Cont.*

	Level		Difference of the First Order		Integration
	PP test				
LnATE	−0.35129 ***	−0.98138 ***	−1.38976 ***	−1.49584 ***	I (1)
LnDE	−0.40736	−1.09469	−1.47458 ***	−1.52114 ***	I (1)
LnWRA	−1.06781	−1.24955	−1.47306 ***	−1.54437 ***	I (1)
LnND	−0.63142	−0.93365 **	−1.33835 ***	−1.46378 ***	I (1)
LnAEE	−0.21908	−0.73768	−1.00202 ***	−1.22309 ***	I (1)
LnERI	−0.87101 ***	−1.33499 **	−1.62875 ***	−1.74869 ***	I (1)

Note: I: Intercept; I + T: Intercept and trend. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

4.3. Digital Economy's Effect on Agricultural Technical Efficiency

To assess the impact of DE on ATE, it is crucial to apply appropriate econometric models. The Feasible Generalized Least Squares (FGLS) method is particularly effective for panel estimation, as it maximizes the advantages of panel data while minimizing estimation errors. It is commonly used when heteroscedasticity and serial correlation are present in the sample data [53]. Given the results from the cross-sectional dependence and panel stationarity tests, this study uses FGLS as the benchmark method for evaluating the influence of DE on ATE, ensuring greater consistency and validity in the panel regression, as shown in Table 4.

Table 4. Assessing the impact of DE on ATE.

	Estimating Static Panel				
	OLS	**FE**	**RE**	**GLS**	**FGLS**
LnDE	0.238 ***	0.300 ***	0.293 ***	0.238 ***	0.230 ***
	(0.0429)	(0.0232)	(0.0229)	(0.0423)	(0.0173)
LnWRA	0.045 ***	0.023	0.030	0.045 ***	0.044 ***
	(0.0161)	(0.0240)	(0.0211)	(0.0159)	(0.0077)
LnAEE	0.053 ***	−0.029	−0.016	0.053 ***	0.054 ***
	(0.0150)	(0.0175)	(0.0162)	(0.0148)	(0.0079)
LnND	−0.042 **	−0.003	−0.004	−0.042 **	−0.040 ***
	(0.0195)	(0.007)	(0.0076)	(0.0192)	(0.0089)
LnERI	−0.053 **	−0.034 ***	−0.033 ***	−0.053 **	−0.047 ***
	(0.0255)	(0.0119)	(0.0118)	(0.0252)	(0.0130)
Constant	−0.534 **	−0.009	−0.044	−0.534 **	−0.496 ***
	(0.2159)	(0.1235)	(0.1297)	(0.2132)	(0.1031)
Observations	240	240	240	240	240

Note: standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$.

The coefficient of DE displays positive, demonstrating that DE exerts a positive facilitating effect on ATE. Besides, we run the estimation based on the ordinary least squares, fixed effects, random effects, and generalized least squares method to guarantee the robustness of the main results. The effect of DE on ATE is robust, as all the signs and coefficients in columns 1–6 of Table 3 are consistent. The coefficients of DE on ATE in FGLS are 0.23 and statistically significant at the 1% level, which shows that a 1% increase in DE leads to a 0.23% increase in ATE.

Regarding the control variables, adequate water resources and agricultural energy efficiency both have a positive impact on elevating agricultural technical efficiency. WRA is associated with a higher ATE. WRA increases ATE, and this reflects the crucial role that irrigation plays in agricultural productivity. Higher AEE reduces the cost of farm mechanization and increases ATE by increasing the substitution of farm machinery for labor. Agricultural production is heavily influenced by climate, and droughts can impede the accumulation of grain dry matter and lead to premature maturation, ultimately reducing food yields. Furthermore, drought forces farmers to reallocate resources, increasing their labor and water inputs to mitigate its effects. ERI significantly reduces the ATE by crowding out original agricultural production inputs through increased environmental investment costs.

5. Robustness Tests

5.1. Replacing the Dependent Variable

First, three indicators of the digital economy—informatization development (INF), internet development (INT), and digital industries (DI)—are utilized as substitutes for the main independent variable (DE). The regression results on ATE using the FGLS method are presented in Columns 1–3 of Table 4. All three indicators have positive impacts on ATE, with statistical significance at the 1% level. Specifically, the estimated elasticities for INF, INT, and DI in relation to ATE are 0.2, 0.261, and 0.168, respectively. These findings align with the results shown in Table 5, further confirming the robustness of the baseline regression results.

Table 5. Robustness test: replacing the dependent variable and two-stage least squares method.

		FGLS		**2SLS**
	(1)	**(2)**	**(3)**	**(4)**
LnINF	0.200 ***			
	(0.0140)			
LnINT		0.261 ***		
		(0.0277)		
LnDI			0.168 ***	
			(0.0154)	
LnDE				0.565 ***
				(0.1874)
LnWRA	0.048 ***	0.057 ***	0.041 ***	0.048 ***
	(0.0072)	(0.0079)	(0.0084)	(0.0179)
LnAEE	0.054 ***	0.058 ***	0.053 ***	0.021
	(0.0070)	(0.0083)	(0.0090)	(0.0241)
LnND	−0.037 ***	−0.039 ***	−0.045 ***	−0.032
	(0.0087)	(0.0100)	(0.0094)	(0.0222)
LnERI	−0.045 ***	−0.067 ***	−0.051 ***	0.027
	(0.0127)	(0.0130)	(0.0133)	(0.0527)
Constant	0.300 ***	−0.276 **	−0.432 ***	0.630
	(0.1038)	(0.1358)	(0.1152)	(0.6881)
Weak identification tests				15.287
Observations	240	240	240	240

Note: standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$.

Second, although heteroscedasticity and serial correlation issues are addressed in the benchmark regression, potential endogeneity bias may persist. This bias can arise from omitted variables or interactions between the dependent and independent variables. To address potential endogeneity concerns, we employ an instrumental variable approach. Specifically, we use the lagged values of energy consumption from electronic communication equipment ($LnECE_{t-1}$) and chip production ($LnCP_t$) as instruments. The estimation results, based on the 2SLS method, are presented in Column 4 of Table 5. Weak identification tests reject the hypothesis of weak instrumental variables, indicating that the instruments are effective. These results further confirm the robustness of the findings. Therefore, Hypothesis 1 is supported by robust results.

5.2. The Asymmetric Effect

To examine the potential asymmetric effects of the DE on ATE, we analyze Equation (2) by estimating the lower, first quartile, median, third quartile, and upper quantiles of the specified level of ATE. Utilizing the two-stage panel quantile regression methodology, we aim to capture unobserved individual variations [54]; we present the results in Table 6, while Figure 3 illustrates the varying impacts across these quantile levels.

Table 6. Calculation of two-step panel quantile regression.

	LnATE				
	Quantiles				
	q10	**q25**	**q50**	**q75**	**q90**
LnDE	0.378 ***	0.279 ***	0.189 ***	0.226 ***	0.230 ***
	(0.0572)	(0.0429)	(0.0421)	(0.0589)	(0.0643)
LnWRA	0.125 ***	0.069 ***	0.033	0.003	0.003
	(0.0203)	(0.0209)	(0.0235)	(0.0141)	(0.0111)
LnAEE	0.090 ***	0.060 ***	0.043 ***	0.013	0.020 *
	(0.0263)	(0.0195)	(0.0134)	(0.0184)	(0.0122)
LnND	−0.072 ***	−0.030	−0.047 ***	−0.026	−0.003
	(0.0274)	(0.0198)	(0.0150)	(0.0231)	(0.0139)
LnERI	0.090 *	−0.046	−0.076 **	−0.084 ***	−0.092 ***
	(0.0515)	(0.0387)	(0.0368)	(0.0249)	(0.0167)
Constant	0.211	−0.497 **	−0.718 ***	−0.490 *	−0.407 *
	(0.3170)	(0.2412)	(0.2402)	(0.2821)	(0.2261)
R^2	0.3010	0.3173	0.2676	0.2749	0.2842

Note: standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

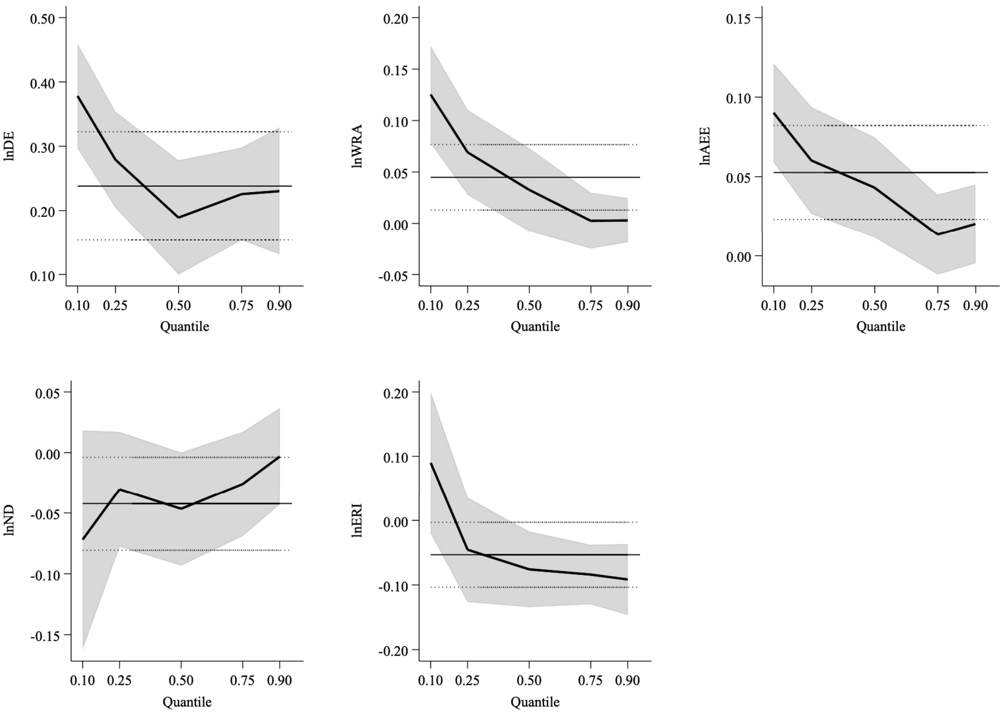


Figure 3. Variations in coefficient estimates obtained via panel quantile regression.

As shown in Table 6 and Figure 3, the impact of DE on ATE across different quantile ranges exhibits stability and uniformity. DE has a positive coefficient, suggesting potential for substantial enhancement of ATE. It is worth noting that DE made a greater impact on ATE in low-ATE. For control variables, the impacts of WRA, AEE, ND, and ERI on ATE exhibit asymmetry. Specifically, the influence of WRA and ND on ATE is notable in regions with low ATE, whereas it is insignificant in those with high ATE. Higher ATEs demonstrated a stronger ability to defend against the challenges of ND, while lower ATE areas need to be alert to the damage caused to ATE by ND. In addition, ERI displays a negative impact on ATE in high-ATE, which may be related to regulatory costs. Higher ATE will compress the optimal allocation of input elements, so the negative impact of ERI will be more significant.

6. Discussion

6.1. Heterogeneity Analysis

We segregated China's 30 provinces into two distinct regions, according to their geographical positioning, in order to discern the regionally varying impact of DE on ATE. The detailed panels are outlined in Appendix A.

The climate differs greatly between the northern and southern regions of China. To analyze the regionally diverse impact of DE on ATE, we divided the 30 provinces of China according to their geographical locations. Table 7 presents the estimated results, which were derived using the FGLS estimation.

Table 7. Estimation of regional heterogeneity.

Variables	North	South
LnDE	0.259 ***	0.300 ***
	(0.0429)	(0.0235)
LnWRA	0.048 ***	0.071 ***
	(0.0116)	(0.0163)
LnAEE	0.149 ***	−0.015
	(0.0145)	(0.0116)
LnND	−0.027 **	−0.054 ***
	(0.0133)	(0.0135)
LnERI	−0.024	−0.024
	(0.0226)	(0.0207)
Constant	−0.563 ***	0.018
	(0.1954)	(0.1667)
Observations	120	120

Note: standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$.

In both the northern and southern areas, DE displays a positive and statistically substantial effect on ATE. A 1% increase in DE leads to a 25.9% increase in ATE in the northern provinces, while in the southern provinces, the increase is 30%. It demonstrates that increasing DE is more efficient in southern areas. The primary reason is the difference in natural resources and economic development. The south is more conducive to agricultural growth in terms of water resource reserves and weather conditions, so the progression of the digital economy in the southern provinces is more conducive to the improvement of agricultural technical efficiency under the same conditions. The south is more conducive to agricultural growth because of the water resources reserves and the weather conditions, so the development of DE in southern provinces is more significant to the improvement of ATE. For control variables, the impact of AEE on ATE in southern provinces is not significant, while the impact in northern provinces is significantly positive. The proportion of mechanization is comparatively higher in the northern region than in the southern region; therefore, AEE may have a greater impact in the north. Thus, Hypothesis 1a is supported to some extent; from the existing literature, our findings on mechanization have not been paid attention to in previous studies [20–22]. We identify the heterogeneity of this effect by dividing the Chinese provinces into north and south. This sample division strategy takes into account the differences in the endowments of various Chinese provinces [23] and is more targeted to policy implementation.

6.2. Mechanism Analysis

6.2.1. Potential Mechanisms

The above results suggest that increasing DE could lead to increasing ATE. In this study, we employ a mediation mechanism to delve into the intricate pathways through which DE exerts its influence on ATE. It is found that the digital economy can improve production efficiency through the optimization of element allocation. With the development of digitization, the level of marketization has improved, the distorted rural labor and capital market has improved, and the agricultural TFP has improved [55]. The marketization of agriculture involves three major elements: agricultural farming structure (AFS), off-farm work (OFW), and arable land transfer (ALT). AFS measures the proportion of cash crops, which changes with labor prices and population structure [56]. Cash crops are more intensively commercialized and have higher total income than traditional crops. [57, 58]. In rural China, OFWs have always been an inevitable topic. [59,60]. As the most important allocation mode of agricultural land, ALT represents the achievements of land marketization reform, and their proportion evaluates the allocation of land elements [61,62].

AFS, OFW, and ALT serve as mediators in our model, enabling us to scrutinize the underlying mechanism linking DE to ATE. The agricultural farming structure (AFS) is represented by the proportion of cash crop sown area to the total sown area. The proportion of non-agricultural employment to total employment is used as an indicator for off-farm work (OFW). The ratio of arable land transferred to total arable land serves as arable land transfer (ALT). All of the aforementioned data resources are sourced from public databases. Compared to ATE, Figure 4 shows the spatial distribution of AFS, OFW, and ALT during 2013–2019. The model for analyzing the mechanism, which incorporates a mediating effect, is established as follows:

$$LnATE_{it} = \delta_1 LnDE_{it} + \beta_1 X_{it} + \phi_{it} \quad (3)$$

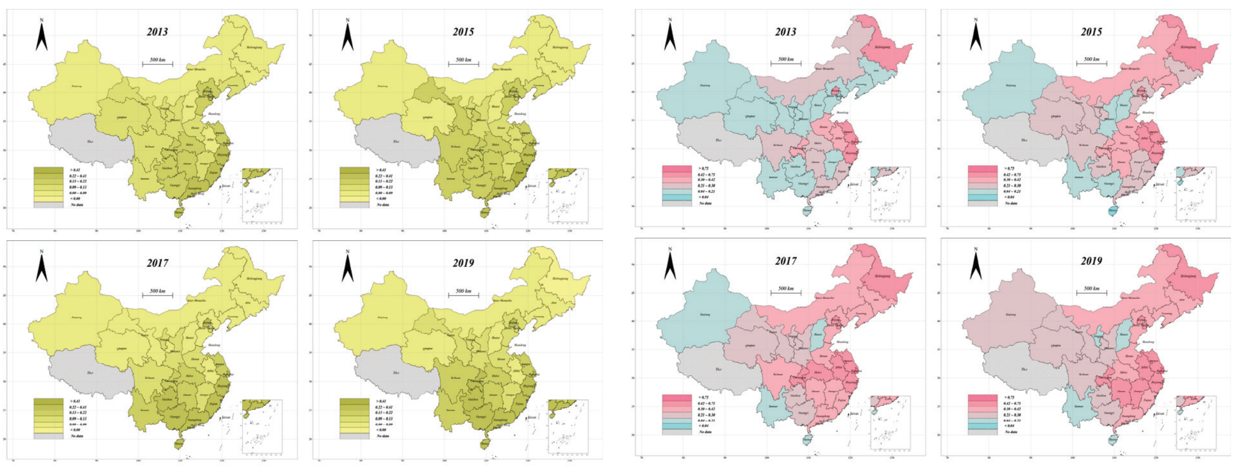
$$LnM_{it} = \delta_2 LnDE_{it} + \beta_2 X_{it} + \mu_{it} \quad (4)$$

$$LnATE_{it} = \delta_3 LnDE_{it} + \delta_4 LnM_{it} + \beta_3 X_{it} + \gamma_{it} \quad (5)$$

where M represents mediators such as AFS, OFM, and ALT i and t represents units and time periods in the panel. A set of control variables is represented by X. δ_1 is the total impact of the digital economy on agricultural technical productivity. δ_3 is the direct impact of DE on ATE, δ_2 and δ_4 is the indirect impact.

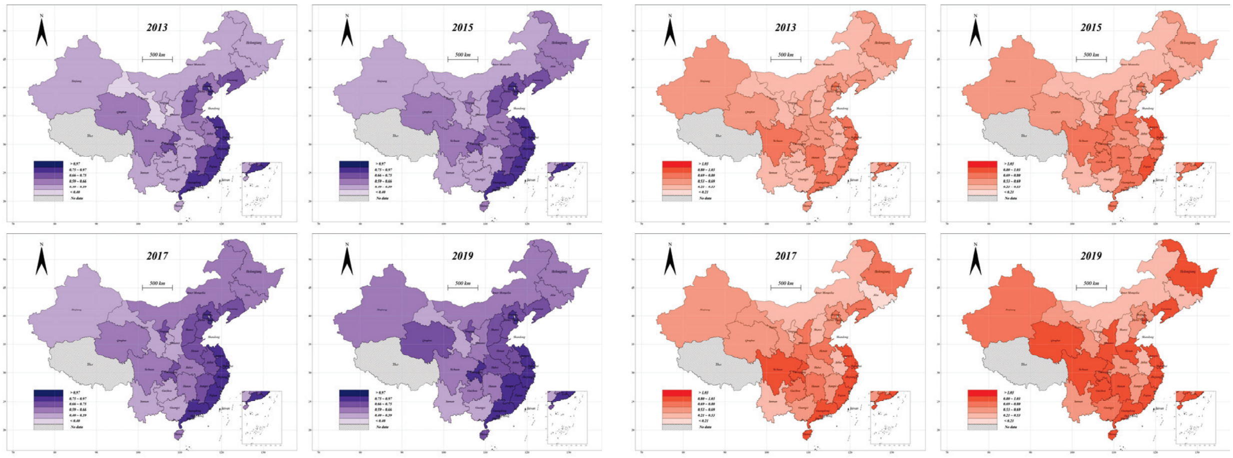
6.2.2. Results of the Mediation Effect Analysis

In Table 8, Column 1 displays the aggregate impact of DE on ATE (δ_1). The elasticity of the aggregate impact is 0.23 and is significant. Columns 2–4 of Table 7 show the indirect impact δ_2 including AFS, PAM, and ALT, are all significant at a threshold of 1% statistical confidence and estimated to be 0.236, 0.177, and 0.521. These results suggest that DE exerts a positive impact on AFS, OFW, and ALT. From Columns 4–5, it can be seen that the elasticities of AFS, OFW, and ALT are 0.275, 0.129, and 0.038, and are significant. This suggests that AFS, OFW, and ALT significantly influence the ATE. Our finding is consistent with the conclusions of existing research: the digital economy can significantly promote the transfer of farmland and improve production efficiency [63], achieve coordination of the digital economy through OFW and AFS, unleash the driving force of digital economy innovation, and improve productivity [64].



(**a**) (**b**)

Figure 4. *Cont*.



(**c**) (**d**)

Figure 4. The spatial distribution of AFS, ALT, OFW, and ATE during 2013–2019. (**a**) Agricultural farming structure (AFS); (**b**) arable land transfer (ALT); (**c**) off-farm work (OFW); (**d**) agricultural technical efficiency (ATE).

Table 8. Mechanism analysis results of AFS, OFW, and ALT.

Variables	LnATE	LnOFW	LnAFS	LnALT	LnATE	LnATE	LnATE
LnOFW					0.275 ***		
					(0.0600)		
LnAFS						0.129 ***	
						(0.0165)	
LnALT							0.038 *
							(0.0214)
LnDE	0.230 ***	0.236 ***	0.177 ***	0.521 ***	0.143 ***	0.210 ***	0.197 ***
	(0.0173)	(0.0128)	(0.0553)	(0.0378)	(0.0250)	(0.0172)	(0.0230)
LnWRA	0.044 ***	−0.009 **	0.185 ***	−0.063 ***	0.045 ***	0.028 ***	0.049 ***
	(0.0077)	(0.0041)	(0.0245)	(0.0115)	(0.0072)	(0.0076)	(0.0080)
LnAEE	0.054 ***	0.009 *	0.080 ***	−0.082 ***	0.047 ***	0.037 ***	0.055 ***
	(0.008)	(0.0051)	(0.0212)	(0.0123)	(0.0087)	(0.0086)	(0.0081)
LnND	−0.040 ***	−0.009 **	−0.135 ***	0.024	−0.037 ***	−0.029 ***	−0.044 ***
	(0.0089)	(0.0041)	(0.0301)	(0.0182)	(0.0091)	(0.0085)	(0.0092)
LnERI	−0.047 ***	0.014 **	0.011	−0.069 ***	−0.054 ***	−0.037 ***	−0.051 ***
	(0.0130)	(0.0068)	(0.0430)	(0.0204)	(0.0128)	(0.0120)	(0.0134)
Constant	−0.496 ***	0.017	−1.748 ***	−0.551 ***	−0.532 ***	−0.177 *	−0.533 ***
	(0.1031)	(0.0652)	(0.3400)	(0.1691)	(0.1068)	(0.1023)	(0.1073)
Observations	240	240	240	240	240	240	240

Note: standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

6.3. Further Discussion

We investigated the convergence of ATE and the effect of DE on its convergence, as shown in Table 9.

Table 9 shows the estimated outcomes of the unconditional β convergence test, categorized according to high, medium, and low levels of digital economy (DE). For these regions, the unconditional β-convergence test solely rejects the convergence hypothesis for ATE in the context of medium levels of DE. This section aims to answer whether DE can exacerbate the convergence of ATE in China in the future.

The role of DE in accelerating agricultural total factor efficiency ATE convergence is explored in this paper. By examining the lagged ATE in both unconditional and conditional analyses, we test DE's contribution to ATE convergence in China. In the full sample analysis, the coefficient shift suggests DE's positive effect on world agriculture convergence. Within-group comparisons show DE facilitates convergence in the full sample and high DE sample. Condition β-convergence results hint at future ATE improvement and accelerated convergence beyond DE. Overall, WRE, AEE, and ERI also significantly impact ATE improvement and convergence. Our findings align with previous studies emphasizing the pivotal role of technological advancements [21,63], in transforming agricultural productivity and fostering efficiency convergence across regions. By enhancing data-driven decision-making, precision farming, and resource optimization, DE narrows the productivity gap between advanced and less developed agricultural sectors, as suggested by the conditional β-convergence results. This reinforces the notion that technological innovations are key drivers of agricultural development and should be a focal point of policy interventions.

Table 9. Unconditional β-convergence and conditional β-convergence on ATE of China.

	Unconditional β-Convergence Tests				**Conditional β-Convergence Tests**			
	All	**Hight**	**Middle**	**Low**	**All**	**Hight**	**Middle**	**Low**
L.lnATE	0.9734 ***	0.8604 ***	1.1054	0.9477 ***	0.7536 ***	0.5038 ***	0.8057	0.6634 ***
	(0.0374)	(0.0734)	(0.0977)	(0.0325)	(0.0664)	(0.1111)	(0.1590)	(0.0794)
L.lnDE					0.0798 ***	0.1500 **	0.0218	0.0954
					(0.0283)	(0.0489)	(0.0551)	(0.0672)
LnWRA					0.0214	−0.0057	0.0762 **	−0.0062
					(0.0214)	(0.0355)	(0.0272)	(0.0415)
LnAEE					0.0190	−0.0254	0.0575 ***	0.0839
					(0.0153)	(0.0283)	(0.0148)	(0.0486)
LnND					0.0001	0.0002	0.0067	−0.0124
					(0.0059)	(0.0151)	(0.0045)	(0.0093)
LnERI					−0.0135	−0.0001	−0.0262 *	−0.0103
					(0.0114)	(0.0211)	(0.0117)	(0.0346)
Intercept	0.0450 **	0.0130	0.1044 **	0.0382	−0.0318	0.2021	−0.1481	−0.3339
	(0.0171)	(0.0155)	(0.0459)	(0.0224)	(0.1077)	(0.1665)	(0.1228)	(0.3504)
Observations	210	70	70	70	210	70	70	70
Province	30	10	10	10	30	10	10	10
Conclusion	con	con	di	con	con	con	con	con

Note: con: convergence; di: divergence. Standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

7. Conclusions and Policy Implications

The key findings of the study are as outlined below:

1. The visualization revealed disparities between eastern and central/western regions, which appeared to narrow from 2013 to 2019 due to government efforts. Notably, a preliminary positive correlation between DE and ATE was observed;
2. DE significantly and positively impacts ATE and has been tested differently to prove that such conclusions obtained in this study are robust. The development of the digital economy is advantageous to agricultural productivity, and considering the disparity in natural resources and economic development, it follows that the impact is more pronounced in the southern region;
3. In addition, this study discusses the mechanisms. We found that marketization is a mediation impact mechanism while DE impacts ATE. Based on the statistical results, OFW, AFS, and ALT are all the mechanism variables of DE, which means that DE will impact ATE by influencing OFW, AFS, and ALT;
4. Finally, we are concerned about the impact of the digital economy on the convergence of agricultural technical efficiency. Due to the development of digital information technology, marketization and the digitalization of agricultural production, as a result, agricultural technical efficiency has been improved. It means that the digital economy fosters the convergence of agricultural technical efficiency.

These empirical findings outlined above carry important policy implications:

1. The government should (1) deepen agricultural marketization reforms, (2) optimize agricultural industrial structures, (3) encourage the transfer of rural labor to non-agricultural sectors, (4) facilitate the transfer of arable land, and (5) optimize agricultural farming structures. These initiatives will enhance the thorough integration of the digital economy and agricultural markets, further releasing agricultural productivity;
2. With the development of digital information technology and the digitization of agricultural production, agricultural technical efficiency has been significantly improved. The government should focus on balanced improvements in agricultural technical efficiency, particularly providing more support to technologically backward regions and resource-scarce areas;
3. For southern cities, enhancing the integration of the digital economy (DE) with existing agricultural practices and leveraging their superior natural resources and climate conditions to foster agricultural growth and improve agricultural technical efficiency (ATE) should be prioritized. Given the conducive environment for agricultural development, the progression of DE in these regions can significantly contribute to the optimization of agricultural input allocation and overall technical efficiency.

While our study sheds light on the pivotal role of the digital economy (DE) in accelerating agricultural total factor efficiency (ATE) convergence, several avenues for future research remain open to further refine and expand our understanding of this phenomenon:

1. Our study was constrained by the availability of data, limiting our analysis to a specific timeframe and geographic scope. To keep pace with the rapid evolution of the digital economy, future research endeavors should strive to collect and analyze updated datasets. This will not only allow for a more contemporary examination of the DE–ATE relationship but also enable researchers to capture any emerging trends or shifts in this dynamic landscape;
2. Despite discussing heterogeneity within our provincial-level analysis, substantial variation still exists within our sample. To address this, future research could endeavor to construct more granular datasets, potentially shifting the focus to a municipal or even more refined perspective. Such an approach would provide deeper insights into the nuanced impacts of the digital economy on agricultural productivity across diverse regions;
3. Our study identified areas for improvement in the construction of the digital economy index. The precision and comprehensiveness of this index are crucial for accurately identifying and analyzing economic issues related to the digital economy. Future research should strive to enhance the development of the digital economy index, incorporating a broader range of indicators and employing more sophisticated methodologies to ensure a more precise and nuanced representation of the digital economy's multifaceted impacts on agricultural productivity.

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Appendix A

Table A1. Digital economy indicators.

Level 1 Indicators	Level 2 Indicators	Measurement	Weighting
Informatization Development (INF)	Informatization Foundation	Fiber optic density	0.0628
		Mobile phone base station density	0.0684
		Percentage of information technology employees	0.0275
	Influence of Informatization	Total telecoms business	0.1125
		Software business income	0.1695
Internet Development (INT)	Fixed End Internet Foundation	Internet access port density	0.0634
	Mobile Internet Foundation	Mobile internet penetration	0.0294
	Fixed End Internet Impact	Share of broadband internet users	0.0357
	Mobile Internet Impact	Share of mobile internet users	0.0116
Digital Industry (DI)	Digital Industry Foundation	Number of websites per 100 businesses	0.0174
		Use of computers in business	0.0426
		Percentage of e-commerce businesses	0.0481
	Digital Trading	E-commerce sales	0.1403
		Online retail sales	0.1707

Table A2. Summary statistics of variables in the econometric model.

Var Name	Obs	Mean	SD	Min	Max
LnATE	240	−0.424	0.351	−1.544	0.222
LnDE	240	−1.633	0.501	−2.617	−0.264
LnWRA	240	−2.146	1.202	−4.923	0.571
LnAEE	240	3.196	1.279	0.583	5.939
LnND	240	−2.294	1.036	−7.169	0.964
LnERI	240	−6.200	0.914	−10.02	−3.709
LnINF	240	−2.727	0.582	−3.863	−1.191
LnINT	240	−2.629	0.378	−3.576	−1.959
LnDI	240	−2.939	0.659	−4.343	−1.019
$LnECE_{t-1}$	240	−3.335	2.318	−10.45	0.671
LnCP	240	1.721	2.063	0	6.730
LnOFW	240	−0.387	0.198	−0.898	−0.0301
LnAFS	240	−2.047	0.824	−4.720	0.711
LnALT	240	−1.178	0.511	−3.061	−0.0931

Table A3. The specific provinces across different regions.

Region	Provinces
North (15 provinces)	Beijing, Hebei, Tianjin, Inner Mongolia, Shanxi, Jilin, Liaoning, Heilongjiang, Henan, Shandong, Gansu, Shaanxi, Ningxia, Qinghai, Xinjiang
South (15 provinces)	Shanghai, Jiangsu, Hainan, Fujian, Hubei, Jiangxi, Guangxi, Hunan, Guangdong, Sichuan, Guizhou, Chongqing, Zhejiang, Anhui, Yunnan

Table A4. The specific provinces across Different levels of DE development regions.

Region	Provinces
Hight (10 provinces)	Beijing, Fujian, Guangdong, Jiangsu, Shandong, Shanghai, Sichuan, Zhejiang, Liaoning, Shaanxi.
Middle (10 provinces)	Hebei, Hubei, Inner Mongolia, Tianjin, Anhui, Qinghai, Hainan, Xinjiang, Hunan, Chongqing.
Low (10 provinces)	Shanxi, Jilin, Heilongjiang, Henan, Gansu, Ningxia, Jiangxi, Guangxi, Guizhou, Yunnan.

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Wheat Value Chains and Vertical Price Transmission in South Africa: A Nonlinear Autoregressive Diagnostic Lag Bound Approach

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Abstract: This study examined the vertical transmission of wheat price among the main value chain, looking at the pricing behaviour of certain role players in the wheat production/supply and the distribution of bread, which is a major staple food consumed in South Africa. A nonlinear autoregressive distributed lag (NARDL) model was used to analyse the yearly time series data for the period of 2000 to 2022. The results of the stationarity test showed that all variables were of order one, I (1). The study used two pairs, namely farmgate price and retail price, and farmgate price and wholesale price, to examine the existence of asymmetry between these prices, with rainfall and temperature as control variables. The results indicate the existence of a positive long-run asymmetry of 35.9% between the farmgate price of wheat and retail price of bread, and 3.49% asymmetry between the farmgate price and wholesale price of wheat. To develop informed policies on food security, this study suggests that the government should enhance regular access to data and sustain its monitoring and communication of food price information across the whole country. For farmers, a policy on price transparency can help them to establish a public platform to share market prices, ensuring that they receive fair prices. This paper also recommends the provision of subsidies for wheat farmers to help the wheat industry, reduce the cost of bread production, and make bread more affordable and accessible for consumers.

Keywords: vertical price transmission; farmgate price; wholesale price; retail price; price asymmetry

1. Introduction

The ability of markets to communicate price signals horizontally and vertically is an essential aspect of many current economic trends (Deb et al. 2020). Due to ongoing changes in the market, producers of agricultural commodities are becoming more interested in price transmission (Rose and Paparas 2023). The exchange of price shocks between manufacturers and retailers illustrates vertical price transmission, one way of assessing the upstream and downstream implications of the linkages in a supply chain (Rose and Paparas 2023). To better understand how prices, interact at different levels of a marketing chain, research on vertical price transmission processes must be done (Tifaoui and Von Cramon-Taubadel 2017).

Wheat was introduced to South Africa in the middle of the 17th century, and by 1684, wheat production was well established in the Cape. According to Kriel (2023), 75% of wheat in South Africa is produced under dryland conditions and 25% under irrigation. The Free State (21%), Northern Cape (17%), and Western Cape (42%) produce most of South Africa's wheat. The remaining provinces produce less. South Africa is still the second-largest sub-Saharan wheat supplier behind Ethiopia by exporting to nearby countries and acting as a passage for cereals brought in from beyond the region. It continues to import more wheat than it grows because it requires 40 to 50 percent of its own requirements in imports.

The annual yields of wheat in South Africa range between 1.5 million and 3 million metric tons, with 2–2.5 tons/ha under dryland but not less than 5 tons/ha under irrigation. Research from a variety of fields, including plant breeding, agronomy, crop physiology, and crop protection, has contributed to the rise in wheat production's efficiency, productivity, and quality over time. However, production has also been affected by climate change, such as excessive or lack of rainfall and high temperatures, which can lead to droughts over the years. According to Pachauri et al. (2014), rising temperatures, as well as rainfall, are projected to lower the production of crops such as wheat, which will have a significant negative impact on the country's food security. It is estimated that the wheat business contributes around ZAR 5 billion annually to the gross value of agricultural produce (Mphateng 2022).

Studies have been carried out to examine price relationships between farm, wholesale, and retail markets in South Africa. A study by Mosese (2020) aimed to determine the nature of price transmission in the South African potato market. A study by Mandizvidza (2013) attempted to fill the knowledge gap on the performance of Limpopo Province's tomato markets by examining vertical price linkages amongst successive marketing levels. Mphateng (2022) analysed the transmission of world wheat prices to the domestic wheat market in South Africa in which they focused on world prices; they suggested that a study on the vertical price transmission of wheat in South Africa should be conducted. This study aims to fill the gap, as suggested by Mphateng (2022); by focusing on domestic prices to examine the price transmission in the wheat-to-bread value chain and it will use a nonlinear autoregressive diagnostic lag (NARDL) model.

Statistics provided by the Department of Agriculture, Land Reform and Rural Development in 2020 revealed that the total annual production of wheat is generally less than the domestic consumption requirements. The observation provided a general indication that wheat production volumes are on the decline while consumption is continually increasing. During the marketing year 2018, the wheat production volume was about 1.80 million tons while the consumption amounted to about 3.23 million tons. This has left a deficit of about 1.43 million tons of wheat. During 2018, wheat production increased by 19% compared to the previous year, 2017. Over the same period, the local wheat utilization/consumption slightly increased by 1.3% from 3.19 million tons to 3.23 million tons. On average, South Africa produced only 56% of the country's consumption requirements over the past ten-year period (2009–2018), and the balance came from imports.

The purpose of this study is to examine the vertical price transition of wheat in South Africa, looking at the transmission of wheat farmgate prices to wheat wholesale prices to retail prices of bread from the period 2000 to 2022. The availability of data was taken into consideration when deciding the period that the study used. With a few studies performed by other authors regarding the price transmission of agricultural commodities, the vertical price transmission of wheat in South Africa was not yet performed; this led to a decision to perform this research. The objectives of this paper include analysing the long-run relationship between the wheat farm price and the wholesale wheat price and retail price, examining the asymmetry between the farmgate price and retail price, and examining the asymmetry between the farmgate price and wholesale price. The hypotheses of this paper are as follows:

H1. *There is no long-run relationship between wheat farmgate, wholesale, and retail prices.*

H2. *There is no existence of price asymmetry between the farmgate price and retail price.*

H3. *There is no existence of price asymmetry between the wholesale price and farmgate price.*

The objectives of this research were achieved under the section of estimation techniques. The first objective was achieved by performing a nonlinear bounds test to check the existence of a long-run relationship between the three prices (farmgate price, wholesale price, and retail price). The second objective of this paper can be found in the results for the estimates of the long-run coefficients for the farmgate price of wheat and the retail price of bread. The last objective was attained from the estimates of the long-run coefficients for the farmgate price and wholesale price of wheat.

2. Literature Review

2.1. Theoretical Literature

2.1.1. Market Power Theory

According to the market power theory, companies merge to reduce output or work together to increase their capacity to determine product prices. Among the arguments that have been provided to account for asymmetric price movements, the most cited is the presence of market power in retail and processing industries (Bakucs et al. 2013). Generally, it is expected that downstream food enterprises, able to exert market power, transmit price movements that threaten their marketing margin faster than price movements that improve it (Bakucs et al. 2013). More specifically, market power in downstream sectors may affect price transmission by depressing purchasing prices in upstream sectors below the level of a perfectly functioning market and deterring entry or fostering exit. Firms with market power can set prices higher than in a market with greater competition (Vaidya 2023). Consumer prices may increase as a result, and this may spread across the supply chain. On the other hand, firms can also use their bargaining power to negotiate lower prices for inputs, resulting in lower prices for producers, and this can be passed on throughout the supply chain (Conforti 2004).

2.1.2. Theory of Asymmetric Information

The economic theory of asymmetric information was developed by three economists, namely Akerlof, Spence, and Stiglitz, in the 1970s and 1980s as a plausible explanation for market failures (Ross 2022). The theory proposes that an imbalance of information between buyers and sellers can lead to market failure (Ross 2022). Asymmetry in information has a big impact on agricultural commodity prices. Businesses may have asymmetric knowledge about future period prices, harvest, or other pertinent variables in a lot of agricultural markets (Perloff and Rausser 1993). This informational inequality may result in market power and the capacity to set prices, which may have an impact on distribution and welfare. Businesses that own market power in processing or exporting industries, for instance, are probably more knowledgeable than other agents, and they can utilise this knowledge to boost their market power in subsequent transactions. When price information was given to farmers in the context of agricultural transactions, like the sale of crops from farmers to traders, average margins earned by traders did not change, suggesting that there was information asymmetry about prices present in these transactions (Mitra et al. 2012).

2.2. Empirical Literature

This section presents the analysis of empirical literature by other scholars using different methodologies in different countries with the objective of identifying gaps that exist and other potential variables.

A study by Rezitis (2019) investigated price transmission in the Finnish dairy sector and a nonlinear ARDL model was applied to monthly price data to analyse vertical price transmission among farm and retail markets for a variety of dairy products in Finland. Hillen (2021) used detailed price data on farm gate, wholesale, export, and retail levels, and they applied asymmetric vector autoregression and vector error correction models to study vertical price transmission in Swiss dairy and cheese chains. A study by Arida et al. (2023) empirically measured and analysed the long-run relationship and asymmetric price transmission of the rice market in Aceh Province, Indonesia. The study used a series of econometric techniques comprising cointegration, causality, and the Error Correction Model (ECM) to investigate the research objectives. The results of all of the studies mentioned present the existence of a positive long-run asymmetry between prices.

A few studies regarding price transmission have been conducted in South Africa. In a study by Ramoshaba (2019), a price transmission mechanism is described with an agricultural product within the dairy industry, which is pasteurised liquid milk. The VECM results showed asymmetric price transmission, implying that retailers and processors react quicker to price increases than to price decrease. Price monitoring policy is suggested to protect the consumers from unfair prices passed on by the retailers. A study by Mosese (2020) aimed to determine the nature of price transmission in the South African potato market. The study made use of the Error Correction Model and the Granger Causality test. The Empirical results reveal the existence of price asymmetry in the South African potato value chain. Furthermore, the results show that retail prices are more responsive to producer price increases than they are to producer price declines.

Mphateng (2022) used the average weekly wheat prices for the months of January 2010 through December 2019 to evaluate how changes in global wheat prices affected South Africa's domestic wheat market. The goals of the study are to apply the Error Correction Model to determine how far the transmission of global wheat prices to domestic prices in South Africa takes place and to establish the extent of the cointegration—long-term relationship—between the two variables. The findings verified that, over time, South Africa's domestic market eventually receives a transmission of global wheat prices. The results also show that domestic wheat prices were found to have a relatively low rate of corrections or modifications towards equilibrium conditions. More research is advised by the study, with a focus on the vertical price transmission from wheat to wheat-flour and other wheat-based items including cereals and bread.

2.3. Wheat-to-Bread Value Chain in South Africa

South Africa's wheat industry plays a vital role in the nation's agricultural economy and contributes significantly to food security. Wheat is grown primarily in the western parts of South Africa, while farmers in the northern regions experience a competitive disadvantage due to pricing based on the Randfontein grain market in Gauteng (Midgley 2016). Even though wheat is one of South Africa's top crops, the country remains a net importer, with imports fluctuating around 1.4 million to 1.8 million tonnes annually (Matohlang Mohlotsane et al. 2018). After wheat is harvested, activities that are done to it involve milling and producing wheat flour, bran, and meal. Bakery products account for a substantial share of the retail price of bread following the deregulation of the wheat industry (Abdelaziz et al. 2022). The wheat-to-bread value chain is illustrated in Figure 1.

Figure 1 above shows the process of how wheat is transferred from farmgate to retail/consumer. There are several types of storage facilities for wheat, all of which also store imported wheat. Subsequently, the wheat is taken to milling firms where it is converted to wheat flour. This flour is then used in baking, such as for bread, rolls, frozen dough, and other wheat-based goods like cereals, pasta, and biscuits. A tiny proportion of low-quality wheat is used to make animal feed (Midgley 2016). The milling, baking, and retail industries are the key players in the value chain.

There are some challenges that are faced by the wheat-to-bread value chain in South Africa. The first one is climate risks where famers are increasingly exposed to climate variability and change, putting them at risk financially without adequate support or partnerships with institutions and government (Midgley 2016). The second one is the shift towards import dependence, as with local production unable to meet demand, there is a growing trend toward increased wheat imports, potentially leading to higher costs for both producers and consumers (Midgley 2016). Consumers have felt the effects in the form of higher pricing for basic wheat-based commodities like bread. The retailer may receive a significant portion of the miller-to-retail margin. Retailers appear to respond faster to shocks that stretch their market margins than to those that squeeze them, which is linked to the food market chain's anti-competitive nature.

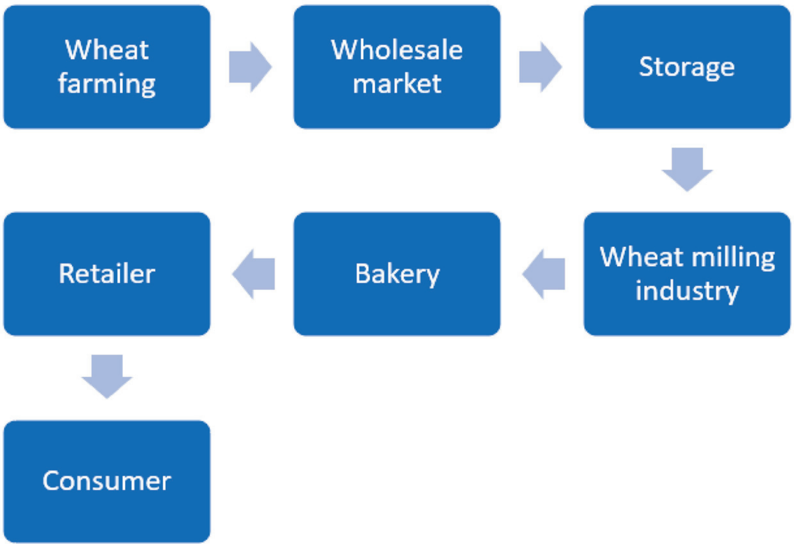

Figure 1. Wheat-to-bread value chain. Source: Author's own drawing.

2.4. Wheat and Bread Prices in South Africa

Farmgate pricing is determined only after a crop has been harvested and the agricultural producer has sold their excess. The average transport difference and handling expenses are subtracted from the SAFEX spot price to arrive at the producer price of wheat in South Africa. Drought and a harsh winter can harm crops, which lowers output and drives up costs (Pettinger 2022). The wholesale price is the market price for the commodity that includes the demand and supply as well as the expected demand and supply of the commodity. Since it includes additional expenses like transportation, marketing, storage, and the profit margin of the participating companies, the market price is often greater than the farmgate price. For South Africa, wheat imports result in the fluctuation of local prices because of effects such as global wheat price movements and changes in the value of the South African currency, which is a rand, as well as the variations in transportation costs. This is one reason why there might be price changes for wheat products in the domestic economy. A sizable portion of South Africa's population is living in poverty and rapidly urbanizing. The consumption of ready-to-eat food increases as cities grow. The majority (70–80%) of the wheat flour produced in South Africa is used to make bread, making it the most significant product in the baking industry (Mphateng 2022). According to estimates from the Department of Agriculture, Land Reform and Rural Development (2020), the nation consumes 2.8 billion loaves of bread annually, or 62 loaves per person. The cost of wheat, manufacturing costs, and transportation costs are only a few of the variables that might affect bread prices in South Africa.

Figure 2 provides the fluctuation of wheat prices (at farmgate and wholesale) and bread prices (at retail level) in South Africa, from the period of 2000 to 2022.

Wheat prices at the farmgate level increased from 55.9% in 2000 to 78.2% in 2002. From 2003 to 2005, the producer price of wheat decreased from 74.6% to 55%, respectively. According to Theunissen (2005), in 2002 and 2003, the profit margin of wheat was high, after which it dropped in 2004 and 2005. Although the price per ton had dropped in 2005, the biggest reason for the loss in profitability was the fact that there was a lower yield due to the drought. In 2007, the prices then rose by 149.9% but fell by 93.1% to a paltry 93.1 percent two years later. It was 10% better based on the wheat production calculation against an increase of 10% relative to the five-year average of 1.91 million tons (2002/2003 to 2006/2007 seasons), which was indicative that this season's final harvest was higher than what has been harvested recently—in the preceding season—which means there will be more cereal that year than the previous (Winter Cereal Trust 2007).

Figure 2. Farmgate price of wheat, wholesale price of wheat, and retail price of bread in South Africa from 2000 to 2022. Source: Author's own drawing.

In 2009, farmgate wheat prices were 93.1%; then, they showed an increasing trend up until 2016, when they were the highest at 200.1%. In 2015–2016, there were droughts in South Africa, and high poverty levels could have impacted the increase in wheat prices. There was a drastic decrease in farmgate prices from being 199.2% in 2019 to 122.42% in 2020. This was caused by a decline in planted areas, and with less than 2 million tons annually, South Africa's wheat production fell by about 50%. With 1.5 million tons harvested, the wheat crop for 2019–20 is the smallest since deregulation in 1997. Wheat prices then increased between 2020 and 2022, from 122.4% to 128.57%, respectively; this is because wheat production in South Africa increased by approximately 2.3 million metric tons compared to 2020.

The market wheat prices in 2000 were 50.59% and they increased to 65.22% in 2002. In 2006, the percentage of wheat prices were 63.23% and they increased to 115.23% in 2008 and then decreased to 71.2% in 2010. The total production of wheat in 2008 was not sufficient to meet the domestic requirements; therefore, South Africa had to import the remainder to meet the domestic consumption, and this resulted in an increase in wheat prices. Except for 2010, when 2.9 million tons were used overall, wheat consumption has always been above 3 million tons annually (Mphateng 2022). The percentage of wheat prices was 84.39% in 2011 which further increased to 94.29% in 2016. From 2018 to 2022, the percentage wheat prices increased from 77.47% to 109.4%, respectively. The increase in wheat prices between 2019 and 2020 was caused by an increase in the local demand for wheat. Since then, the wheat price has shown an increasing trend; this is because of wheat prices in South Africa reaching a record high due to price trends in the international market and domestic exchange rate movements (Omarjee 2022).

Bread price percentage decreased from 70.71% in 2000 to 67.78% in 2003. In 2006, the percentage of bread prices rose from 74.92% to 95.13% in 2009. According to an article by Reliefweb (2007), in importing poor nations, like South Africa, the combination of increased export prices and skyrocketing freight rates in 2007 drove up domestic prices of bread and other staple goods. The year-on-year consumer price index for food in 2008 increased. The percentage of the retail price of bread was 95.13% in 2009, and it decreased to 91.57% in 2010. South Africa has been consuming more than 3 million tons of wheat annually, but in 2010 it was recorded at 2.9 million tons; this decrease in the consumption of wheat means that there was a decrease in the production of bread. After this decrease, the percentage in bread prices started increasing up to 108.56% in 2016, then decreased to 99.17% in 2018 and then increased up to 103.58% in 2022. According to data, South Africa's average annual increase in consumer food prices for the first 11 months of 2021 was 6.5%, up from 4.6% in 2020. The increase in the headline consumer food price inflation has been mostly supported by items from the category of food inflation, such as "bread and cereals". When the price of wheat and wheat products (such as bread) increased, the South African government was unable to take the same action to mitigate the effects of rising costs on its population as they did in 2022 in response to rising oil prices.

3. Research Methodology

3.1. Methodological Design

This paper applied a positivist research philosophy, which means that the study is limited to objective data collection and interpretation. The findings under this research philosophy are typically measured and observable. Put in another way, positivist philosophy maintains that problems can be solved through accurate measurement and data analysis, particularly regarding numerical data (Jansen 2023). The time series research design which the study followed was the explanatory analysis, which attempts to understand the data and the relationships within it, as well as cause and effect. This paper used a quantitative research approach, which involves gathering and analysing numerical data to explain, forecast, or regulate relevant occurrences.

As this paper focused on the wheat-to-bread value chain in South Africa, it used yearly data from the period 2000 to 2022 and the reason for the choice of this period is that the data for one of the variables, which is the farm price of wheat, is only available from 2000 (available at South Africa: producer price index of wheat 2000–2019 (Statista, published by Cowling (2023)). Data for farmgate prices (wheat producer price) were collected from Statista. Data for wholesale prices (wheat market prices) and retail prices (white bread price) were sourced from the South African Grain Information Service (SAGIS); this is because SAGIS is a government-run platform, ensuring that data comes directly from sources, reducing the risk of bias and manipulation. Data for the national average rainfall and temperature (minimum and maximum) were sourced from South African Weather Services (SAWS).

3.2. The Estimated Model

This paper uses nonlinear autoregressive distributed lag (NARDL) to estimate the model. NARDL proposes an expanded nonlinear version of the linear ARDL model. Ben Abdallah et al. (2020) indicates in their study the advantages of using NARDL such as that every variable does not need to have the same integration order. Even with tiny samples, the NARDL model allows for assessing asymmetries and cointegration dynamics. The NARDL model allows for the simultaneous determination of both short- and long-nonlinear interactions, which is necessary to achieve the goals of the study.

This model was used by Ben Abdallah et al. (2020) in their study to find the effects of food price on macroeconomic variables and test the hypothesis of asymmetric price transmission between farmers and retailers, where their explicative variable was the farmgate price of raw milk and the independent variables were different prices of milk products. They first developed a long-run equation, given as follows:

$$lny_t = \alpha_0 + \alpha^+ lnx_t^+ + \alpha_2^- lnx_t^- + \varepsilon_t \quad (1)$$

where lny_t refers to the natural logarithm of the dairy products to be analysed, and $\alpha = (a_0,\ a_1^+, a_2^-)$ is a cointegrating vector or vector of long-run parameters to be estimated. Equation (1) was then adjusted to apply to this research and to achieve the first objective of the study.

$$RP_t = a_0 + a^+ FP_t^+ + a_2^- FP_t^- + a_3^+ WSP_t^+ + a_4^- WSP_t^- + \varepsilon_t \quad (2)$$

Comparing Equations (1) and (2), lny_t is replaced with RP_t because the dependent variable for this equation is retail price, and the dependent variables are farmgate price (FP_t) and wholesale price (WSP_t).

In the following Equations (3) and (4), lnx_t^+ and lnx_t^- are partial sums of positive and negative changes in *lnxt* which designs the logarithm of the independent variable (x).

$$lnx_t^+ = \sum_{i=1}^{t} \Delta lnx_t^+ = \sum_{i=1}^{t} max(\Delta lnx_t, 0) \tag{3}$$

$$lnx_t^- = \sum_{i=1}^{t} \Delta lnx_t^- = \sum_{i=1}^{t} min(\Delta lnx_t, 0) \tag{4}$$

Their NARDL model was expressed as follows:

$$\begin{array}{c} lny_t = \beta_0 + \beta_1 lny_{t-1} + \beta_2^+ lnPPRM_{t-1}^+ + \beta_3^- lnPPRM_{t-1}^- + \sum_{i=1}^{p} \omega 1i \Delta y_{t-1} \\ + \sum_{i=0}^{q} \omega 2i \Delta lnPPRM_t^+ + \sum_{i=o}^{m} \omega 3i \Delta lnPPRM_t^- + \varepsilon_t \end{array} \tag{5}$$

where $\beta_2^+ = -\beta_1/a_1^+$ and $\beta_2^- = -\beta_1/\alpha_2^+$. p, q, and m are lag orders of dependent and independent variables, ε_t is the error correction term of the NARDL model; $\sum_{i=1}^{p} \omega 1i$, $\sum_{i=0}^{q} \omega 2i$, and $\sum_{i=o}^{m} \omega 3i$ are the coefficients of short-run asymmetric cointegration models; $\sum_{i=0}^{q} \omega 2i$, and $\sum_{i=o}^{m} \omega 3i$ are the positive and negative coefficients, respectively, of the exogenous variable; and $\sum_{i=1}^{p} \omega 1i$ are coefficients of lagged dependent variables.

Farmgate-to-wholesale and farmgate-to-retail price transmission are the two levels at which this study examined price asymmetry. The section that follows presents the NARDL model that was used in this investigation.

(i) Farmgate-to-retail price transmission
Equation (5) is then adjusted to apply to this research, and the new equation for farm-to-wheat price transmission is given as follows:

$$\begin{array}{c} lnRP_t = \beta_0 + \beta_1 lnRP_{t-1} + \beta_2^+ lnFP_{t-1}^+ + \beta_3^- lnFP_{t-1}^- + \sum_{i=1}^{p} \omega 1i \Delta RP_{t-1} \\ + \sum_{i=0}^{q} \omega 2i \Delta lnFP_t^+ + \sum_{i=o}^{m} \omega 3i \Delta lnFP_t^- + \varepsilon_t \end{array} \tag{6}$$

Comparing Equations (5) and (6), y_t is replaced with RP_t because the dependent variable for this equation is retail price (RP); *PPRM* (the producer price of raw milk) is removed; and *FP* (farmgate price) is added as an independent variable.

(ii) Farmgate-to-wholesale price transmission

$$\begin{array}{c} lnFP_t = \beta_0 + \beta_1 lnFP_{t-1} + \beta_2^+ lnWSP_{t-1}^+ + \beta_3^- lnFP_{t-1}^- + \sum_{i=1}^{p} \omega 1i \Delta FP_{t-1} \\ + \sum_{i=0}^{q} \omega 2i \Delta lnWSP_t^+ + \sum_{i=o}^{m} \omega 3i \Delta lnWSP_t^- + \varepsilon_t \end{array} \tag{7}$$

For this equation, *FP* (farmgate price) is the dependent variable and *WSP* (whole-sale price) is the independent variable.

3.3. Variable Description

Each variable is described below, and the expectation of their relationships is mentioned for each equation/model.

FP_t refers to the farmgate price of wheat during period (t). The farmgate price of wheat refers to the price that farmers receive for their wheat crops. This price can vary depending on factors such as location, supply and demand, and government policies.

WSP_t refers to the wholesale price of wheat. The wholesale price of wheat refers to the price at which wheat is sold in bulk to retailers, processors, and other buyers. This price can vary depending on factors such as location, supply and demand, and the quality of the wheat.

RP_t refers to the retail price of bread. Retail prices are the prices that customers pay for a product when purchasing it at a retail store and these prices are set by the retailer and are usually higher than the wholesale price.

The study had control variables that assisted with findings of the studies, and these variables include the following:

$Rainfall_t$, which is the average national rainfall data, was added to all the models as a control variable. Rainfall has a significant impact on wheat production, and the effects can vary depending on the amount, timing, and distribution of rainfall.

$Temp_t$, which is the temperature (average), was added to all the models as a control variable. The effects of temperature on wheat production can be both positive and negative, depending on the specific conditions and growth stages of the plant. According to Wollenweber et al. (2003), wheat reacts to extreme heat exceptionally during all the growth phases; however, this response is more pronounced at the time of the formation and ripening of grains, rather than throughout the entire cycle.

4. Results and Discussion

4.1. Descriptive Statistics

Table 1 shows the summary of statistics for all of the variables used in this investigation.

Table 1. Descriptive statistics.

	FP	WSP	RP	Rainfall	Temp
Mean	4.73	4.35	4.49	3.91	6.05
Median	4.82	4.42	4.56	3.91	6.04
Maximum	5.29	4.74	4.68	4.24	6.09
Minimum	4.01	3.92	4.21	3.51	6.01
Std. Dev	0.41	0.21	0.16	0.16	0.02
Skewness	−0.34	−0.33	−0.55	−0.32	0.24
Kurtosis	1.93	2.31	1.64	3.52	1.94
Jarque-Bera	1.55	0.89	2.95	0.66	1.29
Probability	0.46	0.64	0.22	0.71	0.52
Sum	108.86	100.27	103.49	90.01	139.17
Sum Sq Dev	3.78	1.06	0.57	0.59	0.013
Observations	23	23	23	23	23

Source: Author's own computation.

In the descriptive statistics table, we look at the skewness and the kurtosis. Skewness is a statistical measure that describes the asymmetry of a distribution. It may be zero (symmetrical), positive (right-skewed), or negative (left-skewed). The right side of the tail is longer when the skewness is positive, and the left side is longer when the skewness is negative. A symmetric distribution has zero skewness. FP, WSP, RP, and Rainfall are negatively skewed, which means that they have a long-left tail. On the other hand, Temp is positively skewed, meaning that it has a long right tail.

A statistical metric called kurtosis is used to characterise how much a score clusters in the frequency distribution's tails or peak. Mesokurtic or normal, leptokurtic or more than normal, and platykurtic or less than usual, are the three types of kurtoses. The kurtosis of FP, WSP, RP, and Temp is less than three, which means that they are platykurtic relative to normal distribution. Platykurtic variables may indicate that the data has outliers, which can affect the interpretation of the results, as the relationship between variables may be more complex and nonlinear. The kurtosis of rainfall is greater than three, which means it is leptokurtic relative to normal distribution.

4.2. Correlation

The correlation between every variable considered in this study is illustrated in Table 2.

Table 2. Correlation.

	LFP	LWSP	LRP	LRAINFALL	LTEMP
LFP	1.000000				
LWSP	0.783628	1.000000			
LRP	0.833059	0.798545	1.000000		
LRAINFALL	−0.247238	−0.141706	−0.061806	1.00000	
LTEMP	0.275730	0.168679	0.135791	−0.614888	1.000000

Source: Author's own computation.

LFP and LWSP have a correlation of 0.78, which is close to one, meaning that LFP and LWSP have a strong positive correlation, and if one increases, the other one will also increase; the same results are expected when there is a decrease. LFP and LRP have a correlation of 0.83, which is close to one, meaning that LFP and LRP have a strong positive correlation and if one increases the other will also increase; the same results are expected when there is a decrease. LFP and LRAINFALL have a correlation of −0.24, which is not close to −1, meaning that the correlation is not strongly negative and if one increases the other one will decrease, and vice versa. LFP and LTEMP have a correlation of 0.28, which is not close to one, meaning that the correlation of LFP and LTEMP is not strongly positive.

LWSP and LRP have a correlation of 0.79, which is close to one, meaning that LWSP and LRP have a strong positive correlation, and if one increases the other one will also increase; the same results are expected when there is a decrease. LWSP and LRAINFALL have a correlation of −0.14, which is not close to negative one, meaning that the correlation is not strongly negative and if one increases the other one will decrease, and vice versa. LWSP and LTEMP have a correlation of 0.17, which is not close to one, meaning that the correlation between LWSP and LTEMP is not strongly positive. LRP and LRAINFALL have a correlation of −0.62, which is not close to −1, meaning that the correlation is not strongly negative, and if one increases, the other one will decrease, and vice versa. LRP and LTEMP have a correlation of 0.14, which is not close to one, meaning that the correlation of LWSP and LTEMP is not strongly positive. The following section presents the unit root testing of variables used in this study.

4.3. Unit Root Testing

In NARDL, the most used test to check for stationarity is the Augmented Dickey-Fuller (ADF) test. This test has wide popularity due to its resilience against non-linear relationships among variables (Allen and McAleer 2021). The Phillips Perron test modifies the ADF test by correcting for autocorrelation and heteroscedasticity in the errors (Prabhakaran 2019). The ADF test serves as a foundation for the PP test. This is illustrated in Table 3 below.

Table 3. Formal stationarity test.

Series	Model	ADF			PP		
		Lags	*p*-Value	Decision	Lags	*p*-Value	Decision
FP	Trend and Intercept	4	0.264	Non-stationary	2	0.564	Non-stationary
ΔFP	Trend and Intercept	4	0.001	Stationary	2	0.000	Stationary
WSP	Trend and Intercept	4	0.032	Stationary	2	0.250	Non-stationary
ΔWSP	Trend and Intercept	4	0.002	Stationary	2	0.000	Stationary
RP	Trend and Intercept	4	0.838	Non-stationary	2	0.863	Non-stationary
ΔRP	Trend and Intercept	4	0.001	Stationary	2	0.000	Stationary
Rainfall	Trend and Intercept	4	0.021	Stationary	2	0.021	Stationary
ΔRainfall	Trend and Intercept	4	0.001	Stationary	2	0.000	Stationary
Temp	Trend and Intercept	4	0.001	Stationary	2	0.000	Stationary
ΔTemp	Trend and Intercept	4	0.000	Stationary	2	0.000	Stationary

Source: Author's own computation using E-views 10.

All of the variables demonstrate stationarity at the first difference I (1), meaning that the factors are integrated into order one. The results presented by the stationarity test allow the use of the nonlinear autoregressive distributed model to check the relationship and the asymmetry of prices. The next section presents the testing of cointegration, for which the bounds test is used.

4.4. Autoregressive Diagnostic Lag Model (ARDL)

The ARDL method uses the bound test to test for cointegration. In the bound test, the value of f-statistics determines whether there is cointegration, based on the results of the lower and upper limit. Table 4 below presents the ARDL bounds test.

Table 4. Bounds test results.

Test Statistics	Values	K = 5
F-statistics	2.23	
	Critical values for the lower bound limit I(0)	Critical values for the upper bound limit I(1)
Critical Values		
10%	2.45	3.52
5%	2.86	4.01
2.5%	3.25	4.49
1%	3.74	5.06

Source: Author's own computation.

According to the data in Table 4, the f-statistic of 2.23 is less than 2.86 at the lower bound and 4.01 at the upper bound at a 5% significance level. These findings do not support the existence of a long-term relationship between farm price, wholesale price, and retail price. Because the results indicate no long-run relationship between variables, it is generally recommended not to proceed with estimating the ARDL. The following section therefore focuses on NARDL.

4.5. Test for Cointegration

The bounds test, which may also be used to look for long-term correlations between several variables, is utilized by the NARDL method to test for cointegration. Based on the findings of the lower and upper bounds, the bounds test's f-statistics value establishes if cointegration exists. To determine whether there is a long-term link between the three prices (farmgate, wholesale, and retail), Table 5 shows the results of the boundaries test.

Table 5. Bounds test results: farmgate price, wholesale price, and retail price.

Test Statistics	Values	K = 5
F-statistics	4.88	
	Critical values for the lower bound limit I(0)	Critical values for the upper bound limit I(1)
Critical Values		
10%	2.45	3.52
5%	2.86	4.01
2.5%	3.25	4.49
1%	3.74	5.06

Source: Author's own computation.

According to the data in Table 5, the f-statistic of 4.88 is more than 2.86 at the lower bound and greater than 4.01 at the upper bound at a 5% significance level. These findings support the existence of a long-term relationship between the retail price of bread in South Africa, the wholesale price of wheat, and the farmgate price of wheat, as well as providing evidence of nonlinear cointegration among the variables. These findings support the primary goal of the study, which was to determine whether there was a long-term relationship between the three prices (farmgate, wholesale, and retail). As shown in Table 5, the first null hypothesis—that there is no long-term association between the retail price of bread, the wholesale price of wheat, and the wheat farmgate price—is rejected.

Even with delays or asymmetries, changes in farmgate pricing are likely to be followed by changes in the wholesale price of wheat and then the retail price of bread. These prices are connected by underlying market forces, such as supply and demand, production costs, and market power (Nguyen and Mobsby 2016). The theory that these results relate to is the cost pass-through theory because changes in farmgate prices affect wholesale and retail prices.

Table 6a,b below present the bounds testing for nonlinear cointegration, which will be looking at two different pairs, farmgate price and retail price and wholesale price and farmgate price.

Table 6. (**a**) Bounds test results: farm price and retail price. (**b**) Bounds test results: wholesale price and farm price.

	(a)	
Test Statistics	**Values**	**K = 5**
F-statistics	6.78	
	Critical values for the lower bound limit I(0)	Critical values for the upper bound limit I(1)
Critical Values		
10%	2.26	3.35
5%	2.62	3.79
2.5%	2.96	4.18
1%	3.41	4.68

	(b)	
Test Statistics	**Values**	**K = 5**
F-statistics	3.24	
	Critical values for the lower bound limit I(0)	Critical values for the upper bound limit I(1)
Critical Values		
10%	2.26	3.35
5%	2.62	3.79
2.5%	2.96	4.18
1%	3.41	4.68

Source: (**a**) Author's own computation using E-views 10. (**b**) Author's own computation.

Table 6a presents the results of the bounds test for nonlinear cointegration, looking at the pair of farmgate price and retail price with added control variables, which are rainfall and temperature. At a 5% significance level, the f-statistic of 6.78 is greater than 2.62 at the lower bound and greater than 3.79 at the upper bound. These findings support the notion that there is a nonlinear cointegration between the variables. A study by Ben Abdallah et al. (2020) confirms that if cointegration exists, the NARDL model is appropriate for estimating the model.

At a 5% significance level, the f-statistic of 3.24 is greater than 2.62 at the lower bound and is also less than 3.79 at the upper bound, meaning that the results are inconclusive. The following section presents the results of NARDL long-run and short-run estimates, which check if there is price asymmetry between the different prices.

4.6. The Nonlinear Autoregressive Distribution Lag (NARDL) Estimation

The NARDL estimation performs the long-run and short-run results of the variables, looking at the first pair of farmgate price and retail price, and the second one, which is wholesale price and farmgate price. Table 7a,b below shows the outcomes of the long-run equation and how they are interpreted using the coefficient and probability.

Table 7. (**a**) Unrestricted long-run equation: farmgate price and retail price. (**b**) Unrestricted long-run equation: farmgate price and wholesale price.

(a)				
Variables	**Coefficient**	**St. Error**	**T-Statistic**	**Probability**
LFP_POS	0.35	0.05	6.17 ***	0.01
LFP_NEG	0.10	0.08	1.20	0.27
LRAINFALL_POS	0.21	0.19	1.10	0.31
LRAINFALL_NEG	0.40	0.23	1.67	0.14
LTEMP	−0.68	1.04	−0.65	0.53
(b)				
Variables	**Coefficient**	**St. Error**	**T-Statistic**	**Probability**
LWSP_POS	−3.49	5.55	−0.62	0.57
LWSP_NEG	−10.98	13.08	−0.83	0.46
LRAINFALL_POS	−4.80	4.66	−1.02	0.37
LRAINFALL_NEG	−3.58	4.36	−0.82	0.47
LTEMP	−67.79	83.21	−0.81	0.47

(**a**) Note: * Statistically significant at 10% level, ** statistically significant at 5% level, *** statistically significant at 1% level. Source: Author's own computation. (**b**) Source: Author's own computation using E-views 10.

Table 7a presents the long-run equation of retail price (LRP), farmgate price (LFP), rainfall (LRAINFALL), and temperature (LTEMP), where LRP is the dependent variable. Table 7a above shows that a unit increase in farmgate prices (LFP_POS) is associated with a 35.9% increase in retail prices, and the results are significant because the *p*-value is less than the 5% significance level, which means that there is a positive relationship between farmgate prices and retail prices. The relationship between the retail price of bread and negative changes in farmgate price is positive, meaning that a unit decrease in farmgate price is associated with a 10.5% decrease in retail price. However, the results are insignificant because the *p*-value exceeds the 5% significance level. The results also show the existence of long-run asymmetry between farmgate price and retail price, as the coefficient of LFP_POS is greater than that of LFP_NEG.

Mosese (2020) states that the retail price of potatoes is more responsive to positive shocks in farm prices than they are to negative shocks, which leads to a conclusion of the existence of long-run asymmetry between farmgate prices and retail prices. The results were also the same with Ben Abdallah et al. (2020); they confirmed the existence of a long-run asymmetric relationship between raw milk, and all examined dairy product prices.

Rainfall has a positive relationship with the retail price of bread. Retail prices rise by 21.90% for every unit increase in rainfall; nevertheless, the results are not statistically significant because the *p*-value exceeds the significance level of 5%. The retail price of bread decreases by 40.07% for every unit decrease in rainfall; nevertheless, the results are not statistically significant because the *p*-value exceeds the significance level of 5%. Temperature has a negative relationship with retail price. A unit increase in temperature results in a 68.26% decrease in retail prices of bread and these results are insignificant because the *p*-value is greater than the 5% significance level.

Table 7b presents the long-run equation of farmgate price (LFP), wholesale price (LWSP), rainfall (LRAINFALL), and temperature (LTEMP), where LFP is the dependent variable. The response of farmgate prices to positive changes in wholesale prices is negative, meaning that a unit increase in wholesale prices will result in a 3.49% decrease in farmgate prices. A unit decrease in wholesale price (LWSP_NEG) is associated with a 10.98% increase in farmgate price; this is because of the existence of a negative relationship, meaning that when one decreases, the other increases. Both of these results are insignificant because the *p*-value is greater than the 5% significance level. Since the coefficient on the positive and negative changes are different, it indicates asymmetry in the relationship between farmgate wheat prices and wholesale wheat prices.

Rainfall has a negative relationship with farmgate prices. A unit increase in rainfall results in a 4.80% decrease in the farmgate price, and a unit decrease in rainfall results in a 3.58% increase in the farmgate price. These results are insignificant because the *p*-value is greater than the 5% significance level. The temperature has a negative relationship with the farmgate price. A unit increase in temperature results in a 67.78% increase in the farmgate price and these results are insignificant because the *p*-value is greater than the 5% significance level.

The following Table 8a,b presents the short-run estimates of the nonlinear autoregressive distributed lag model for each pair.

Table 8. (**a**) Unrestricted constant no trend (short run): farmgate price and retail price. (**b**) Unrestricted constant no trend (short run): farmgate price and wholesale price.

(a)

Variables	Coefficient	St. Error	T-Statistic	Probability
LFP_POS	−0.03	0.03	−0.91	0.39
LRAINFALL_POS	0.40	0.07	5.62 ***	0.01
LRAINFALL_NEG	0.02	0.06	0.43	0.68
LTEMP	0.14	0.20	0.69	0.51
ECM Coint Eq (−1)	−0.92	0.10	−8.63 ***	0.01

(b)

Variables	Coefficient	St. Error	T-Statistic	Probability
LWSP_POS	1.7927	0.2548	7.0334 ***	0.0059
LWSP_NEG	−3.4775	0.5411	−6.4268 ***	0.0076
LRAINFALL_POS	−0.0736	0.2585	−0.2848	0.7943
LRAINFALL_NEG	−2.0056	0.3712	−5.4021 ***	0.0124
LTEMP	−12.5648	1.6898	−7.4355 ***	0.0050
ECM Coint Eq (−1)	−0.3430	0.0476	−7.2018 ***	0.0055

Note: (**a**) * Statistically significant at 10% level, ** statistically significant at 5% level, *** statistically significant at 1% level. Source: Author's own computation. (**b**) * Statistically significant at 10% level, ** statistically significant at 5% level, *** statistically significant at 1% level. Source: Author's own computation.

Table 8a presents the short-run equation of the retail price (LRP), farmgate price (LFP), rainfall (LRAINFALL), and temperature (LTEMP), where LRP is the dependent variable. In the short-run, retail prices and farmgate prices have a negative relationship, meaning that a unit increase in farmgate prices (LFP_POS) results in a 3.07% decrease in retail prices. However, the results are insignificant because the *p*-value is greater than the 5% significance level. The results show the existence of asymmetry in the short run. It is possible that cost adjustments, including packaging costs, are what resulted in the short-run asymmetric transmission (Ben Abdallah et al. 2020).

A unit increase in rainfall results in a 40.15% increase in retail price, and these results are significant, because the *p*-value is less than the 5% significance level and it is significant at 1% and the relationship is positive. A unit decrease in rainfall is associated with a 2.91% decrease in retail price; however, these results are insignificant because the *p*-value is greater than the 5% significance level. A unit increase in temperature is associated with a 14.36% increase in retail price and the results are insignificant because the *p*-value is greater than the 5% significance level and the relationship is positive.

The coefficient of cointegration equation (ECM Coint Eq (−1)) can be indicated as an error correction term. The ECM should have a coefficient that is negative and less than one and significant to ascertain the speed of adjustment and correlation between the short-run and long-run variables, and the return to equilibrium. The statistical significance of the adjustment speed, which is −0.92, is established by the *p*-value being less than 5% of the significance level. This clarifies that any short-term imbalances will be fixed during the first period and will be adjusted back to equilibrium at 92% of these imbalances.

Table 8b presents the short-run equation of the farmgate price (LFP), wholesale price (LWSP), rainfall (LRAINFALL), and temperature (LTEMP), where LFP is the dependent variable. From the table above, it is shown that a unit increase in wholesale prices is associated with a 1.79% increase in farmgate prices, and the results are significant at 1%, which means that there is a positive relationship between wholesale prices and farmgate prices. The response of farmgate prices to negative changes in wholesale prices is negative, meaning that a unit decrease in wholesale price is associated with a 3.47% increase in farmgate prices; these results are significant because the *p*-value is less than the 5% significance level, and there is an existence of asymmetry between the farmgate price of wheat and wholesale price of wheat.

A unit increase in rainfall results in a 0.07% decrease in farmgate prices, these results are insignificant because the *p*-value is greater than the 5% significance level. A unit decrease in rainfall results in a 2.01% increase in farmgate prices, these results are significant because the *p*-value is less than the 5% significance level and the relationship is negative. A unit increase in temperature results in a 12.56% increase in farmgate prices and these results are insignificant because the *p*-value is greater than the 5% significance level and the relationship is negative.

As the *p*-value is below the 5% significance level, the adjustment speed, which is −0.34, is statistically significant. This clarifies that any short-term imbalances will be fixed during the first period and will be restored back to equilibrium at 34% of these imbalances.

4.7. Diagnostic Tests

Diagnostic tests are used to help identify issues like dynamic, omitted variables, non-constant errors, non-linearity, and long memory structures (Sekar 2010). The tests that are used in this section are tests for normality, serial correlation, and heteroskedasticity. The conclusion for each test is based on its null hypothesis, H_0, and whether it is accepted or rejected. Table 9a,b presents the results of the diagnostic tests for each pair.

Table 9. (**a**) Diagnostic results: farmgate price and retail price. (**b**) Diagnostic results: farmgate price and wholesale price.

(a)

Test	Null Hypothesis	T-Statistics	Probability	Results
Breusch–Godfrey LM test	There is no correlation	1.23	0.38	There is no correlation
Jarque–Bera test (JB)	Residuals are normally distributed	0.35	0.83	Normally distributed
Breusch–Pagan–Godfrey	There is homoscedasticity	1.76	0.25	There is homoscedasticity
White	No heteroscedasticity	0.51		No heteroscedasticity

(b)

Test	Null Hypothesis	T-Statistics	Probability	Results
Breusch–Godfrey LM test	There is no correlation	0.0462	0.9567	There is no correlation
Jarque–Bera test (JB)	Residuals are normally distributed	3.4477	0.1783	Normally distributed
Breusch–Pagan–Godfrey	There is homoscedasticity	0.2553	0.9716	There is homoscedasticity
White	No heteroscedasticity	1.4586	0.4262	No heteroscedasticity

Source: Author's computation.

The diagnostic test for the pair of farmgate price and retail price is given in Table 9a. The Breusch–Godfrey LM test, a correlation test, yields a *p*-value of 0.38, over the 5% significance level. In other words, the null hypothesis—that there is no correlation—is accepted. The null hypothesis is accepted, and the residuals are normally distributed if the *p*-value for the normality test is higher than the 5% significance level. Given that the

Breusch–Pagan–Godfrey test's *p*-value is higher than the 5% significance level, the null hypothesis—that homoscedasticity exists—is accepted. The null hypothesis that there is no heteroscedasticity is accepted when the White test, the final diagnostic test, yields a *p*-value larger than the 5% significance level.

The diagnostic test for the pair of farmgate price and wholesale price is given in Table 9b. The Breusch–Godfrey LM test, which measures correlation, yields a *p*-value higher than the 5% significance level. In other words, the null hypothesis—that there is no correlation—is accepted. The null hypothesis is accepted, and the residuals are normally distributed if the *p*-value for the normality test is higher than the 5% significance level. Given that the Breusch–Pagan–Godfrey test's *p*-value is higher than the 5% significance level, the null hypothesis—that homoscedasticity exists—is accepted. The null hypothesis that there is no heteroscedasticity is accepted when the White test, the final diagnostic test, yields a *p*-value larger than the 5% significance level.

4.8. Stability Test

This paper employed two recursive tests which involve the CUSUM test and CUSUM of squares to check the model as to whether it is good or not. The stability test for both pairs is given in the figures below (Figures 3–6).

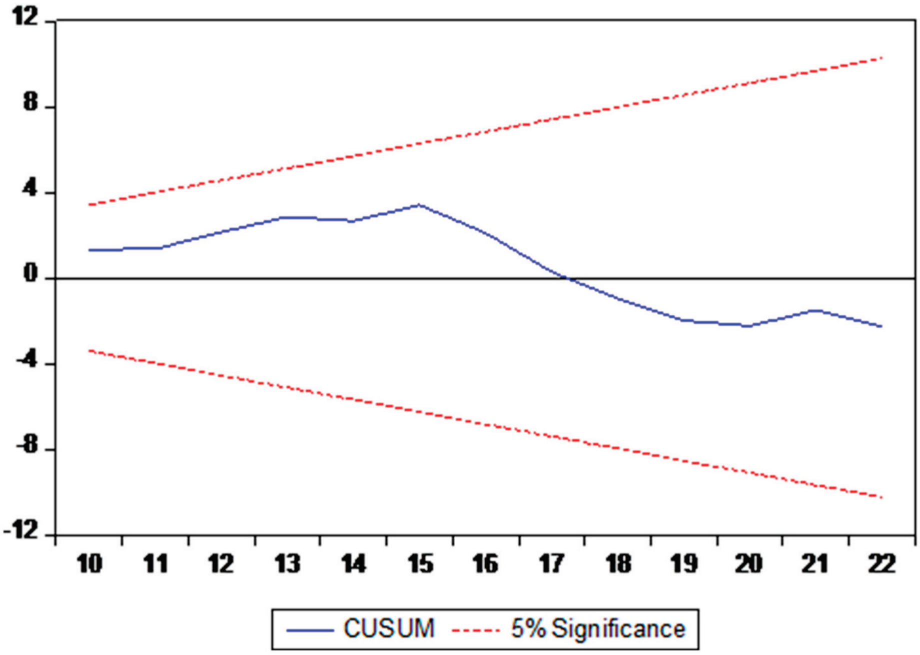

Figure 3. CUSUM test—farmgate price and retail price. Source: Author's own computation.

The CUSUM line is in between the 5% significance level, meaning that the series is stable, which is good for the model.

The CUSUM of square line is in between the 5% significance level, meaning that the series is stable, which is good for the model.

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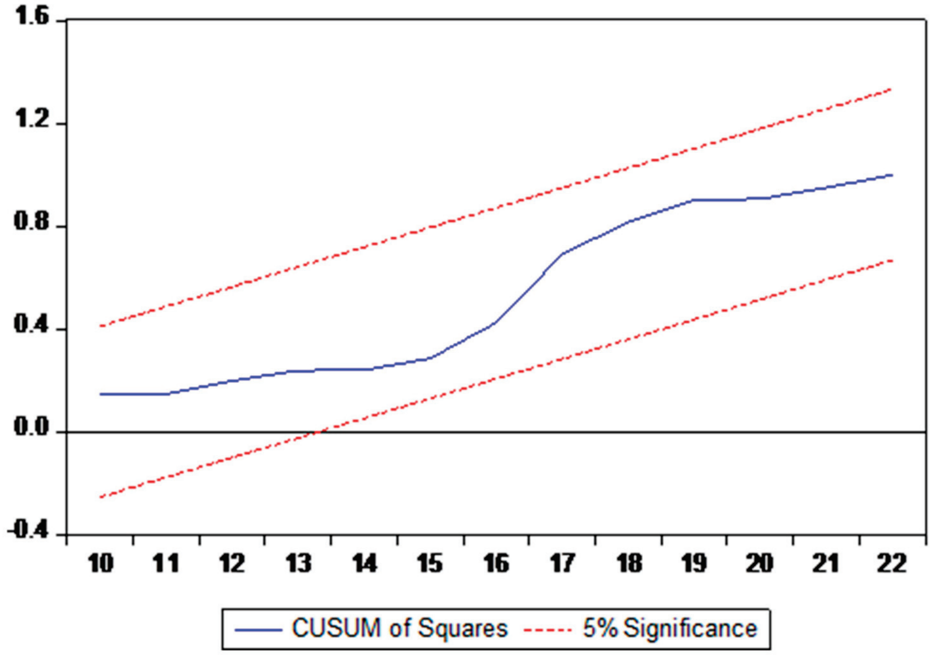

Figure 4. CUSUM of Squares test—farmgate price and retail price. Source: Author's own computation.

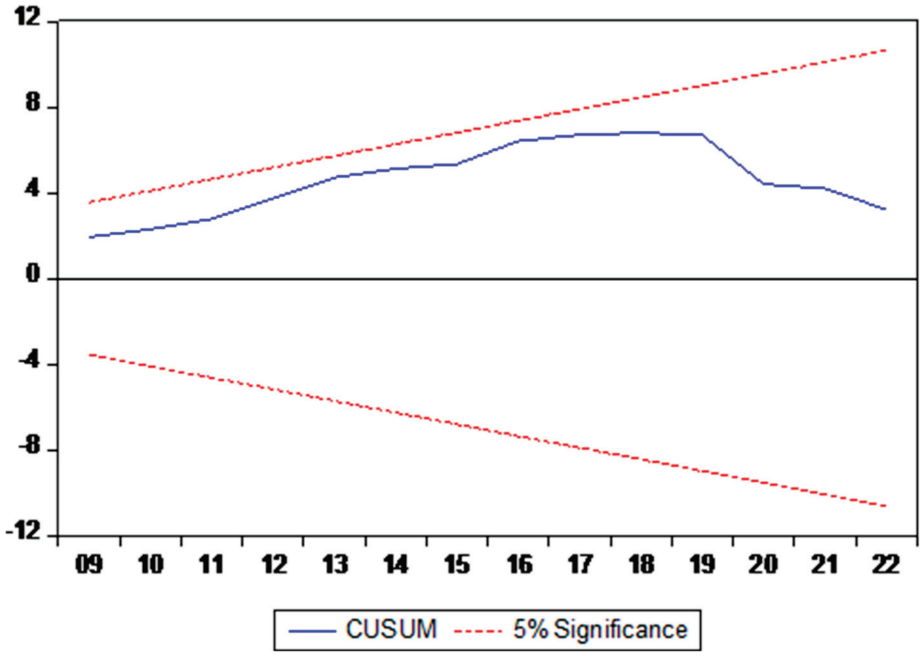

Figure 5. CUSUM test—farmgate price and wholesale price. Source: Author's own computation.

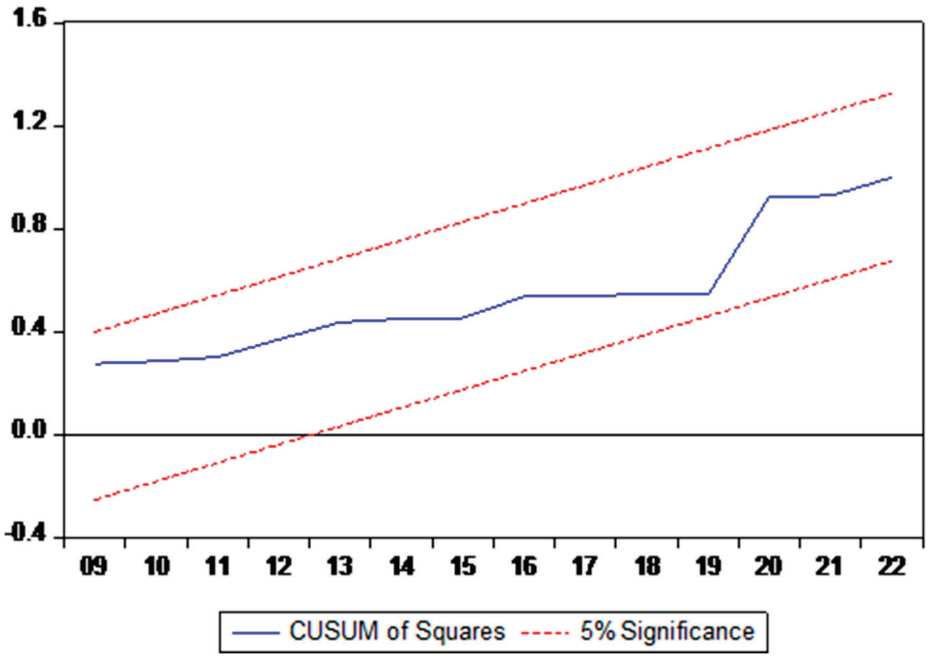

Figure 6. CUSUM of Squares test—farmgate price and wholesale price. Source: Author's own computation.

5. Conclusions and Recommendations

This paper can be related to the price theory, which states that for food and agricultural items, supply shocks have a greater impact on price formation than demand shocks, this is because demand tends to be steady due to established consumption habits (Mgale and Yan 2020). The other theory that the paper can be related to is the cost pass-through theory, which states that each market adjusts its prices of the products or services provided to meet the adjustments of its own costs. The existence of price asymmetry between wheat farmgate price, the wholesale price of wheat, and the retail price of bread can be related to both theories. The farm prices of wheat, which is the main ingredient for making bread, depend on the production of wheat; if there is more supply, then the prices will be less, and if there is less supply, the prices will be more. These price changes can affect retailers because it will not be easy for them to just change the prices of bread at the same time that the price of wheat changes, and therefore this will affect consumers. Government subsidies can assist in this matter because if there is a lower supply of wheat, farmers will not quickly change their prices. However, this does not affect the wholesalers because the margin between the farmgate price and wholesale price of wheat is relatively small, and the farmers receive a fair share of the final price paid by consumers. Price theory also assumes that consumers and producers behave rationally to maximise their individual utility and profits.

Market intervention can improve market efficiency and address asymmetric information through various measures. Asymmetric information can be addressed through information-related interventions. This can be by requiring firms to disclose relevant information, enabling investors and consumers to make informed decisions, and providing information, such as market data and research, also helps reduce information asymmetry. Regulatory interventions are another crucial tool to address asymmetric information, by certificating common standards, ensuring market participants meet minimum requirements, and by verifying market participants' credibility through licencing and accreditation mechanisms and enforcing mechanisms such as penalties for non-compliance. Effective implementation requires collaboration among regulatory bodies, institutions, and market participants. By leveraging technology, education, and economic incentives, South Africa can promote a more transparent and efficient market.

The findings of this study indicated that there is an existence of long-run and short-run asymmetry between the wheat farm price and the retail price of bread and between the wheat farmgate price and wholesale price of wheat. The relationship between wheat price and retail price is positive, and the relationship between farmgate price and wholesale price is negative. However, the results for the relationship between the farmgate price of wheat and wholesale price do not conform to the expectations of the study, which was a positive relationship between these prices. The existence of asymmetry between the farmgate price and retail price in South Africa can be caused by multiple factors such as marketing margins, value-added processes, taxes and levies, profit margins, and seasonality, to mention a few. The existence of asymmetry between farmgate price and wholesale price can be caused by market power, information asymmetry, transaction costs, and imperfect price transmission.

The South African government policy that has a significant impact on the price of wheat and bread is the trade policy. Trade policy is a government's strategy concerning international trade, including the regulation of imports and exports, and the protection of domestic industries. Many countries provide subsidies to their wheat farmers, while South Africa does not. The policy also states that the South African government has imposed tariffs on imported wheat to protect domestic producers, but this can increase the cost of wheat for consumers. The government's decision on subsidies, tariffs, and trade agreements can impact the profitability of wheat farming, the cost of wheat for consumers, and the overall availability of bread. For the government to be able to make well-informed decisions regarding food security, this study suggests that it accelerates its efforts to track food prices across the nation. Another recommendation made by the study is the provision of subsidies for wheat farmers to help the wheat industry reduce the cost of bread production and make bread more affordable and accessible for consumers.

The Sustainable Development Goals (SDGs) that the study aims to achieve are as follows:

Zero hunger—ensuring access to safe, nutritious, and sufficient food such as bread.

Decent work and economic growth—promoting fair prices for wheat farmers and supporting sustainable agriculture.

Reduced inequalities—reducing the gap between the producer price of wheat, wholesale price of wheat, and the retail price of bread, ensuring fair returns for farmers and wholesalers, and affordable bread for consumers.

Partnership for the goals—collaboration with stakeholders, including government, farmers, wholesalers, and consumers to address price asymmetry and ensure a sustainable food system.

However, it will not be easy to implement these developments; there could be challenges faced. One of the biggest challenges would be the intervention of government by providing subsidies to the farmers, as the economy of South Africa is not performing well, but hopefully it will be included in the next budget speech. The findings of the study are the existence of asymmetry between the farmgate price of wheat, wholesale price of wheat, and retail price of bread. However, the study did not venture comprehensively into the underlying causes of the price asymmetry in South Africa; this is an area that requires further research. Since this paper is mainly focused on finding the asymmetry between prices, further research on the relationship between the prices (the farmgate price of wheat, wholesale price of wheat, and retail price of bread) can also be conducted, as it was not really specified in the analysis and findings. Further research on the relationship between prices can be done with or without the control variables mentioned in this study (rainfall and temperature).

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Review

Dairy Goat Production: Socioeconomic, Environmental, and Cultural Importance Across Time (1970–2022) and Possible Scenarios (2050)

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Abstract: Inequality, malnutrition, poverty, and environmental degradation are some of the global challenges facing humanity. These are aggravated in the context of climate change (CC), envisioning as a utopia to guarantee food security without risking sustainability. Considering the increase in scientific attention on dairy goat production (DGP), we aimed to carry out an exhaustive analysis regarding the evolution of DGP to determine both its socioeconomic and cultural importance during the period 1970–2022 and its possible scenarios for 2050. Over the last half century (1970–2022), dairy goats (DG; 214.01 million heads) have shown an inventory growth of 182%, and this is estimated to increase by 53.37% over the next 28 years (2023–2050). While DGP increased 196% during 1970–2022, it is projected to increase around 71.29% by 2050. Notably, however, the economic value of DGP almost quadrupled (+375%) during 1991–2022, and the same trend is estimated for 2023–2050. Historically, Asia has excelled in both goat inventory and goat milk production volume. This research highlights the crucial role of both goats and DG in the socioeconomic issues in various regions of the world, as they most often represent the only source of income for millions of smallholder families, particularly in developing countries. In the face of CC challenges, goats in general, and DG in particular, show an exceptional potential to be considered the "*animal of the future*" due to their refined and sophisticated ethological, adaptive, and physiological plasticity under generally clean, green, and ethical production schemes, mainly in marginal contexts in the arid and semi-arid zones of the world.

Keywords: climate change; food security; goat's milk; marginal contexts

1. Introduction

Since 1987, the UN has been driving initiatives aimed at achieving a sustainable future for all. Therefore, in 2015, UN member countries adopted 17 interrelated sustainable development goals (SDGs) to address global challenges such as poverty, inequality, environmental degradation, climate, malnutrition, peace, and social justice, among others [1,2]. Because the world's population is projected to have reached 9.7 billion people by 2050, ensuring food security (FS) without compromising sustainability emerges as a major challenge [3,4]. This human census represents more than double the number of people that the earth can support; according to the Global Footprint Network, by 2024, humanity will be using natural resources 1.7 times faster than the regenerative capacity of ecosystems [5]. Overusing natural resources compromises the security of humanity's resources for future generations [6]. As the world's population grows, the predictability of climate conditions becomes more uncertain and erratic, so ensuring food availability, affordability, quality, and safety have become a primary concern for humanity. Added to the above is an exacerbating increase in socioeconomic disparities and effects on public health; all of the above becomes a real threat to environmental sustainability [7–12].

Mitigating the threats of hunger and malnutrition in the face of climate change (CC) represents another major challenge that threatens the fulfillment of the SDGs related to FS [13,14]. There are multiple interconnected relationships between malnutrition and poverty that lead to hunger, influenced by the limited supply and availability of food, both from a quantity and quality standpoint. In addition, micronutrient deficiencies in the usual diet have become a significant global health drawback, affecting billions of people around the world who suffer from food insecurity [15,16]. Various studies have raised the need to address the impacts and consequences of CC in terms of food losses. There is diverse information regarding the interaction among CC, food production, and FS; therefore, immediate actions are required to address the challenges of CC [7–9,17–23]. Historically, studies on the impacts of CC on FS have focused primarily on agricultural crops, leaving aside livestock, forest farming, diseases, and pests. However, CC also affects animal production, which is an important component of FS [24]. In this regard, a global increase in the consumption of animal products, either meat, milk, eggs or fish, has been observed, generating significant increases in the global production of these foods for human consumption [25–28]. Given the increases in the demand for animal products for human consumption, it is necessary to recognize the importance of livestock as a provider of food, nutritional security, livelihoods, and income in developing countries [29].

Milk is considered one of the almost perfect foods in its natural form, as it provides fundamental nutrients such as proteins, fats, carbohydrates, vitamins, and minerals. Easily digested and absorbed, milk becomes an important food for infants, lactating women, children, and the elderly [30], being one of the most valuable and regularly consumed foods by humans globally [31]. According to FAO, in 2022, while bovine milk accounted for 81% of global milk production (MP), goat-based milk only contributed 2% [25]. However, dairy goat production (DGP) plays a preponderant role in many parts of the world, not only from a nutritional point of view, but also from a cultural one [32]. In addition, in recent years, goat milk production (GMP) has experienced rapid growth, and a 53% increase in GMP is projected in 2030 [33]. This is probably triggered because of its undoubtedly high nutritional value [34–36]. Moreover, goat production (GP) is founded on a sustainable nature, particularly in marginal contexts of developing countries, based on the refined and sophisticated ethological, adaptive, and physiological plasticity of goats generated in the contexts of clean, green, and ethical production [34,37–39]. This places DGP as a relevant option from a CC perspective, as well as in the face of the challenge of FS, to comply with the SDGs. Moreover, DGP has a high biological, safety, and nutritional value, with important functional and nutraceutical characteristics [40–44].

In this regard, important studies have been generated analyzing the evolution of DGP in the world [33,40,45–50]. However, it is essential to analyze the contribution of DGP from multiple angles to measure its contribution in a more holistic sense and comply with the SDGs. This study aims to integrate a holistic vision with other economic, environmental, and socio-cultural components to generate and promote strategies aimed at encouraging a responsible use of resources, while fostering the sustainability of natural resources. In this type of global study, it is essential to analyze statistics that include the largest number of countries. Considering the above, after an exhaustive search, FAO statistics were the only ones that included the largest number of countries and years. When a lack of required information regarding PGD was detected in several countries of Oceania, a second search was carried out focused on the countries of this continent. To this end, various government and producer association websites were consulted. However, the information obtained showed greater inconsistencies, which limited the ability to carry out an analysis across time. Our research aims to highlight the importance of placing GP within global strategies to meet the SDGs. The last point highlights the high evolutionary potential of GP in the face of the devastating effects of CC, emphasizing the central role of both GP and DGP from an environmental, socioeconomic, and cultural perspective in diverse regions of the world [36–39,51–59]. Our working hypothesis states that the arguments to be presented should reevaluate the role of DGP as a productive, sustainable, and resilient option to achieve a true FS in the face of the CC, and in parallel, to comply with the SDGs of the 2030 agenda.

2. Importance of Goat Production in the World

Worldwide, goats represent a vital component in the animal production systems of rural economies, offering an alternative source of employment to increase the incomes of smallholder farmers (SF) and their families [60]. In many regions of the world, GP is the only source of household income. In others, GP is a critical economic income against crop losses, thus contributing to FS, and promoting poverty reduction. GP ensures the livelihoods of many landless families, SF, and marginal livestock producers in rural communities [61]. In these regions, goats are also culturally important [62], representing the preferred livestock of producers due to their unique characteristics of ethological, adaptive, and physiological plasticity [34]. The last feature allows to goats to thrive in a variety of agro-ecological zones [61,63] and adapt to diverse environments, especially due to their great capacity to resist drought and water scarcity [64]. Some of these characteristics include short gestation periods, high fecundity, high prolificacy, rapid growth rate, remarkable feed conversion efficiency, greater resistance to diseases, adaptation to extreme climates, and efficient use of plant resources of low nutritional value. This undoubtedly provides important employment opportunities in rural areas [61,65]. Moreover, goat milk (GM) has been consumed for thousands of years by diverse civilizations since goats were one of the first animals domesticated by man around 6000 and 7000 BC [66,67]. Additionally, GM has been valued for its digestibility and nutritional benefits, making it an essential food source in diverse cultures [42,47]. This places GM as a central asset to cover the nutritional needs and support the economic livelihoods of millions of people around the world [47,61,64]. The last scenario has generated an increase in global demand for GM that, together with low initial investments of economic capital, low production costs, and rapid returns on invested capital, minimize economic risk and make DGP a profitable and sustainable activity for rural households [68]. Undoubtedly, goats show exceptional potential to be considered as "*animals of the future*" by generating rural and urban prosperity, especially in the face of the challenges of food insecurity framed in climate uncertainty. For this reason, goats become great contenders to comply with the SDGs [64]. From this point on, when mentioning America, we will be referring to the American Continent (i.e., the continent), while we will use the USA to refer to the United States of America (i.e., the country)

3. Geographical Distribution of Goat Dairy Production

According to the FAO, in 2022, the goat population in the world amounted to 1145.49 million heads (Mh), of which 18.68% corresponded to the DG inventory (DGI; 214.01 Mh) (Table 1). Europe (72.20%) stands out with the highest percentage of DGI, with respect to the global goat inventory, followed by The Americas (23.48%) and Asia (18.15%). In addition, Europe (285.40 kg h^{-1}) stands out with the highest yield per goat, which is 218.17% higher than the world average yield (Table 1). Further, important year-to-year increases have been reported, such as the one observed in 1990 of 14.07 Mh compared to 1989 as well as 9.25 Mh between 2019 vs 2018. If this trend continues, an increase of 53.37% is estimated to occur by 2050 (Figure 1). Historically, Asia has had the highest

DGI. In 2022, it held 49.30%, followed by Africa, Europe, America, and Oceania with 41.44%, 5.01%, 4.26%, and <0.001%, respectively. During the last decade of this study (i.e., 2013–2022), the DGI increased by 19.35%, with Asia showing the largest surge (20.55%). Africa showed the second highest growth (+20.08%), followed by Europe (+16.54%) and The Americas (+4.09%). The only region showing a decrease in the DGI was Oceania (−6.41%) (Figure 1) [25].

Table 1. Dairy goat inventory (millions of heads) in 2022 and its relation to the global goat inventory.

Area	Population (Mh)		%	Yield (kg h^{-1} y^{-1})
	Goat	Dairy Goat		
World	1145.386	214.013	18.68	89.70
Europe	14.836	10.712	72.20	285.40
Asia	581.189	105.507	18.15	102.80
America	38.791	9.108	23.48	90.90
Africa	506.160	88.685	17.52	50.30
Oceania	4.411	0.001	0.03	29.40

Source: FAO, 2024.

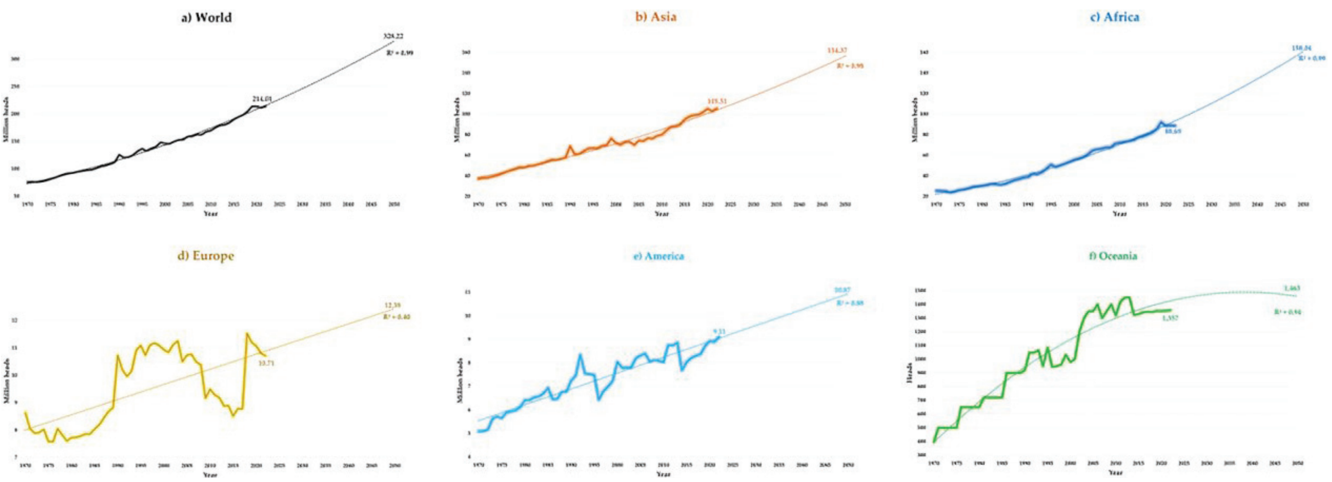

Figure 1. Trends in the dairy goat inventory (millions of heads) from 1970 to 2022 (solid line) and forecast for 2050 (dashed line) based on a time-series model using data from FAO (2024).

The top 10 countries displaying the largest DGI (214.01 Mh) in 2022 were India (15.44%), Bangladesh (9.82%), Mali (9.45%), Sudan (8.87%), South Sudan (3.75%), Indonesia (3.54%), Mongolia (3.38%), Pakistan (3.36%), Nigeria (3.20%), and Iran (3.09%), which together owned 63.90% of the global DGI in 2022. Notably, from the top 10, six belong to Asia and four to Africa; the fifth country in Africa is Somalia (2.88%). Regarding to Europa, the top 5 DGI countries include Greece (1.06%), Spain (0.84%), Romania (0.57%), France (0.57%), and Italy (0.41%). Concerning The Americas, the largest DGI was shown by Brazil (2.71%), Mexico (0.36%), Haiti (0.31%), Jamaica (0.26%), and Bolivia (0.23%). Finally, in Oceania, the only country that reported DGI was Papua New Guinea with 1357 heads (Table 2; the colors used in the Line-Continent, are the same as those used in the Figures) [25].

The time series analyses of the FAO data for the period 1970–2022 generated a second-degree polynomial trend for the case of the global DGI, with significant R^2 values for Asia, Africa, and Oceania. On the contrary, Europe and The Americas showed a linear trend, which reflects the better performance of the "Inventory Across Time" variable. At the global level, a potential DGI increase of 53.37% is projected up to 2050, which surprisingly would be led by Africa with 78.19%, followed by Asia (46.3%), Europe (15.6%), The Americas (19.3%), and Oceania (7.8%) (Figure 1) [25]. This trend could be explained by the growing interest in the genetic value of native or autochthonous goat breeds, where the scientific community has highlighted a particular interest due to their environmental resilience, especially their resistance to drought and parasitosis [47].

Table 2. Dairy goat inventory (millions of heads) from 1970 to 2020 and forecast to 2050.

Area/Year	1970		2020		2050 [1]	
World	**76.01**	**100% [2]**	**213.89**	**100%**	**328.22**	**100%**
Asia	**36.89**	**48.53%**	**105.26**	**49.21%**	**154.37**	**47.03%**
India	6.50	8.55%	36.32	16.98%	40.31	12.28%
Bangladesh	4.35	5.72%	18.80	8.79%	54.72	16.67%
Indonesia	2.60	3.42%	7.32	3.42%	10.63	3.24%
Mongolia	0.55	0.72%	6.48	3.03%	18.63	5.68%
Pakistan	1.94	2.55%	6.80	3.18%	13.34	4.06%
Africa	**25.40**	**33.42%**	**88.63**	**41.44%**	**158.04**	**48.15%**
Mali	2.20	2.89%	20.86	9.75%	48.82	14.88%
Sudan	1.71	2.26%	18.21	8.51%	27.39	8.35%
South Sudan	0.69	0.90%	8.49	3.97%	11.30	3.44%
Niger	3.10	4.08%	6.59	3.08%	15.83	4.82%
Somalia	7.84	10.31%	6.14	2.87%	7.70	2.35%
Europe	**8.63**	**11.35%**	**11.07**	**5.18%**	**12.38**	**3.77%**
Greece	3.09	4.06%	2.33	1.09%	3.00	0.91%
Spain	MV [3]	MV	1.89	0.88%	5.02	1.53%
Romania	MV	MV	1.29	0.60%	1.03	0.31%
France	0.76	1.00%	1.18	0.55%	1.50	0.46%
Italy	0.80	1.05%	0.83	0.39%	1.25	0.38%
America	**5.09**	**6.70%**	**8.93**	**4.18%**	**10.87**	**3.31%**
Brazil	2.29	3.01%	5.67	2.65%	6.87	2.09%
Mexico	1.25	1.64%	0.77	0.36%	1.47	0.45%
Haiti	0.53	0.70%	0.62	0.29%	1.16	0.35%
Jamaica	MV	MV	0.54	0.25%	1.03	0.31%
Bolivia	0.35	0.46%	0.47	0.22%	0.88	0.27%

[1] Forecast for 2050 based on a time-series model using data from FAO (2024); [2] Percentage values are based on world total; [3] Missing value.

The last scenario is of central importance in the face of increasing CC uncertainty, a situation that is exacerbated in most of the arid and semi-arid zones of the planet [33,47]. Although the Saanen and Alpina breeds remain popular worldwide for their high level of MP, a growing body of global research has identified other local breeds with important genetic characteristics to increase GMP. In this regard, there are several local breeds in desert areas that produce milk with a higher fat and protein content than their European counterparts (i.e., Saanen and Alpina), a situation that has revalued these native goats by GM industrializers. This reassessment is also important from a conservational standpoint because various autochthonous genetic groups face the risk of disappearing due to indiscriminate crossbreeding [47,69–72].

4. Dairy Goat Production: Main Global Trends

Considering the information reported by the FAO, in 2022, the global GMP (GGMP) was 19.2 million tons (Mt), which represented 2.06% of world MP. Undoubtedly, cattle and buffalo showed the greatest contribution to world MP at 80.98% and 15.43%, respectively. Nonetheless, it is essential to note that GGMP almost tripled its production volume in the last 50 years, with increases from 6.48 (1960) to 19.19 Mt (2022). If this trend continues, GGMP could reach 32.87 Mt (i.e., +71.29%) in 2050 (Figure 2). In addition, in 2022, DG produced almost 52.59% more milk than dairy sheep, despite having a 13.26% smaller stock [25]. Interestingly, GM, unlike bovine milk, does not have a broad culture of direct consumption; GM is used instead in the production of dairy products, which are usually intended for self-consumption or sold as traditional and high-quality products [73].

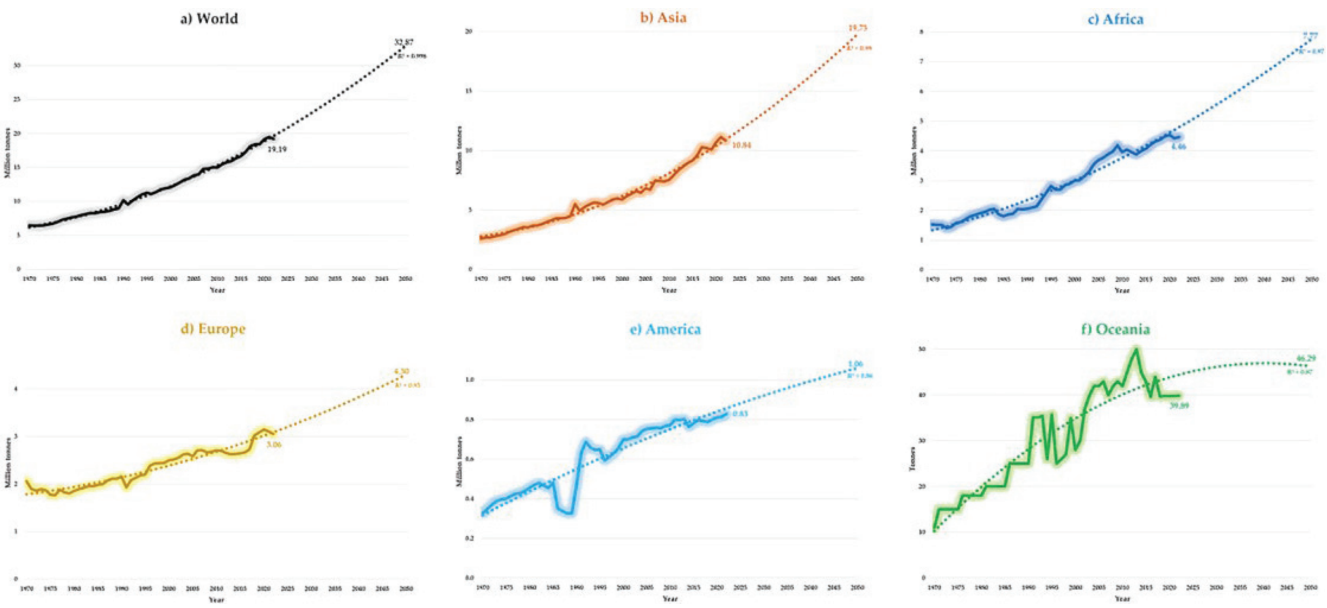

Figure 2. Trends in dairy goat production (millions of tons) from 1970 to 2022 (solid line) and forecast for 2050 (dashed line) based on a time-series model using data from FAO (2024).

In 2022, GGMP (i.e., 19.2 Mt) was mainly concentrated in Asia (56.49%), followed by Africa (23.26%), Europe (15.93%), and The Americas (4.31%), while Oceania's contribution was tiny (< 0.001%). In our analyses (i.e., 2013–2022), GGMP increased by 21.81%, and like the DGI, Asia displayed the largest increase (+29.92%), followed by Europe (+15.04%), Africa (+12.89%), and The Americas (+3.83%). Once again, Oceania showed a negative trend (−16.90%) (Figure 2) [25]. A more detailed scrutiny of GGMP shows that the top 10 countries with the highest production of GM were India (32.6%), Sudan (6.0%), Pakistan (5.3%), Bangladesh (4.8%), France (3.7%), Turkey (2.8%), South Sudan (2.7%), Spain (2.5%), Netherlands (2.3%), and Indonesia (1.9%) (Table 3). Together, these 10 countries generated about 65% of the GM produced globally. The main GM producing countries are located in Asia (5), Europe (3) and Africa (2). The countries that complemented the top five at the continental level were Greece (1.83%) and Russia (1.22%) in Europe; Somalia (1.93%), Nigeria (1.83%), and Algeria (1.69%) in Africa; and Brazil (1.55%), Jamaica (1.03%), Mexico (0.90%), Haiti (0.28%), and Bolivia (0.15%) in The Americas. Finally, Papua New Guinea was the only country in Oceania to report a GMP of 39.89 t in 2022 (Table 3).

Regarding the time series analysis (i.e., 1970–2022), a second-degree polynomial trend was observed for the GGMP variable, observing significant values for R^2 in all the regions analyzed. Based on these data (i.e., FAO, 2022), a global potential increase (+71.29%) of GGMP in 2050 was projected. In this projection, Asia (82.12%), Africa (73.9%), Europe (40.7%), The Americas (27.9%), and Oceania (16.05%) stand out (Figure 2) [25]. Broadly speaking, DG are in the intertropical and arid areas of the world. According to FAO, these areas are mainly made up of low-income and food-deficit countries, where 61% of the world's goats are located. DGP is linked to the country's income level since GM represents a primary source of food. Interestingly, DGP also occurs in high-income and technologically developed countries [33,47,54,59]. Historically, the world average yield per DG (YDG) is higher than that of dairy sheep. Certainly, in 1970, the YDG reported was 85.30 kg per head (kg h^{-1}). In dairy sheep, the YDG was 43.40 kg h^{-1}. In 2022, the same trend was noted, with corresponding values of 89.70 kg h^{-1} and 40.90 kg h^{-1}. However, is worth mentioning that such performance varies widely within and between continents. Indeed, in 2022, Europe generated the highest annualized YDG at 285.40 kg h^{-1}, whereas other regions displayed significant variations. Specifically, Asia, The Americas, Africa, and Oceania generated corresponding values of 102.80, 90.90, 50.30, and 29.40 kg h^{-1} (Table 1). Such trends are undoubtedly determined by the degree of specialization of the breeds, the technological level of the farms, the availability of feed (i.e., quality and quantity), and the needs of the dairy industry [25,33].

Table 3. Dairy goat production (millions of tons) from 1970 to 2020 and forecast for 2050.

Area/Year	1970		2020		2050 [1]	
World	**6.48**	**100% [2]**	**19.18**	**100%**	**32.87**	**100%**
Asia	**2.57**	**39.67%**	**10.69**	**55.73%**	**19.75**	**60.06%**
India	0.62	9.63%	6.26	32.65%	12.64	38.45%
Pakistan	0.18	2.72%	0.97	5.03%	1.43	4.35%
Bangladesh	0.35	5.36%	0.75	3.90%	1.23	3.73%
Turkey	0.48	7.43%	0.59	3.07%	0.86	2.61%
Indonesia	0.10	1.60%	0.36	1.88%	0.47	1.44%
Africa	**1.52**	**23.49%**	**4.53**	**23.63%**	**7.77**	**23.63%**
Sudan	0.21 [3]	3.20%	1.17	6.08%	1.90	5.77%
South Sudan	0.09 [3]	1.37%	0.54	2.83%	0.84	2.56%
Somalia	0.44	6.79%	0.37	1.93%	0.41	1.23%
Niger	0.16	2.39%	0.41	2.12%	0.97	2.95%
Algeria	0.12	1.87%	0.33	1.74%	0.78	2.38%
Europe	**2.06**	**31.77%**	**3.15**	**16.41%**	**4.30**	**13.08%**
France	0.28	4.30%	0.71	3.70%	1.03	3.12%
Spain	0.31	4.85%	0.52	2.73%	0.68	2.05%
Netherlands	MV [4]	MV	0.41	2.12%	1.54	4.69%
Greece	0.35	5.36%	0.36	1.88%	0.46	1.41%
Russia	MV	MV	0.25	1.33%	0.22	0.66%
America	**0.33**	**5.07%**	**0.81**	**4.23%**	**1.06**	**3.22%**
Brazil	0.07	1.06%	0.29	1.52%	0.38	1.15%
Jamaica	MV	MV	0.19	1.00%	0.26	0.78%
Mexico	0.19	2.99%	0.17	0.88%	0.26	0.78%
Haiti	0.02	0.33%	0.05	0.26%	0.06	0.20%
Bolivia	0.01	0.17%	0.03	0.15%	0.04	0.14%

[1] Forecast for 2050 based on a time-series model using data from FAO (2024); [2] Percentage values are based on world total; [3] Estimated value, considering that South Sudan was recognized as a country until 2012. [4] Missing value.

Except for the average of Europe, the YDG is still low in the rest of the continents, and large variations are observed, which undoubtedly generates a wide opportunity for improvement. Regarding the dimensions of this opportunity, in 2022, the difference between the countries with the highest and the lowest yields was 832.20 kg h^{-1}. This is based on the average values of the Netherlands (i.e., 844.8 kg h^{-1}) with respect to Mali (i.e., 12.6 kg h^{-1}). In 2022, the top 10 of the countries with the highest YDG that complemented the Netherlands (i.e., kg h^{-1}) were Switzerland (630.4), France (593.4), Norway (574.3), Lithuania (490.4), Belarus (489.7), Ukraine (432.6), Austria (403.4), Jamaica (357.3), and Taiwan (346.6). In addition, Europe's YDG was 2.18 times higher than the global average, recalling that Europe generated about 16.0% of GM in the world, with only 5.01% of DGI (Table 1) [25]. This scenario was undoubtedly influenced by the greater degree of specialization, commercialization, systematization, connectivity, and innovation observed in Europe [33]. However, the YDG values reported by FAO should be considered cautiously in some cases. In fact, significant variations were detected for some countries. During the period from 2013 to 2015, the official statistics of Greece and Italy reported an average YDG of 260.42 and 159.69 kg h^{-1}, respectively. However, the FAO reports significantly different values for the same period, with 147.5 kg h^{-1} for Greece and 49.43 kg h^{-1} for Italy [25,74,75].

Additionally, in most countries, official statistics do not include self-consumption or informal selling, as well as the use of constants to calculate DGP, which complicates efforts to quantify the economic value generated by goats. Indeed, DGP for self-consumption as well as a source of income in rural households is important in the countries of the Mediterranean, the Middle East, Eastern Europe, and parts of Latin America [76]. In addition, GM and other goat products play a fundamental role in many cultures, where they are used as gifts, exchanges, celebrations, religious rituals, and even as organic fertilizers in various crops [33,77,78]. Although most GM is used to make cheese, it is also consumed in the form of whole milk, yogurt, and sweets. In this regard, in the United States and other developed countries, GM is consumed by people who are lactose intolerant or suffer from a digestive disorder. In Europe, it is mainly consumed in the form of fine cheeses, gourmet cheeses, and some with designation of origin. In China, a considerable amount of GM is used to make powdered milk [33,79–81].

5. Dairy Goat Production: Socioeconomic and Cultural Importance in the World

As previously mentioned, most DG are raised by smallholders and are not part of specialized animal production systems, making it difficult to truly estimate the contribution of DGP to livelihoods. Unquestionably, the input of DGP under intensive and stabled conditions is, in general, minor. Moreover, in some European countries and in the United States, producers of this type of industrialized schemes along with diverse research institutions are reconsidering the use of grazing, either grasslands or rangelands, to reduce costs and, in parallel, maintain natural behaviors, enhance the environment, and increase both biodiversity and animal welfare [47,48,82,83]. In the above, the type of climate and the distance to markets are central factors that make the use of DG grazing more profitable during part or all of the year when compared to feeding goats with total rations based on a mixture of grains (i.e., corn and soybeans), which also compete with human consumption. Moreover, considering the ability of goats to take advantage of more effective browsing than sheep and cattle, the food ethology of goats generates a plus to reduce the load of parasites [47] and, at the same time, decrease the possibility of fires [47]. Therefore, goat management in pastures and/or semi-intensive schemes (i.e., daytime grazing with night confinement) is of greater global importance in production units focused on MP [57,84–87]. DGP has been demonstrated to be an environmentally and economically relevant and socially responsible activity, as it is carried out mostly in marginal ecosystems from a biotic, economic and social point of view. These areas are generally accompanied with a significant water deficit, a scenario mainly observed in arid and semiarid lands [34]. In addition, while DGP is essential for many families worldwide as it represents the only source of family income, it represents an alternative source of income for others. It is also the only income against crop losses, thus ensuring the livelihood of thousands of families under marginal conditions, including biological, social, ecological, and economic conditions [60,61]. Furthermore, the economic, social, and cultural importance of goats is increasingly recognized, contributing to poverty reduction and improving social stability. However, more information is needed regarding the management practices of this activity, particularly the economic and social issues [88,89].

Although the social importance of DG is indisputable, it is necessary to analyze and dimension the global economic importance of DG. The latter could provide key information regarding the importance of goats, not only as a source of income for rural communities but also in their role in promoting sustainable development from an economic, biological, and social perspective [90–92]. In this regard, in 2022, the FAO reported a global dairy production value of USD 470,546.54 million. Bovine MP generated the highest economic income with 80.73%, followed by buffalo milk (15.30%). In contrast, GM only represented 1.94% of such revenues. However, the economic value of the DGP (EVDGP) has almost quadrupled during the analyzed period, denoting an increase of 375% during the 30 years analyzed; this trend was not even close to being shown neither by cattle nor by buffaloes. If this trend continues, in 2050, the EVDGP could reach up to USD 22,430.59 million (+375%) (Figure 3). It is central to note that for the EVDGP variable, the FAO only reported information from 1991 to 2022. This is in contrast to the rest of the variables analyzed, for which information was available from 1961 to 2022 [25].

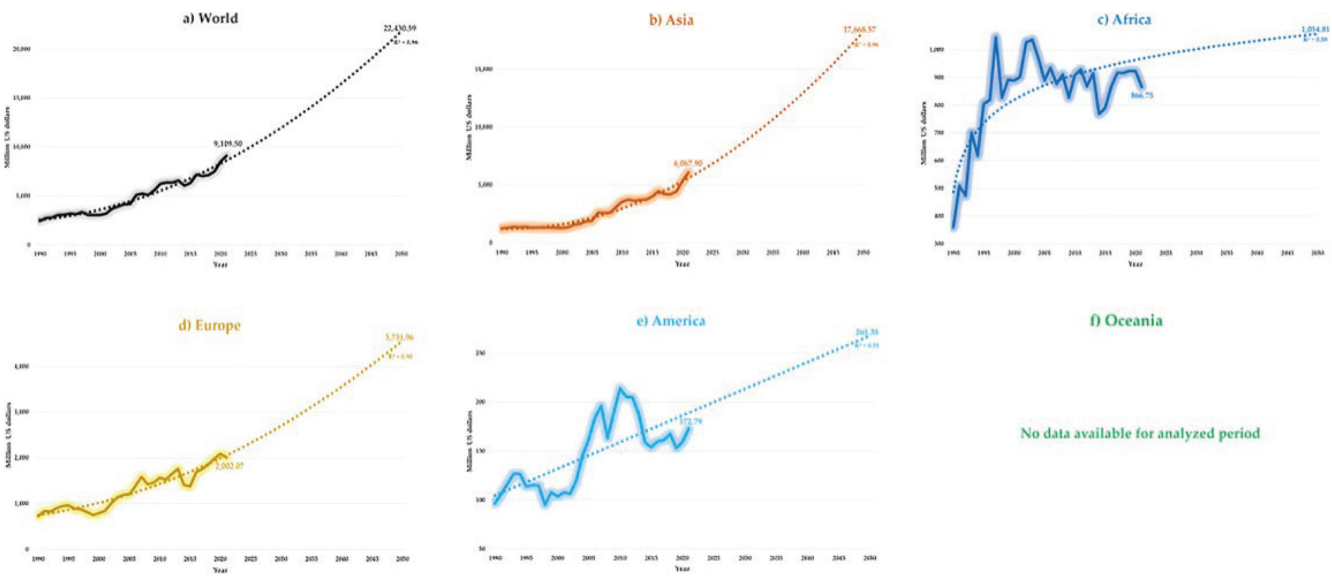

Figure 3. Trends in the economic value of goat milk (million USD) from 1990 to 2022 (solid line) and forecast for 2050 (dashed line) based on a time-series model using data from FAO (2024).

As expected, in 2022, Asia was the main contributor with respect to the global economic value of the DGP (i.e., 66.61%), followed by Europe, Africa, and The Americas with corresponding values of 21.98%, 9.51%, and 1.90% (Figure 3). Regarding Oceania, FAO only reported the EVDGP from 1993 to 1998, with values no greater than USD 0.032 million; therefore, such a negligible contribution was not computed in the further analyses. During 2013–2022, the global EVDGP increased by 42.9%, with Asia leading with the largest increase (i.e., 63.17%) followed by Europe (31.53%). On the contrary, Africa and The Americas registered negative trends in the EVDGP, with respective values of −6.72% and −15.83% (Figure 3). In the case of the EVDGP variable, there was a lack of specific information. In 2022, the global EVDGP was estimated at USD 9109.50 million. However, at the country level, the information reported by FAO only considered 16 countries, which represented 29.11% of the DGP, denoting major inconsistencies [25].

However, even with the inconsistencies, our working hypothesis is aligned with the results obtained and projected in these analyses. Indeed, the results confirm the central role that DGP plays in maintaining the social and economic livelihoods in many regions of the world. Certainly, goats provide important advantages not only as a source of economic income but also by providing miscellaneous products with high nutritional value and high sales opportunity for millions of SF, particularly in the developing countries [60,61,88,93]. This is particularly true in several regions of the world where malnutrition is prevalent, such as defined regions in Africa, Asia, and South America, where GM tends to be an essential component of the diet [15,16,88,91]. In addition to its nutritional contribution, DGP systems are undoubtedly important drivers of economic stability and poverty alleviation, especially in rural areas where SF have goats as their main and even only source of income. Undeniably, the fact that GP generally requires a low initial investment coupled with the relatively high yields associated with DGP systems, make goats an attractive option for marginalized and low-income populations [68,88,93]. This undoubtedly allows goats to emerge and consolidate themselves as an attractive option in the global efforts to meet the 17 SDGs, especially those related to ending poverty, where the first three SDGs stand out (SDG 01: no poverty, SDG 02: zero hunger, and SDG 03: good health and well-being).

Another socioeconomic advantage of DGP is the reduction of vulnerability to economic shocks, considering that the sale of DGP and its by-products (i.e., cheese and yogurt) represent a steady stream of income, helping to diversify the economy of the SF. This is directly related to social mobility. In many developing countries, DGP contributes significantly to household income, allowing families to cover the costs of essential goods and services, such as education and health care [29,60,76,90–92]. Additionally, in many cultures, women are responsible for handling goats. This responsibility provides women not only with a source of income but also with the opportunity to contribute to the household finances, improving their economic independence and social status, as well as contributing to their empowerment. Indeed, the fact that women generate income and participate in decision-making is one of the strategies through which DGP helps to address gender disparities, thus promoting social equity [94–98]. Again, this empowerment of women is closely related to SDG 05 (gender equality) and SDG 10 (reduce inequalities). Furthermore, it is essential to emphasize that, fortunately, the positive impact of DGP extends beyond the individual and the household, as it has an effect at the community level. Certainly, DGP contributes to rural development by generating employment opportunities, stimulating the improvement of local economies [79,99,100]. In addition, DGP encourages the development of associated industries, such as milk industrialization, technical assistance services, and agricultural production, especially fodder, among others, thus creating a domino effect that benefits the entire region [47,61,64,101,102].

Indisputably, based on a sustainability scheme, DGP favors the conservation of the environment and guarantees the long-term viability of rural livelihoods, considering that goats are well adapted to various climatic conditions and can thrive in areas where other animals cannot do so. Indeed, the ability of goats to produce on marginal lands and consume a wide variety of vegetation helps the conservation of natural resources and reduces the risk of overgrazing and soil erosion [34,37–39,68,90–92,103,104]. Another fundamental feature of the socioeconomic importance of DGP lies in the influence it exerts upon the culture of many societies, highlighting its role in sustaining traditional livelihoods, culinary heritage, and social cohesion. In many cultures, GM is intertwined with traditional practices and customs, while playing roles in cultural identity and heritage. Both production and consumption of GM are deeply rooted in rituals, festivals, and daily practices, which often have symbolic meanings in cultural ceremonials [36–39,52,53,55–58]. In addition, the preservation of ancestral goat breeding techniques, as well as traditional GM processing recipes, are habitually transmitted across generations in diverse regions worldwide, contributing to cultural heritage and promoting a sense of community, belonging, and continuity. By maintaining traditional knowledge and practices, DGP strengthens cultural heritage, supports rural economies, and enhances FS [32,33,42,47,77,78,88,105–108]. These cultural facets allow us to build a new dimension, resizing the socio-cultural value of DGP, reinforcing the need to protect it, and promoting it as a vital component of global cultural diversity and agricultural sustainability. The precedent scenarios strengthen the fundamental importance of DGP beyond the purely environmental, economic, social, and nutritional scopes.

6. Conclusions

As reviewed, DGP plays a central role in the global effort to advance the SDGs, especially SDG 2, which calls for zero hunger. Indeed, DGP contributes significantly to small farmers and nutrition globally, which is particularly important in marginal and vulnerable regions, most of which are located in arid and semi-arid areas of the world. This is due to the great capacity for adaptation shown by goats, allowing them to not only subsist but even flourish in adverse climatic conditions; their low environmental impact; and the high nutritional value of goat milk and its derivatives. In this way, goats in general, and dairy goats in particular, are positioned as a key source of food. In addition to being one of the farm animals of zootechnical interest, goats are best adapted to face adverse environmental conditions, and goats are one of the oldest animals to be domesticated by humans. Moreover, DGP is concentrated in countries where goat farming is strongly related to socio-cultural features contextualized by a low availability of biotic and economic resources yet aligned to a noticeable resilience to face adverse conditions. When talking about the sustainability and viability of small-scale production systems, DGP can undoubtedly be considered as a trigger for socioeconomic development for millions of small farmers, mainly concentrated in developing countries. Therefore, it is central to consider DGP as a key player within global strategies to mitigate the effects of climate change, ensure small farmer livelihoods, and contribute to the fulfillment of the SDGs of the 2030 agenda, especially zero hunger.

In addition to the fact that goat milk has a high nutritional value and digestibility, it generates sustainable economic opportunities, with low investment costs and rapid return on capital, thus improving ways of life in diverse rural areas worldwide. The resilience of dairy goats to climate change, coupled with their great capacity to thrive in marginal areas, reinforces their relevance as a key component to address food insecurity and promote true sustainable development in rural communities. Indeed, the high capacity of dairy goats to adapt to extreme climatic conditions, parallel to their genetic potential to improve milk production, allow goats to play a central role in several regions of the world, particularly in Africa, Asia, and Latin America. Here, goats serve as a key source of nutrients in very large populations with reduced biotic and economic inputs, where the greatest dairy goat census growth is projected to occur. Therefore, to enhance this impact, it is essential to know more about those native breeds with a dairy emphasis since they also generally display greater resistance to drought and produce milk richer in fat and protein compared to European breeds. Hence, it is essential to highlight the importance of preserving and promoting the breeding and production of these native dairy breeds to ensure the sustainability and genetic diversity of the genus *Capra*. Moreover, dairy goats also contribute to promoting sustainable agriculture in a holistic and ecological production format, allowing their manure to be used to fertilize crop fields and to control and prevent fires through forest grazing as another ecosystem service.

Although the share of goat milk in global milk production is relatively low, as compared to cattle and buffalo, DGP has shown an unprecedented growth compared to their ruminant counterparts, with close to 200% growth during the last three decades, especially in Asia and Africa, where it is an essential source of nutrition and livelihoods for millions of people. The projections made in this study indicate a continuous increase in goat milk, which should contribute to the improvement in the livelihoods of millions of small farmers, who are generally poor and marginalized. For this reason, dairy goats have become a key component to reduce poverty as well as to face climate change worldwide. In addition, the growing demand for goat milk products in local, regional, national, and international markets reveals that this sector has significant potential to drive sustainable economic development, particularly in developing economies. Undoubtedly, large- and small-scale producers must coexist to meet such an increase in market demand, as well as to provide employment and manage the natural resources in a sustainable manner. Greater investments in technologies and the gathering of reliable and accurate data are undeniably required to improve productivity and, in turn, maximize the impact of DGP on the eradication of hunger and poverty. This information should always be contextualized in low environmental impact schemes of production. As with any animal species, a lower environmental impact does not occur by chance; it is the result of evidence-based regulations, adequate financial support, community sharing, sensible incentives, and clearly defined outcomes, all of which are aligned with a market willing to pay a fair price for quality products. Hence, the challenge is to facilitate the transition and insertion of subsistence producers into marketing chains, with a focus on understanding and addressing of their strengths, threats, opportunities, and weaknesses. Indubitably, it is critical to adjust traditional models, or even more, to generate new integration marketing models. This approach subsequently allows the inclusion of diverse producers along with service providers, markets, and policymakers to manage economic, environmental, and social changes in the face of the challenges of climate uncertainty.

Other opportunity areas for future research to strength DGP include greenhouse gas emissions mitigation, the generation of cost-effective rations made from unconventional feeds and by-products, the development of novel thermotolerant vaccines and those able to differentiate infected animals from vaccinated ones, and the development of vaccines capable of reducing greenhouse gas emissions coupled with genetic progress through molecular analysis. Special attention should be paid to the promotion of applied and innovative research, allowing the sector to be aligned with future production and market trends, as well as resizing the undoubtedly central role that women have within goat production schemes. In addition, the European model clearly shows that DGP can be modern, safe, and profitable, with high-quality products and global markets. Therefore, small-scale producers still face many challenges in generating a nutritious and hygienic product with adequate support, fair prices, and incentives. Addressing these challenges could enhance social, economic, and ecological benefits. This, in turn, should reduce the nutritional and food-availability gap, increase cognitive capacity, and enhance the development of human capital. The final goal is to reduce poverty, while increasing in a concomitant fashion economic development and the social mobility of the producer and his family.

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Impact of Hop Residue Reuse on the Chemical and Sensory Properties of Craft Beer

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Abstract: Hops are an important component of beer brewing, providing aromatic and bittering properties that are essential to consumer appeal. A significant amount of hop residue is generated in the dry-hop brewing process that cannot be reused due to bittering residues that disqualify them as animal feed or other products. The purpose of this research was to reuse four varieties of hop waste (Citra, Mosaic, Hallertau Blanc, and Mandarina Bavaria) through a repalletization process with the objective of integrating them into a new craft beer brewing process. Chemical properties such as the phenolic content, antioxidant capacity, and α- and β-acids were significantly reduced ($p < 0.05$) due to the reuse of the repelletized hops, leading to a decrease in the bitterness levels in all of the craft beers brewed with dry-hop residues. Finally, the sensory study conducted with non-habitual craft beer consumers revealed significant general acceptability for beers brewed with repelletized dry-hop residues (Mandarina Bavaria, Citra, and Mosaic). The reuse of hop residues for brewing presents a promising opportunity for further development in the food industry.

Keywords: craft beer; HPLC; aroma; flavor; bitterness

1. Introduction

Beer is an ancestral alcoholic beverage widely consumed in the world [1]. Over time, the definition of beer has evolved as man's understanding of the beverage has broadened, and it is now described as a product of the transformation of barley malt and hop-based wort by yeast under controlled conditions [2]. In many countries, the craft brewing industry has experienced a rapid expansion in the number of breweries and has gained market share from the large global breweries [3]. The global beer market was valued at USD 768.55 billion in 2022 and is projected to reach a value of USD 996.49 billion by 2030. The global market is projected to grow, exhibiting a compound annual growth rate (CAGR) of 3.30% during the forecast period [4]. The unique sensory properties of craft beers take place thanks to the incredible creative freedom of producers, who experiment with a great diversity of hops, malts, yeasts, and other unconventional materials such as fruits, honeys, and aromatic herbs in order to build consumer loyalty and differentiate themselves from their competitors [5,6].

Beer hop residues have gained attention for their potential in recovering bioactive compounds. These wastes, generated in large quantities by the brewing industry, contain a variety of valuable compounds such as polyphenols, antioxidants, and pigments [4]. The utilization of byproducts as a valuable product stream in the high-volume brewing industry has been extensively researched and applied to optimize the environmental and economic sustainability [7]. There is a growing interest to investigate the utilization of brewery byproducts among craft breweries [8]. The brewing process produces several byproducts, including spent grain, spent yeast, and hops (*Humulus lupulus* L.) [9]. Hops are primarily known as an aromatizing ingredient in beer, with the added benefits of antioxidant potential and antimicrobial properties [10]. Research on hops has generally focused on its bittering, aromatic, and preservative properties [11,12].

The most valuable hop compounds for the brewing industry are hop acids, essential oils, and flavonoids [13]. Hop acids are referred to as α- and β-acids (also known as humulones and lupulones, respectively). In their pure state, hop acids occur as pale-yellow solids. They are weak acids, poorly soluble in water, and have almost no bitter taste [14]. When hops are used at the beginning of the brewing process, their essential oils volatilize, imparting bitterness in the beer. This is ideal for beer styles that emphasize the aromas of other adjuncts, such as fruits or aromatic herbs. Conversely, when hops are added at the end of the boil or later stages of production, essential oils are retained, giving the beer a strong aromatic component from the hops. This is ideal for "hoppy beers", where the hop aroma is the main component of the sensory profile of the final product [15,16].

In order to enhance the hop aroma in beers, the brewing industry frequently uses the technique known as "dry hopping", which consists of adding additional hops during the fermentation and maturation stages. This technique makes it possible to extract the aromatic components from the solid fraction of hops using the alcohol naturally present in the beer. These hops, with distinctive and unique aroma characteristics, are grown by producers in several countries: Amarillo, Citra, Mosaic and Sorachi Ace (Washington, DC, USA); (Hallertau Blanc, Polaris and Mandarina Bavaria (Hallertau, Germany); Nelson Sauvin (Nelson, New Zealand) [17].

Dry hopping is usually performed at cold temperatures (below room temperature) to minimize the solubilization of α-acids and their isomerization to iso-α-acids. This approach allows for the extraction of volatile components without significantly increasing the bitterness of the product [17,18]. The present study aims to take advantage of the hop residue through the repelletizing process to insert it in a second process of craft beer production with sensory characteristics acceptable to consumers. Obtaining the new hop residues would not only reduce environmental pollution but also offer opportunities to develop value-added products in various industries, such as food, pharmaceuticals, and cosmetics.

2. Materials and Methods

2.1. Materials and Reagents

For the Pale Ale-type barley malt (Bestmaltz, Bessenbach, Germany), the yeast used was US-05 (Fermentis, Aubagne, France), and the following five types of hops:

Cascade, Citra, Mosaic, Hallertau Blanc, and Mandarina Bavaria (Yakima Chief Hops, Washington, DC, USA).

2.2. Craft Beer Brewing

The brewing process of the craft beer is shown in Figure 1. The malt grains of the Pale Ale variety (12 kg) were subjected to a milling process in a crown grinder.

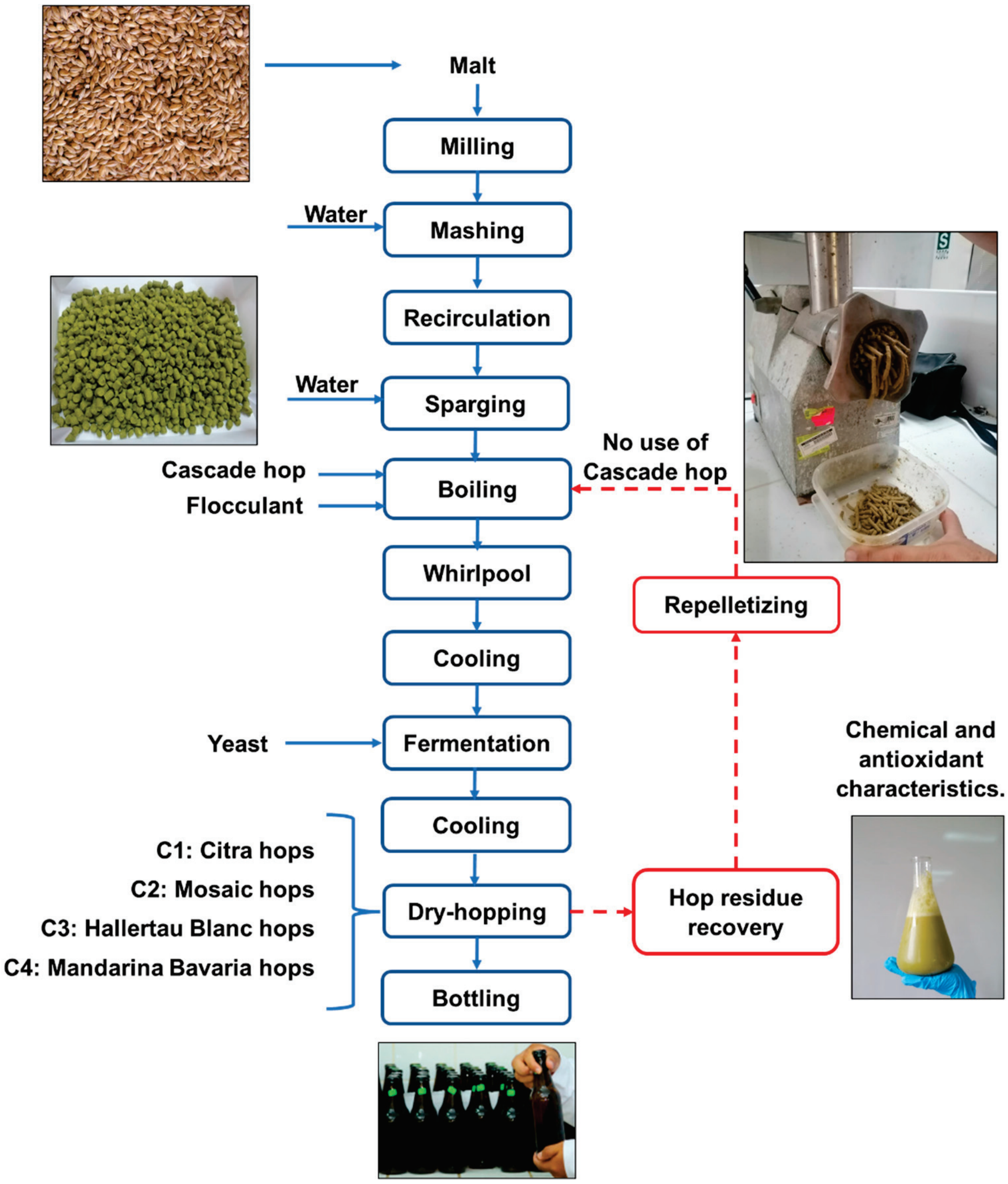

Figure 1. Flow chart for craft beer brewing and the reuse of residual hops.

Using a stainless-steel pot, the malt was mixed with water (40.25 L) at 70 °C and stirred vigorously for 60 min. Subsequently, the wort or mash was then collected by opening a pipe installed at the bottom of the stainless-steel pot, allowing it to flow back into the pot. The recirculation was repeated until the must had a clear, crystalline appearance with no remaining traces of grain. Next, the must was separated from the wet grain by opening the lower spout of the mash pot and draining all of the sweetened liquid into a second stainless-steel pot (boiling pot). Additionally, a batch washing was performed by adding water (30.75 L) at 70 °C to the mash pot still containing the wet grain. Then, the diluted mash (wet grain/washing water) was stirred using a stainless-steel shovel. The recirculation stage was repeated until the drained mash showed no trace of grains. The diluted mash was collected in the boiling pot through the lower spout of the mash pot. In the boiling stage, the wort collected from the previous stages was heated to a temperature of 100 °C, at which time Cascade hop (CH) pellets were added as bittering hops. This temperature was maintained for a period of 60 min. At minute 45 of the boiling process, unflavored gelatin (20 g) was added as a flocculating agent. Once the boiling stage was finished in the boiling pot, the whirlpool was performed, where the bitter wort was stirred in a clockwise circular motion with a stainless-steel paddle for 10 min. Using a food-grade plate chiller (SS Brewtech, 1TBG-225-Glycol, San Diego, USA), the sour wort was cooled to a temperature of 25 °C. With the help of sanitary hoses connected to a stainless-steel head pump (Xinxishan, MP-15RM, Shijiazhuang, China), the fluid was conveyed to a conical fermenter (SS Brewtech, California, USA) with a maximum capacity equal to 26.5 L. The fermentation stage began with the addition of commercial yeast (SafAle US-05) and lasted for 7 days at a controlled temperature of 21 °C. After the fermentation process, the cooling system was activated by means of a glycol chiller, circulating a cooling liquid through the fermenter coil system to reduce the temperature to 7 °C for 14 days. On the seventh day of the cold conditioning stage, dry hopping was performed. This process consisted of purging the settled yeast in the fermenter cone to condition the experimental hop pellets (Citra, Mosaic, Hallertau Blanc, and Mandarina Bavaria). At the end of the 14 days, the dry-hop residues were separated and the beer obtained was collected in a stainless-steel pot, to which 250 g of blonde sugar was added for the natural carbonation process. The mixture was dissolved, and finally it was bottled using a bottle filler tube and a manual capping machine.

2.3. Repelletizing of Dry-Hop Residues

After 14 days of cold conditioning in the brewing process (first batch), the dry-hop waste was collected from the fermenter cone by using a sterile Erlenmeyer flask wrapped in aluminum foil to prevent the oxidation of any component of the byproduct and stored cold for preservation. A filter screen was used to separate the beer from the collected hop waste, manually squeezing out as much liquid as possible, leaving a hop paste. The residual paste was dried at room temperature for a period of 3 days until the optimum consistency for repelletizing was obtained. To obtain new pellets, the hop paste was standardized to a moisture content of 12% and fed to a pelletizer (Twothousand®, TJ22B, Shenzhen, China) with dimensions of 210 × 240 × 450 mm, nozzle diameter of 0.2 cm, and productivity of 120 kg/h. The new hop pellets were spread on a smooth surface and left to dry at room temperature for one day. The newly produced hop pellets were vacuum-packed in high-density polyethylene bags using SHIELD equipment (DZ-300/PD, Zhejiang, China), and then stored at room temperature until use for the production of new batches of beer at the brewing stage, following the usual brewing process.

2.4. Chemical Characterization

The moisture content was determined using an oven (POL-EKO-APARATURA®, SW115STD, Bielsko-Biała, Poland) according to AOAC 931.04 [19]. The ash was determined by incinerating organic matter at 650 °C for 3 h in a muffle (THERMOLYNE, 347034984, Waltham, MA, USA) according to AOAC 923.03 [20]. The Dumas method was used to determine the protein content according to the AOAC 990.03 method [21]. The fat content was analyzed according to Manirakiza et al. [22] in a Soxhlet fat extractor (FOSS, Soxtec TM-2043, Waltham, MA, USA) using petroleum ether (CDH Fine Chemical, Gurugram, India) as a solvent. Finally, the content of other compounds was determined by the following equation: % Carbohydrates = 100% − % moisture − % ash − % protein − % fat.

2.5. Determination of α- and β-Acids by HPLC

To obtain the extracts for the hop samples, 200 mg of each was used and placed in contact with 20 mL of methanol in an ultrasonic bath (Branson Ultrasonics, CPX5800H-E, Danbury, CT, USA) for 20 min. The samples were then filtered and taken to a rotary evaporator (IKA, RV 10C S000, Staufen, Germany) at a reduced pressure and a constant temperature of 40 °C until they were dry. The samples were resuspended at 1 mg/mL with methanol, filtered through 0.2 µm syringe filters, and deposited into amber vials. An amount of 20 µL of the filtered sample was then injected into the HPLC equipment (Hitachi CM, Düsseldorf, Germany), which entered the C18 column stationary phase and with the help of the mobile phase, as follows: Solution A: water + formic acid (0.1%) and Solution B: acetonitrile with 0.1% formic acid; the flow rate was 1 mL/min and chromatograms were obtained at a wavelength of 280 nm. The run was by gradient with the following percentages: 0 min (55% A + 45% B), 2 min (55% A + 45% B), 12 min (25% A + 75% B), 17 min (5% A + 95% B), 30 min (5% A + 95% B), 35 min (10% A + 90% B), 40 min (55% A + 45% B), and 45 min (55% A + 45% B). The HPLC system consisted of a pump (CM 5160), autosampler (CM 5260), column oven (CM 5310), and diode array detector (CM 5430). A C18 column (250 mm, 5 mm, and 4 µm) was used as the stationary phase. A standard dilution of α-acids (Cohumulone and N+adhumulone) and β-acids (Colupulone and N+adlupulone) at 2 mg/mL was prepared with methanol. Sufficient aliquots were extracted for standard preparation at concentrations of 0.125, 0.25, 0.50, 1.5, and 2 mg/mL. They were then passed through a 0.2 µm syringe filter and deposited in amber vials for analysis. The samples were analyzed in triplicate (this profile was visualized in Figure 2) and the calibration curves obtained for the alpha and beta acid standards were as follows: Cohumulone (Y = 15664541.9X + 742863.687; R^2 = 0.9996), N+adhumulone (Y= 35135534.6X +1161599.780; R^2 = 0.9998), Colupulone (Y = 10082454X + 801840.423; R^2 = 0.9989), and N+adlupulone (Y = 8617967.22X + 391922.702; R^2 = 0.9996), where X is the concentration (mg/mL) and Y is the area under the curve. The results of α- and β-acids were expressed in mg/g hops.

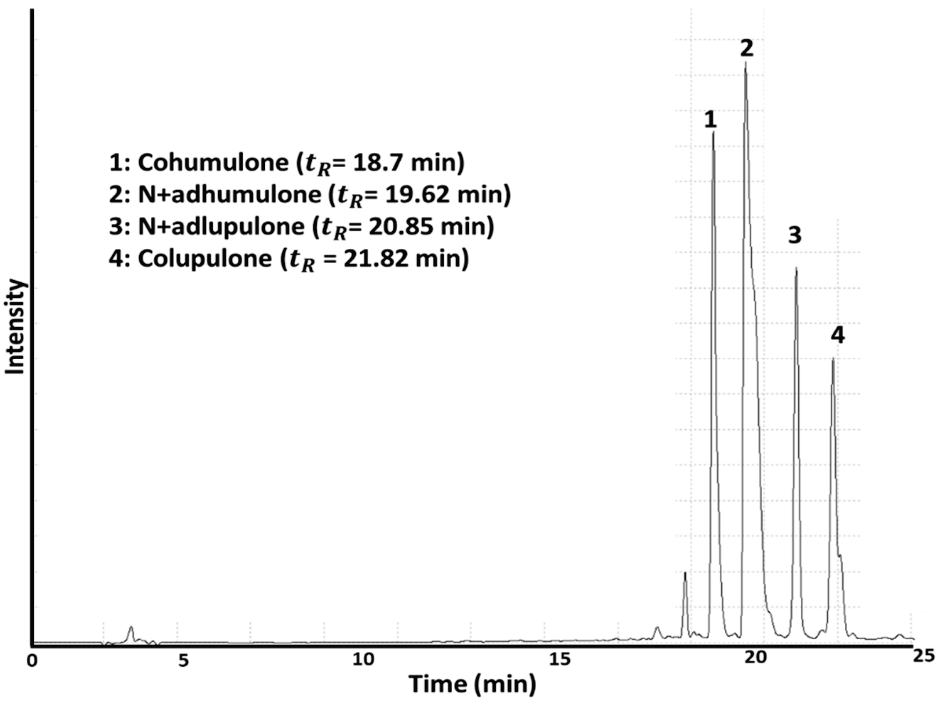

Figure 2. Chromatographic profile of α- and β-acids in hops; t_R: time retention.

2.6. Determination of Total Phenolic Compounds

The total phenolic compound content of the hop extracts was determined using the Folin–Ciocalteu assay and adapted from Saura-Calixto et al. [23]. First, solutions of gallic acid ($C_7H_6O_5$) at a concentration of 450 μg/mL (0.0225 g of $C_7H_6O_5$ reagent in 50 mL of distilled water), 20% sodium carbonate (Na_2CO_3) (2 g of Na_2CO_3 in 10 mL of distilled water sonicated for 5 min), and 2N Folin–Ciocalteu reagent were prepared. From the $C_7H_6O_5$ solution (450 μg/mL), different concentrations were formulated for the construction of a calibration curve (7.2, 14.4, 21.6, 28.8, and 36 μg/mL). In Eppendorf tubes, 20, 40, 60, 60, 80, and 100 μL volumes of $C_7H_6O_5$ were added and 100 μL of Folin–Ciocalteu 2N was added (the mixture was allowed to stand for 5 min); then, 50 μL Na_2CO_3 (20%) was added to all of the tubes to be completed with distilled water (1080, 1060, 1040, 1020, and 1000 μL, respectively, to each tube). After 1 h of resting, 200 μL of each tube was added to a microplate well to be read at a wavelength of 730 nm on a Synergy™ H1 multimode microplate reader (BioTek Instruments, Inc., Cheadle, UK). The calibration curve was as follows: $Y = 0.0567X - 0.0664$ ($R^2 = 0.994$), where X is mg GAE/mL and Y is the absorbance.

The phenolic extracts of the hops were obtained by using 25 mL test tubes. In each test tube, 2 g of hops (with and/or without repelletizing) were mixed with 10 mL of a methanol/water solution (50/50) at a pH = 2 (2N HCl solution); then, the mixture was subjected to an ultrasonic bath for 30 min, followed by centrifugation (Sigma, model 2-16P, Osterode am Harz, Germany) at 3000 rpm for 20 min. The supernatant obtained after centrifugation was considered the phenolic extract of the hops and stored under refrigeration (T = 5 °C). Subsequently, 800 μL of the phenolic extract sample was added in an Eppendorf tube and mixed with 100 μL of Folin–Ciocalteu 2N. The mixture was then rested for 5 min. An amount of 50 μL of Na_2CO_3 (20%) plus 300 μL of distilled water was added. Again, the mixture was left to stand for 2 h in the dark. Finally, 200 μL of the prepared mixture was taken and the absorbance was measured in the multimodal microplate reader. The total phenolic compound results were expressed as mg of gallic acid equivalent in one gram of hops on a dry basis (mg GAE/g d.b) and were performed in triplicate for each sample.

2.7. Antioxidant Capacity

The antioxidant activity in the hops was determined using the method developed by Kim et al. [24] with modifications. Solutions of Trolox at a concentration of 1 mM (0.0125 g of Trolox reagent in 50 mL of 80% methanol) and DPPH at a concentration of 1 mmol (3.9 mg of DPPH reagent dissolved in 100 mL of 80% methanol) were prepared. The DPPH solution was prepared in an amber glass bottle as a protection against light and homogenized on a magnetic stirrer (VELP Scientifica®, ARE, Usmate Velate, Italy) for one hour for refrigerated storage (5 °C); this preparation was performed at the time of analysis. A calibration curve was constructed from the 1 mM Trolox solution at different concentrations (500, 400, 200, 100, 50, 25, 10, and 5 μM); then, 10 μL of each concentration was taken and 190 μL of the DPPH solution was added, allowed to stand for 10 min, and measured at 515 nm in the multimodal microplate reader Synergy™ H1 (BioTek Instruments, Inc., Cheadle, UK). The calibration curve was as follows: $Y = 0.0683X + 6.4908$ ($R^2 = 0.9965$), where X is μmol Trolox/mL and Y is % DPPH. Finally, the phenolic extracts of the hops (10 μL) were reacted with the DPPH radical (190 μL), and the same reaction procedure was followed to obtain the calibration curve, as previously described. The final antioxidant capacity concentrations (μmol Trolox/g b.s) were determined in triplicate on a dry basis.

2.8. Determination of International Bitterness Units (IBUs)

The bitterness unit was determined according to the ASBC method Beer-23A [25]. Beer (5 mL) was transferred into a 50 mL centrifuge tube and acidified with 3N HCl (0.5 mL). Isooctane (10 mL) was added and the mixture was shaken by hand three times before extraction on a rolled bed for 15 min. The mixture was centrifuged (Sigma, model

2-16P, Germany) at 3000 rpm twice for 5 min each time to aid the phase separation. An aliquot of the clear isooctane layer was transferred into a cuvette, and absorbance was measured with a spectrophotometer (Jasco, V-670, Tokyo, Japan) at 275 nm against a blank of orthophosphoric acid and isooctane. The recorded absorbance was multiplied by an empirical factor of 50 to give IBU values in mg/L.

2.9. Sensory Analysis

The sensory analysis of the beer was performed with a set of 120 untrained panelists. The samples were previously refrigerated (T = 6.00 ± 0.50 °C). The following descriptors were analyzed: general appearance, aroma, bitterness, sweetness, color, hop flavor, turbidity, malt flavor, alcohol carbonation, and foam persistence. The panelists received a sensory primer with a continuous range of preference and/or level of acceptance, where 1 = very low/significant dislike, 5 = medium/neither like nor dislike and 7 = very high/significant like. Using a completely randomized design (CRD), the data were treated by an analysis of variance (ANOVA) to determine the significant differences in the factor, the type of craft beer. Using a Tukey test ($p < 0.05$), significant differences between treatments (types of craft beer) were determined with the use of Minitab® statistical software version 19.1.1.0.

2.10. Statistical Analysis

For the statistical analysis of the chemical characterization, antioxidant capacity, total phenolic compounds, and α- and β-acids in the different types of hops, as well as the bitterness level (IBU) in the craft beers brewed, a completely randomized design (CRD) and analysis of variance (ANOVA) were employed to assess the significance ($p < 0.05$) of the factor (type of hops). Tukey's test ($p < 0.05$) was used to identify the difference between treatments using Minitab® version 19.1.1.0 statistical support software.

3. Results and Discussion

3.1. Characterization of Hop Residues

Table 1 shows the comparison between the chemical characteristics of residual hop mash after brewing in the first batch (L1, L2, L3, and L4) and its repelletized hop residues (R1, R2, R3, and R4) on a dry basis. In general, the results showed that all of the residual hop pastes exhibited a significant effect of repelletizing on the moisture content in the samples ($p < 0.05$). For the other chemical characteristics, the effects were partial. For example, in the case of the carbohydrate and fat content, the effect of repelleting ($p < 0.05$) was observed only between L2 and R2. Similarly, for the protein content, the effect was observed between L1 and R1. However, for the ash content, no effect of repelleting was observed, with the exception of the L2 and R2 samples. In addition, it was noted that CH exhibited differences in the ash content compared to all other hop pastes but showed no differences in the fat content with any of them. These results were compared to the chemical composition reported in previous studies for dried hop cones, where the comparison with moisture (10%) was close, higher in protein (15%), and lower with respect to ash (8%) [26–30]. In relation to carbohydrates, the values are between 68 and 71% (Table 1), which is in agreement with Almaguer et al. [11]. According to this author, hops can contain up to 45% cellulose, monosaccharides, and pectins, in addition to approximately 7% fiber. As for the fat content, previous studies have shown that their composition includes resins, which contain α-acids, the main component responsible for the bitter taste of beer [31].

Table 1. Chemical characterization of the hops and repelletized residues.

Hop	Moisture	Ashes *	Proteins *	Fat *	Carbohydrates *
CH	7.826 ± 0.058 ^{g}	3.564 ± 0.100 ^{c}	20.429 ± 0.252 ^{b}	6.743 ± 0.153 ^{a}	69.624 ± 0.137 ^{cd}
L1	62.961 ± 0.002 ^{a}	2.674 ± 0.066 ^{d}	20.221 ± 0.250 ^{b}	5.592 ± 0.156 ^{abc}	71.412 ± 0.150 ^{ab}
R1	9.801 ± 0.002 ^{e}	1.822 ± 0.002 ^{e}	21.981 ± 0.268 ^{a}	4.781 ± 0.156 ^{bc}	71.534 ± 0.700 ^{a}
L2	60.296 ± 0.002 ^{c}	4.025 ± 0.016 ^{a}	20.354 ± 0.288 ^{b}	6.888 ± 0.161 ^{a}	68.733 ± 0.453 ^{d}
R2	6.918 ± 0.000 ^{h}	4.080 ± 0.009 ^{a}	21.863 ± 0.321 ^{ab}	4.009 ± 1.639 ^{c}	70.420± 0.418 ^{abc}
L3	64.587 ± 0.004 ^{b}	3.800± 0.020 ^{b}	21.180 ± 0.209 ^{b}	6.288 ± 0.158 ^{ab}	69.623 ± 0.497 ^{cd}
R3	8.866 ± 0.002 ^{f}	4.155 ± 0.003 ^{a}	20.324 ± 0.161 ^{b}	6.167 ± 0.210 ^{ab}	69.458 ± 0.388 ^{cd}
L4	59.339 ± 0.001 ^{d}	1.790 ± 0.017 ^{e}	21.069 ± 0.386 ^{a}	6.058 ± 0.213 ^{ab}	70.171 ± 0.683 ^{bc}
R4	7.747 ± 0.000 ^{g}	3.623 ± 0.006 ^{c}	20.289 ± 0.215 ^{ab}	5.381 ± 0.053 ^{abc}	69.927 ± 0.339 ^{cd}

CH: Cascade hop; L: residual paste; R: repelletizing; 1: Mandarina Bavaria; 2: Citra; 3: Mosaic; 4: Hallertau Blanc. Different letters present significant statistical differences ($p < 0.05$). * On a dry basis.

3.2. Total Phenolic Compounds and Antioxidant Capacity

Table 2 shows that the phenolic compound content of CH was higher than all hops (C1, C2, C3, and C4). The effect of the brewing process generated a significant loss of phenolic compounds on the repelletized hops R1, R2, R3, and R4 ($p < 0.05$), as the phenolic compounds of the hops are transferred to the beer. Similarly, the antioxidant capacity presented the same reduction trend, explained by the effect of the boiling temperature in the brewing process. However, the antioxidant capacity was not proportional to the content of phenolic compounds for the different hops; a striking example is shown in the content of total phenolic compounds of the Mandarina Bavaria and Citra hops (C1 < C2), since their values were different with respect to the antioxidant capacity (C1 > C2). This same behavior was observed in the residues of the repelletized hops, as the content of phenolic compounds R1, R2, R3, and R4 did not present a significant difference ($p < 0.05$). However, in the antioxidant capacity, the difference was in the order R2 > R1 > R3. Terpinc et al. [32] point out that the correlation between the content of phenolic compounds and the antioxidant capacity can be negative. It is important to note that several phenolic compounds found in hops are transferred to beer, influencing its overall flavor, particularly its fullness, astringency, and colloidal formation. The oxidation of flavonoids can impact the astringency, turbidity, and color, while low-molecular-weight phenols, such as 4-vinylsyringol, can impart off-flavors to the beer during storage [33]. The levels of phenolic compounds for the repelletized hops (Table 2) were lower than those presented by Petrón et al. [34], who determined values for beer lees (Yellow/Citra/Simcoe hop compounds) values between 5.841 and 10.339 mg GAE/g, which provided a radical scavenging activity (RSA: %) between 73.383 and 91.041% by using the DPPH method. Also, these values (R1, R2, R3, and R4) were slightly lower than by Ruiz-Ruiz et al. [35], who indicated the value of 150 mg GAE/100 g of discarded Cascade hops. The differences in the results at the level of phenolic compounds can be attributed to the technological process, since the temperature, pH, presence of microorganisms, and polar solvents can affect the polyphenols found in the beer matrix, thereby affecting their quantitative and qualitative composition [36].

Table 2. Characterization of the phenolic compounds and antioxidant capacity in hops.

Hop	Total Phenolic Compounds (mg GAE/100 g) *	Antioxidant Capacity (μmol Trolox/g) *
CH	229.333 ± 0.751 [a]	496.467 ± 2.060 [ab]
C1	216.023 ± 4.240 [b]	504.963 ± 17.589 [a]
R1	121.583 ± 1.178 [c]	286.269 ± 24.125 [c]
C2	227.135 ± 1.373 [a]	463.669 ± 7.699 [a]
R2	123.802 ± 4.685 [c]	343.669 ± 19.558 [b]
C3	221.288 ± 2.603 [ab]	326.449 ± 14.713 [bc]
R3	121.940 ± 5.517 [c]	148.509 ± 10.090 [d]
C4	214.792 ± 4.215 [b]	348.835 ± 9.588 [b]
R4	118.138 ± 1.319 [c]	328.171 ± 10.754 [bc]

CH: Cascade hop; C: dry-hop control; R: repelletizing; 1: Mandarina Bavaria; 2: Citra; 3: Mosaic; 4: Hallertau Blanc. Different letters present significant statistical differences ($p < 0.05$). * On a dry basis.

3.3. IBU Values in Craft Beers and Content of α- and β-Total Acids in Hop Residues

Beer bitterness was evaluated by calculating the IBU values (Table 3). As expected, all of the beers formulated with the dry-hop and repelletizing processes had a higher bitterness value than the beer obtained with the CH. The effect of the repelletizing process significantly influenced the IBU values of the dry hop ($p < 0.05$), while the IBU values of the beers obtained with C1 and C2 dry hops presented higher and significant ($p < 0.05$) values than the beers obtained with their residual repelletized hops. The beer produced by C1 and C2 presented the highest IBU values, which indicated that the hops derived by Mandarina Bavaria and Citra confer a higher bitterness to the final product. The IBU values for CH, C3, C4, R1, R2, R3, and R4 were within the range of bitterness observed in 34 commercial lager beers (8–36 mg/L) from different countries (Australia, Belgium, Cuba, Czech Republic, Denmark, France, Germany, Hungary, Italy, Netherlands, Poland, Peru, Romania, South Africa, Turkey, the UK, and the USA) according to the study conducted by Oladokun et al. [37].

Table 3. International Bitterness Unit values in beer.

Beer	IBU (mg/L)
CH	17.290 ± 4.079 [d]
C1	41.197 ± 5.799 [a]
C2	40.588 ± 3.727 [ab]
C3	27.427 ± 1.106 [cd]
C4	29.255 ± 3.499 [bc]
R1	28.342 ± 2.921 [cd]
R2	18.095 ± 5.031 [cd]
R3	23.998 ± 3.935 [cd]
R4	26.407 ± 5.212 [cd]

CH: Cascade hop; C: dry-hop control; R: repelletizing; 1: Mandarina Bavaria; 2: Citra; 3: Mosaic; 4: Hallertau Blanc. Different letters present significant statistical differences ($p < 0.05$).

Table 4 presents the α- and β-acid content for the different hop treatments in craft brewing, where CH corresponds to the Cascade hops or the starting hops for conventional brewing, C symbolizes the hops used in the dry-hop method to obtain craft beer, L corresponds to the residues of the hops used in the dry-hop method, and R is the repelletized residues that are finally used in the new craft brewing process. First of all, it can be observed that the cohumulone content in the CH was higher for all of the dry-hop hops, even in the residual and repelletized hops. Likewise, for the N+adhumulone content, the dry-hop C1 hop was superior to all of the treatments (including the residual and repelletized hops). Schindler et al. [38] indicate that the α-acid contents for the hops on a dry basis should be between 5 and 7%, as shown in Table 4 (α-acids = Cohumulone + N+adhumulone), and it can be seen that this was met for CH (5.3%), C2 (5.2%), and C4 (5.7%); however, for C1 (20%) and C3 (11%), this was not met. Another important finding was that N+adhumulone presented the majority α-acid in the dry-hop hops (control, residual, and repelletized), though this did not occur in CH. The effect of the treatments throughout the brewing process led to a significant reduction in α-acids due to the dry-hopping treatment. This reduction was not caused by the hop boiling, as the hop addition was performed cold. The reduction in cohumulone and N+adhumulone in the dry hops can be attributed to a combination of factors, such as the adsorption on the yeast and other solids, the chemical interactions with the beer compounds, microbial degradation, changes in the solubility and stability, oxidation, and environmental conditions such as the pH. These elements contribute to the complexity of the chemical and biological processes in beer, influencing the final composition of the product [16,39]. It should be noted that the addition of these hops aims to modify the bitterness (cohumulone), flavor, and aroma profile (N+adhumulone) of the final product [40]. The occurrence of bitter and aromatic characteristics in beer is strongly related to the chemical composition of the hops, the amount added, the type of hops, and the timing of hop dosing to the wort [41]. Conventionally, beer bitterness is achieved by adding hops to the hot wort at the beginning of the boil. The main reason for adding hops at this stage is to facilitate the thermal conversion of hop bitter acids (α-acids) into flavorful bitter compounds (iso-α-acids) and water-soluble bitterness. The yield of iso-α-acid increases with the boiling time, while most of the volatile compounds are lost through evaporation [15]. Iso-α-acids were not quantified in this study, as evidence suggests that conventional hopping (boiling) results in very low isomerization yields. Their utilization in cold hopping would be more complex. For example, at the end of boiling, less than 35–40% of the α-acids are typically transformed into iso-α-acids [42].

Table 4. Total α-acids and β-acids in the different types of hops (g/g).

Hop	α-Acids *		β-Acids *	
	Cohumulone	N+adhumulone	Colupulone	N+adlupulone
CH	0.052 ± 0.000^{a}	0.001 ± 0.000^{i}	0.077 ± 0.002^{a}	0.084 ± 0.000^{a}
C1	0.033 ± 0.001^{a}	0.167 ± 0.001^{a}	0.057 ± 0.001^{b}	0.067 ± 0.002^{b}
C2	0.024 ± 0.001^{f}	0.028 ± 0.000^{d}	0.019 ± 0.000^{f}	0.039 ± 0.001^{f}
C3	0.049 ± 0.002^{b}	0.062 ± 0.001^{b}	0.025 ± 0.001^{e}	0.047 ± 0.003^{e}
C4	0.027 ± 0.001^{e}	0.030 ± 0.002^{d}	0.031 ± 0.001^{c}	0.062 ± 0.001^{c}
L1	0.018 ± 0.001^{g}	0.024 ± 0.000^{f}	0.025 ± 0.000^{e}	0.034 ± 0.001^{g}
L2	0.011 ± 0.001^{h}	0.029 ± 0.002^{de}	0.006 ± 0.000^{g}	0.012 ± 0.000^{h}
L3	0.030 ± 0.001^{d}	0.035 ± 0.001^{c}	0.029 ± 0.001^{d}	0.031 ± 0.001^{g}
L4	0.023 ± 0.001^{f}	0.026 ± 0.001^{ef}	0.026 ± 0.002^{e}	0.055 ± 0.001^{d}
R1	0.009 ± 0.001^{h}	0.013 ± 0.001^{g}	0.001 ± 0.001^{h}	0.002 ± 0.001^{i}
R2	0.011 ± 0.001^{h}	0.011 ± 0.001^{g}	0.000 ± 0.000^{h}	0.000 ± 0.000^{i}
R3	0.023 ± 0.001^{f}	0.000 ± 0.000^{i}	0.001 ± 0.001^{h}	0.002 ± 0.001^{i}
R4	0.005 ± 0.001^{i}	0.004 ± 0.001^{h}	0.000 ± 0.001^{h}	0.000 ± 0.000^{i}

CH: Cascade hop; C: dry-hop control; L: residual paste; R: repelletizing; 1: Mandarina Bavaria; 2: Citra; 3: Mosaic; 4: Hallertau Blanc. Different letters present significant statistical differences ($p < 0.05$). * On a dry basis.

Regarding the quantification of β-acids, it was observed that the N+adlupulone content was higher than the colupulone content in all of the hop samples (CH, dry-hop, and residual samples). However, in the repelletized hops, the concentration of β-acids was significantly lower, likely due to the same effect observed in the α-acids. The β-acid content for the CH and dry hops was in the range of 9–10%, as indicated by Liu et al. [43]. The β-acids in the hops are important for beer quality because they act as antioxidants, protecting flavor and color during storage [44]. Additionally, they influence foam formation and stability by interacting with other compounds in beer, and possess antimicrobial properties that help prevent the growth of undesirable microorganisms [45,46]. Although they do not directly affect bitterness, they can modify the flavor and aroma profile during fermentation and aging, generally improving the quality and durability of the product.

3.4. Sensory Attributes Evaluation

The sensory analysis (Table 5) provided interesting results on the attributes evaluated. In terms of the overall acceptability, it was observed that craft beers brewed with repelletized residues of the four types of hops studied were better rated by consumers. For example, beers R1 and R2 showed a significantly higher overall acceptability than their respective controls, C1 and C2 ($p < 0.05$). In contrast, beers R3 and R4 showed no significant differences compared to C3 and C4. These results indicate that beers brewed with repelletized hop residues may very well be accepted and consumed by a public that is not necessarily in the usual market for the consumption of craft beers, especially bitter beers. This preference for beers brewed with repelletized hop residues by the panelists is explained by a low preference for bitterness and hop flavor, and a significant preference ($p < 0.05$) for sweetness. Multiple studies have analyzed the relationship between bitterness perception, preference, and food consumption, finding that people with greater sensitivity to bitterness generally exhibit less liking for bitter products [47–49]. Furthermore, it has been observed that more adventurous tasters (judges) tend to rate bitter fruits and vegetables more favorably than less adventurous tasters (consumers), who typically assign lower ratings to these foods. [50]. Associations between bitter taste and the consumption of bitter alcoholic beverages do not always follow a linear pattern [51]. Some findings suggest that higher perceived bitterness may correlate positively with intake [52,53]. These findings suggest the need for further research to explore the moderating influence of personality traits on the potential relationships between bitterness perception, liking, and the consumption of bitter products [54]. The results did not show significant differences regarding the aroma, color, turbidity, carbonation, foam, alcohol, and overall malt flavor ($p < 0.05$). Based on the type of panelists used in this sensory analysis, the final product is well suited for this target audience within the brewery market, offering promising potential for both consumption and sales.

Table 5. Sensory characteristics of craft beer brewed with hop residues.

Characteristics	Beer								
	CH	C1	C2	C3	C4	R1	R2	R3	R4
General acceptability	6.87 ± 1.45 a	4.26 ± 1.91 d	4.42 ± 2.03 d	5.98 ± 1.72 ab	5.86 ± 1.87 bc	6.84 ± 1.78 a	6.55 ± 1.36 ab	6.49 ± 0.99 ab	5.02 ± 1.06 cd
Aroma	6.53 ± 1.34 a	5.26 ± 1.87 b	4.94 ± 1.88 b	5.84 ± 1.93 ab	5.68 ± 1.93 ab	5.35 ± 2.00 b	5.55 ± 1.38 b	5.65 ± 1.21 ab	5.43 ± 1.18 b
Color	6.76 ± 1.41 a	5.98 ± 1.14 abcd	5.39 ± 1.45 d	6.26 ± 1.67 abc	6.44 ± 1.30 ab	6.29 ± 1.97 abc	5.76 ± 1.55 bcd	5.79 ± 0.89 bcd	5.52 ± 1.21 cd
Turbidity	5.45 ± 1.72 abc	4.97 ± 1.57 bc	4.96 ± 1.59 bc	5.78 ± 1.69 ab	6.01 ± 1.90 a	5.46 ± 2.38 abc	5.67 ± 1.67 abc	5.98 ± 1.41 a	4.60 ± 1.51 c
Carbonation	5.99 ± 1.65 a	5.77 ± 1.74 ab	5.08 ± 1.85 abcd	5.34 ± 1.90 abcd	4.89 ± 1.79 bcd	4.73 ± 1.73 d	5.69 ± 1.66 abc	5.64 ± 1.31 abcd	4.78 ± 1.21 cd
Foam	6.30 ± 1.67 a	5.70 ± 1.59 ab	5.11 ± 1.93 b	5.10 ± 1.77 b	5.05 ± 1.54 b	5.15 ± 1.24 b	5.56 ± 1.60 ab	5.67 ± 0.99 ab	5.04 ± 1.00 b
Bitterness	5.56 ± 1.47 bcd	6.08 ± 2.23 ab	6.68 ± 1.67 a	5.62 ± 1.73 bcd	5.55 ± 1.59 bcd	5.16 ± 1.40 cd	5.67 ± 1.29 bcd	5.92 ± 1.31 abc	4.98 ± 1.26 d
Sweetness	4.64 ± 1.40 ab	3.23 ± 1.68d	3.40 ± 1.67 cd	4.18 ± 1.74 bc	3.81 ± 1.67 bcd	5.10 ± 1.32 a	4.87 ± 1.38 ab	5.18 ± 1.40 a	4.13 ± 1.17 bc
Hops flavor	5.71 ± 1.49 ab	6.01 ± 1.87 a	5.46 ± 1.95 ab	5.56 ± 1.70 ab	6.15 ± 1.64 a	4.79 ± 2.01 b	5.41 ± 1.33 ab	5.36 ± 1.24 ab	5.07 ± 1.03 b
Malt flavor	5.41 ± 1.66 bc	5.86 ± 1.60 ab	5.31 ± 1.87 bc	5.63 ± 1.60 abc	5.07 ± 1.70 bc	5.17 ± 1.37 bc	5.91 ± 1.55 a	5.46 ± 0.89 bc	4.83 ± 1.06 c
Alcohol	5.02 ± 1.84 ab	5.04 ± 1.97 ab	5.10 ± 1.93 ab	5.33 ± 1.83 ab	4.94 ± 1.29 ab	5.63 ± 2.46 a	5.53 ± 1.73 ab	5.58 ± 1.49 a	4.51 ± 1.22 b

CH: Cascade hops; C: dry-hop control; R: repelletizing; 1: Mandarina Bavaria; 2: Citra; 3: Mosaic; 4: Hallertau Blanc. Different letters present in the same line significant statistical differences ($p < 0.05$).

4. Conclusions

The findings of this study demonstrate that the dry-hop residues obtained from the craft brewing can be effectively reused by subjecting the residues to a repelletization process (at room temperature). The contents of phenolic compounds, the antioxidant capacity, and α- and β-acids were significantly reduced ($p < 0.05$) in the residual hops compared to the starting hops due to the effects of the thermal process in the second brewing batch. However, the use of the residual hops for brewing generated significant sensory acceptability even surpassing the beer brewed with the starting hops, which exhibited higher bitterness values (IBUs). The use of an untrained sensory panel demonstrated that beers brewed with Mandarina Bavaria, Citra, and Mosaic hop residues have great potential for application in the brewing industry. Further studies are recommended to identify specific sensory profiles with trained panels (judges) on the beers obtained and specific treatments to optimize the residual dry-hop extraction and maximize its use. In addition, it is essential to conduct studies among consumers to evaluate the acceptability of the beers developed in this study in comparison with low bitterness beers such as Pilsen-type beers.

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Optimizing Growth and Bioactive Compound Production in Split Gill Mushroom (*Schizophyllum commune*) Using Methyl Jasmonate

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Abstract: The split gill mushroom (*Schizophyllum commune*) is a valuable natural resource with high nutritional value and diverse bioactive metabolites, underscoring its potential for sustainable applications. By applying elicitors, this study highlights the quality enhancement of *S. commune* fruiting bodies, a commercially significant resource. While elicitors have been shown to stimulate beneficial bioactive compound production, research on their use in *S. commune* remains limited. This study applied methyl jasmonate (MeJA) at various concentrations (0, 4, 13, 22, 31, and 40 μM) to optimize growth, improve nutritional value, promote triterpenoid and phenolic compound synthesis, and boost antioxidant activity in *S. commune*. The results demonstrated that MeJA's effects on growth and bioactive compounds are concentration-dependent. A concentration of 22 μM was identified as the most effective, resulting in the highest growth performance, including cap diameter (2.01 cm), fresh weight (24.10 g), and biological efficiency (15.21%). Furthermore, all MeJA treatments significantly enhanced triterpenoid, phenolic compound, and antioxidant activity compared to the control. These findings present a promising approach to enhance the sustainable use of *S. commune* as a natural resource by improving its quality and bioactive properties. Additionally, this research contributes to understanding the role of MeJA in promoting the growth and production of bioactive compounds in mushrooms, offering insights for advancing mushroom-based natural resource management.

Keywords: split gill mushroom; methyl jasmonate; triterpenoid compounds; phenolic compounds; antioxidant activity

1. Introduction

Mushrooms are an essential natural resource, widely valued for their high nutritional content and their role as a source of bioactive compounds and health-promoting nutrients. Their significant protein content and diverse nutrient profile make them an important component of global food systems. In addition to their nutritional benefits, mushrooms are recognized for their potential as sustainable sources of bioactive compounds, which offer considerable health advantages and contribute to natural resource utilization [1]. The increasing demand for mushrooms has spurred the cultivation of various species, establishing mushrooms as one of the most important agricultural resources [2]. This demand underscores their economic and ecological significance, with the global mushroom market now valued at approximately 42 billion USD annually [3]. In 2017, 2189 novel fungal species were identified, encompassing numerous substantial macrofungi, including mushrooms. The bulk of these species were classified under the phylum Ascomycota (68%, or 1481 species), followed by Basidiomycota (31%, or 684 species). To date, 1789 species of mushrooms are classified as edible, 798 as medicinal, and 561 species are recognized for their dual role as both edible and medicinal [4]. These attributes highlight the importance of mushrooms as a renewable and sustainable natural resource with broad applications in nutrition, medicine, and biotechnology.

The split gill mushroom (*Schizophyllum commune*), a globally distributed natural resource, is widely consumed in many Asian countries, including North East India, Thailand, Malaysia, Laos, and Myanmar [5,6]. It is valued both as a food source and in traditional medicine due to its rich nutritional composition, featuring high protein (24.5%) and fiber content (19.9%) along with a low-fat profile [7]. These attributes position *S. commune* as a sustainable and health-promoting resource with broad applications. Beyond its nutritional value, *S. commune* is a source of bioactive compounds such as phenolic compounds and triterpenoids. Its cell wall contains a unique polysaccharide structure of β-glucan cross-linked with chitin. The β-glucan in this mushroom, known as schizophyllan, forms a triple-helical structure and is characterized as a β-1,3-D-glucan polymer with β-1,6-D branches [8,9]. Schizophyllan is renowned for its diverse biological activities, including immune system enhancement through macrophage activation and anti-inflammatory, antioxidative, and anticancer properties, particularly in gastric, lung, and cervical carcinoma cells. It also exhibits prebiotic, antiviral, and antibacterial effects [10]. The remarkable biological properties of *S. commune* make it a valuable natural resource for multiple industries, including medicinal and pharmaceutical sectors, as well as alternative and traditional foods across Asia. These applications demonstrate the sustainable utility of *S. commune* as a renewable natural resource with the potential to address nutritional and health challenges while supporting various industrial needs [8].

Despite the popularity and economic value of *S. commune*, its production in Thailand faces several challenges that hinder its potential as a sustainable natural resource. These challenges include limited availability of natural substrate sources and an unsuitable seasonal environment for fruiting body development, resulting in low product yields, small fruiting bodies, and faster substrate degradation compared to other edible mushrooms. This leads to low biological efficiency and limits the full utilization of *S. commune* as a valuable natural resource. Therefore, there is an urgent need for the development of improved cultivation methods to enhance both the yield and quality of *S. commune*. Plant hormones, which play crucial roles in regulating various biological processes, offer a promising solution for improving mushroom production. These hormones stimulate fungal growth [11,12], induce morphogenetic changes [12,13], promote spore germination [12,14], and enhance secondary metabolism [12,15]. Methyl jasmonic acid (MeJA), a phytohormone and signaling molecule associated with plant responses to injury, is widely present in plants and has been found to influence fungal development as well. External application of MeJA induces the expression of fungal genes and enhances the activity of defense proteins, regulating enzymes that lead to the accumulation of beneficial secondary metabolites, including triterpenoids and phenolic compounds [16–20]. This study aims to explore the impact of supplementing MeJA to improve the yield, triterpenoid and phenolic contents, and antioxidant activity of *S. commune*. The findings could contribute to the management and cultivation of *S. commune*, as MeJA plays a crucial role in enhancing antioxidant activity in mushrooms by activating antioxidant enzymes, stimulating secondary metabolite production, and improving stress tolerance. Its application provides an effective strategy for increasing the nutritional and medicinal value of mushrooms, making it a valuable tool in sustainable agriculture and natural resource management.

2. Materials and Methods

2.1. Preparation of the Substrate and Cultivation of S. commune

The cultivation of *S. commune* fruiting bodies took place concurrently in Pathum Thani, Thailand, in April 2024. The substrate used for cultivation was prepared by combining 100 kg of rubberwood sawdust with 5 kg of fine bran. Lime was added in an amount sufficient to adjust the pH of the substrate to neutral. The mixture was thoroughly blended, and its moisture content was adjusted to 65–70% by adding water. For the cultivation process, 900 g of the prepared substrate was packed into mushroom-growing bags.

The substrate was sterilized in an autoclave at a temperature of 123 °C and a pressure of 15 pounds per square inch for 2 h. After sterilization, the substrate was allowed to cool to ambient temperature over a 24 h period. Once cooled, the substrate was inoculated with *S. commune* spawn. The inoculated bags were then transferred to a greenhouse with adequate ventilation, maintained at a temperature of 25 °C and a relative humidity of 85%, to promote the colonization of *S. commune* mycelium.

2.2. Analysis of the Physical Properties and Nutrient Content of a Mushroom Cultivation Substrate

The physical characteristics and nutrient composition of the substrate were assessed prior to the cultivation of *S. commune*. To prepare the substrate for analysis, it was oven-dried at 60 °C for 48 h and then passed through a 2 mm sieve to evaluate the specific physical properties of the substrate. The pH and electrical conductivity of each substrate sample were measured in water at a 1:10 weight-to-volume (w/v) ratio. A PC950 pH meter (Apera Instrument, Columbus, OH, USA) was used to determine pH, while electrical conductivity measurements were conducted using a Eutech CON 2700 conductivity meter (Thermo Fisher Scientific, Waltham, MA, USA). The organic carbon (OC) content was determined with a CHNS/O Analyzer (628 series) from Leco Corporation, St. Joseph, MI, USA. Organic matter (OM) was estimated by multiplying the organic carbon value by 1.724, and the carbon-to-nitrogen (C/N) ratio was calculated by dividing the organic carbon content by the nitrogen content.

The nutrient composition, including total nitrogen, phosphorus, and potassium, was analyzed following the method outlined by Thepsilvisut et al. [21]. Total nitrogen in the mushroom cultivation substrates was measured using a CHNS/O Analyzer, an elemental analyzer. Phosphorus content was determined using a UV Spectrophotometer (UV-1280, Shimadzu, Japan) at a wavelength of 420 nm, while potassium levels were evaluated with flame atomic absorption spectroscopy with a Thermo Scientific iCE™ 3400 (Waltham, MA, USA).

2.3. Determination of Growth and Yield of S. commune Using MeJA

In the cultivation process of *S. commune*, six MeJA treatments were injected, which included 0 (control), 4, 13, 22, 31, and 40 µM. For each treatment, 120 mL of MeJA was injected into each bag, divided into four applications, with each application using 30 mL per bag. When the fruiting body opening stage was reached, the prepared MeJA solution was injected using a syringe. The solution was injected above the slits (each bag had three slits for fruiting body opening, as shown in Figure 1), with 10 mL per slit. The solution was administered in the morning (08:00–09:00) for 4 consecutive days, once daily, on alternate days, and then they were left for 10 days. Following the final application, bags were left undisturbed for 10 days until the first generation of mushrooms was ready for harvest.

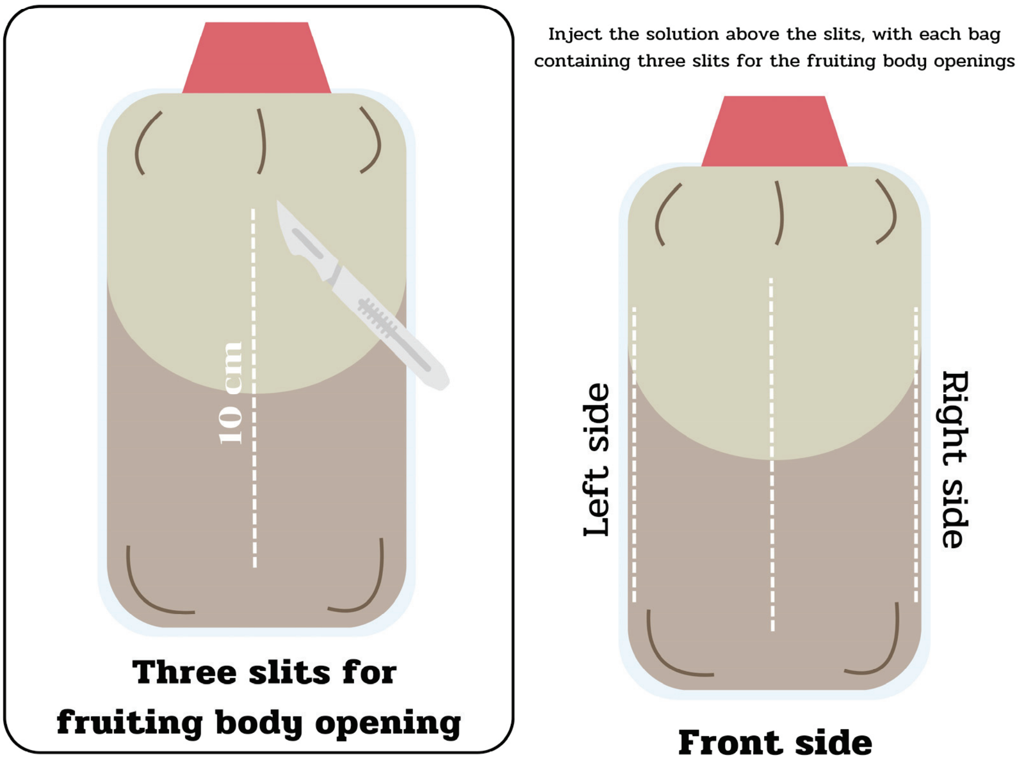

Figure 1. Characteristics of the fruiting body cultivation of the *S. commune* by cutting the bag into 3 compartments, 10 cm each.

After the harvest period, the initial batch of mushroom yield was collected in a single harvest. The harvested mushrooms were evaluated based on the following parameters: fruiting body density, cap diameter (in cm), fresh weight (in grams), and dry weight (in grams). To measure the cap diameter, 10 fruiting bodies were randomly selected, and their diameters were determined using a vernier caliper. The average value of these measurements was recorded. The biological efficiency (%BE) was calculated using the following formula:

$$\text{Biological efficiency } (\%\text{BE}) = \frac{\text{Fresh fruiting body weight (g)}}{\text{Dry weight of substrate (g)}} \times 100 \quad (1)$$

Biological efficiency refers to the ability of mushrooms to extract nutrients from the substrate to produce the biomass of the fruiting bodies. This efficiency is expressed as the ratio of the fresh fruiting body weight to the dry weight of the substrate, presented as a percentage [22].

2.4. Analysis of Mineral Content and Proximate Composition of the S. commune Fruiting Bodies

2.4.1. Sample Preparation

The fresh fruiting bodies of *S. commune* were dried in an oven at 60 °C for 48 h. Once dried, the samples were ground into a fine powder using a commercial blender to facilitate the analysis of their nutritional composition. The analysis included determining the moisture content, crude protein, crude fat, crude fiber, ash, total carbohydrates, and energy content. The results will be reported as percentages based on dry weight, with energy values expressed in kilocalories (kcal). All assessments were carried out following the methods specified by AOAC [23].

2.4.2. Mineral Analysis

The mineral content of the powdered dried fruiting body of *S. commune* was analyzed, including total nitrogen, phosphorus, potassium, calcium, magnesium, and zinc. Total nitrogen in the mushroom cultivation substrates was measured using a CHNS/O Analyzer, an elemental analyzer. The total phosphorus content was measured calorimetrically at 820 nm using a UV Spectrophotometer with the vanadomolybdate method [23]. The analysis of potassium, magnesium, calcium, and zinc was conducted using flame atomic absorption spectroscopy with a Thermo Scientific iCE™ 3400.

2.4.3. Moisture Content

Approximately 1.0 g of the dried mushroom powder sample, as described in Section 2.4.1., was placed into the crucible for drying. After that, it was dried in an oven at 120 °C for 3 h [1], and then transferred into a desiccator. The dish containing the dried sample was then reweighed, and the heating and cooling process was repeated until a constant weight was obtained. The moisture content was calculated using the following equation:

$$\text{Moisture (\%)} = \frac{\text{weight lost (g)}}{\text{weight of sample}} \times 100 \tag{2}$$

2.4.4. Crude Protein Content

The Kjeldahl method was used to calculate the crude protein. Ground samples of the *S. commune* weighing 0.5 g were digested in a Kjeldahl flask with 98% sulfuric acid, followed by steam distillation. The titration of the resulting distillate was carried out using 0.1 N sulfuric acid, and the protein percentage was then determined using the provided formula.

$$\text{Crude protein content (\%)} = \frac{(\text{A} - \text{B}) \times \text{N} \times 1.4007 \times 5.71}{\text{weight of sample}} \tag{3}$$

where

A = the amount of sulfuric acid used to titrate a sample;
B = the amount of sulfuric acid used to titrate a blank;
N = normality (0.1) of sulfuric acid.

2.4.5. Crude Fat Content

The crude fat content was determined using an automatic extraction system (AnkomXT 15 extractor). A 1.0 g sample of finely ground mushroom was placed in the extractor, and petroleum ether (boiling point of 35–65 °C) was added. The extraction process lasted for 1–2 h, after which the ether was evaporated until the flask was dry. The fat content was calculated by measuring the difference in weight of the flask before and after the evaporation of the ether. The fat percentage was then determined using the following formula:

$$\text{Crude fat content (\%)} = \frac{\text{W1} - \text{W2}}{\text{weight of sample}} \times 100 \tag{4}$$

where

W1 = sample weight with filter bag XT4;
W2 = sample weight with filter bag after extraction.

2.4.6. Crude Fiber Content

The crude fiber content was determined using the ANKOM Delta system. The procedure involved boiling a precise amount of air-dried powdered sample with sulfuric acid, followed by rinsing with water to remove the acidity. The residue was then boiled with potassium hydroxide (KOH) and rinsed with water to remove the alkalinity. The insoluble residue was dried at 120 °C, weighed, and then burned at 550 °C until only ash remained. The crude fiber content was calculated using a specific formula:

$$\text{Crude fiber content (\%)} = \frac{(\text{W2} - (\text{W1} \times \text{C1}))}{\text{weight of sample}} \times 100 \quad (5)$$

where

W1 = weight of the filter bag;
W2 = total weight of the fiber and filter bag;
C1 = weight after burning divided by the weight of the empty filter bag before extraction.

2.4.7. Ash Content

The ash content was determined by placing approximately 1 g of mushroom sample in a crucible and heating it at 550 °C for 4 h in a muffle furnace (CARBOLITE, ELF models, Hope Valley, UK). After the ashing process, the crucible was allowed to cool in a desiccator. The weight of the crucible before and after ashing was compared to calculate the ash content using the following formula:

$$\text{Ash content (\%)} = \frac{\text{W1} - \text{W2}}{\text{weight of sample}} \times 100 \quad (6)$$

where

W1 = weight of the sample after burning;
W2 = weight of the crucible.

2.4.8. Total Carbohydrate

The content of the available carbohydrates was calculated using the following formula:

$$\text{Total carbohydrates (\%)} = 100 - (\text{\%moisture} + \text{\%protein} + \text{\%fat} + \text{\%ash} + \text{\%fiber}) \quad (7)$$

2.4.9. Energy Values

The energy values of the mushroom samples were calculated using the following formula:

$$\text{Energy (kcal)} = (\text{Protein (g)} \times 4) + (\text{Fat (g)} \times 9) + (\text{Carbohydrates (g)} \times 4) \quad (8)$$

2.5. Measurement of Bioactive Compounds and Antioxidant Activity

2.5.1. Preparation of *S. commune* Extract

The ethanol extraction process was conducted following the method outlined by Chutimanukul et al. [24]. The *S. commune* fruiting bodies were first dried in an oven at 60 °C for 48 h. After drying, the fruiting bodies were ground into a fine powder and stored in sealed containers until further analysis. To perform the extraction, 5 g of powdered mushroom was mixed with 50 mL of 95% ethanol (*w*/*v*) and homogenized at room temperature. The mixture was then filtered using Whatman® Grade 1 qualitative filter paper. The maceration and extraction process was repeated every 3 days over a total period of 9 days. Following the extraction, the ethanol-containing extract was concentrated and dried under a vacuum using a Rotavapor® R-300 (BUCHI, Flawil, Switzerland).

2.5.2. Determination of the Total Triterpenoid Content Analyses of *S. commune* Extracts

The total triterpenoid content in *S. commune* extracts was measured using a modified method based on the procedure by Chutimanukul et al. [24]. A 300 μL sample of the extract was placed in a centrifuge tube, to which 50 μL of a vanillin–acetic acid solution (5 mg/mL) and 800 μL of 70% perchloric acid were added. The mixture was incubated for 15 min at 60 °C in a water bath and then cooled in an ice bath. Following this, 5 mL of acetic acid was added, and the mixture was allowed to sit undisturbed for 15 min at room temperature. The absorbance at 548 nm was measured using a Multiskan GO microplate reader (Thermo Scientific, Waltham, MA, USA), with the blank solution used as a reference. The triterpenoid content was determined by converting the absorbance values into mg of Ursolic acid equivalents (mg Urs/g DW).

2.5.3. Determination of the Total Phenolic Content of *S. commune* Extracts

The total phenolic content of *S. commune* extracts was determined using a modified Folin–Ciocalteu method [25], based on adjustments by Rahimah et al. [26]. The ethanol extract stock solution was prepared by dissolving the extract in absolute ethanol. For the assay, 20 μL of the extract was combined with 100 μL of Folin–Ciocalteu's reagent (diluted 1:10) and 80 μL of 7.5% sodium carbonate. The mixture was incubated for 30 min, after which the absorbance was measured at 765 nm using a microplate reader. The total phenolic content was quantified by converting the absorbance readings into mg of Gallic acid equivalents (mg GAE) per g of DW (mg GAE/g DW).

2.5.4. DPPH Radical Scavenging Activity

The antioxidant activity of *S. commune* extracts was evaluated using their ability to scavenge 2,2-diphenyl-1-picrylhydrazyl (DPPH) radicals, following a method adapted from Soares et al. [27]. Extracts of *S. commune* were dissolved in absolute ethanol to prepare concentrations of 1, 2, 3, 4, and 5 mg/mL. A 100 μL aliquot of each sample was mixed with 100 μL of a 6×10^{-5} M DPPH solution in a 96-well microplate. The mixture was incubated in the dark at room temperature for 30 min to prevent light interference. The absorbance was measured at 520 nm using a microplate reader. The percentage of DPPH inhibition was calculated using the following formula:

$$\text{Inhibition}(\%) = \frac{\text{Acontrol} - \text{Asample}}{\text{Acontrol}} \times 100 \tag{9}$$

where

$A_{control}$ is the absorbance of the DPPH solution;
A_{sample} is the absorbance of the solution containing the sample.

The antioxidant activity from the DPPH radical scavenging assay was expressed as the IC_{50} value, which is the concentration of the extract required to scavenge 50% of the DPPH radicals. Butylated hydroxytoluene (BHT) was used as the positive control, while the negative control consisted of samples without mushroom extract. The IC_{50} values were reported in milligrams per milliliter (mg/mL).

2.6. Statistical Analysis

The experiment was conducted using a completely randomized design (CRD) with five replicates for each treatment. Each replicate consisted of 10 mycelium bags, and all experiments were performed simultaneously. The experimental data were analyzed using a one-way analysis of variance (ANOVA), followed by Duncan's multiple range test to compare means. Statistical significance was determined when the *p*-value was less than 0.05. All statistical analyses were performed using IBM SPSS Statistics 21.

3. Results and Discussion

3.1. Physical Properties and Nutrient Content of S. commune Substrate Cultivation Were Studied

In the experiment, the *S. commune* was grown on a substrate with a pH value of 5.94, which displayed specific physical and chemical characteristics. The pH of the substrate plays a crucial role before spawning, influencing the substrate's ionic state and the structure, appearance, and biological functions of fungal cells. This, in turn, affects the absorption of nutrients and their synthesis [24,28]. According to the report by Imtiaj et al. [29], the optimal pH range for mushroom cultivation is between 5 and 9, which is favorable for mycelium proliferation. The substrate's electrical conductivity (EC) was found to be 1.39 dS m^{-1}, with the optimal range for mycelium growth and the development of mushrooms being 0.87 to 1.98 dS m^{-1} [30]. Additionally, the organic carbon content and organic matter content of the substrate were 25.09% and 43.25%, respectively (Table 1). The carbon sources derived from sawdust, such as cellulose and hemicellulose, are complex carbohydrates that need microbial activity to degrade into simpler compounds. Subsequently, the mushroom mycelium uses organic carbon and organic matter to generate fresh microbial cells in the fermentation process, which in turn releases vital nutrients to support mushroom growth [24].

Table 1. Chemical properties and nutrients of *S. commune* substrate used in this study.

Components of the Substrate	Contents
pH	6.94 ± 0.75
EC (dS m^{-1})	1.39 ± 1.54
Organic carbon (%)	25.09 ± 1.99
Organic matter (%)	43.25 ± 0.87
Total nitrogen (%)	0.60 ± 2.54
Total phosphorus (%)	0.02 ± 1.73
Total potassium (%)	0.01 ± 1.94
C/N ratio	41.72 ± 1.85

The data are presented as mean ± standard deviation (SD) (n = 5).

The examination of the substrate's nutrients indicated that nitrogen is a crucial element for the efficient growth of *S. commune*, with a concentration of 0.60%. Before spawning, the substrate contained 0.02% total phosphorus and 0.01% total potassium. Although present in smaller amounts, phosphorus and potassium contribute to the development of mushroom mycelium and support normal physiological processes [1]. This ratio is critical as it influences nutrient utilization from the substrate and directly affects the growth and development of the mushroom mycelium. Therefore, it is vital to establish a balanced nitrogen and carbon ratio to maintain an optimal C/N ratio between 35 and 55 for successful mushroom cultivation [31].

3.2. Study on Growth and Yield of S. commune

Mushrooms provide numerous nutritional benefits that make them a valuable component of natural resources, offering a sustainable source of essential nutrients, bioactive compounds, and health-promoting properties. As natural resources, mushrooms contribute significantly to human health, agricultural sustainability, and the broader ecosystem. The development of *S. commune* showed that the growth substrate plays a crucial role in supplying necessary nutrients for mushroom growth and development. Adding MeJA to the substrate improves the ability of the mushroom to break down complex organic compounds by releasing enzymes, enabling the mycelia to absorb smaller nutrients. This process effectively stimulates the growth and productivity of *S. commune*. The study found that the application of MeJA at concentrations of 22 and 31 μM resulted in an increased density of *S. commune* fruiting bodies around the slits, leading to a high density (+++) of mushrooms in these slits. Furthermore, the application of MeJA at concentrations of 3 and 40 μM resulted in a medium density (++) of mushrooms around the slits, while the control treatment showed a low density (+) of mushrooms around the slits (Figure 2). In addition, the use of MeJA at a 22 μM concentration led to an increased diameter of the *S. commune* cap compared to the control treatment. Upon measuring the cap diameter, it was determined that the average cap diameter with MeJA treatment at 22 μM was 2.01 cm. In contrast, the control treatment resulted in an average cap diameter of 1.65 cm (Table 2). This difference may be attributed to methyl jasmonate (MeJA), a natural plant growth regulator that plays an important role in various physiological processes, including the development of *S. commune* mycelium, which ultimately forms the fruiting bodies. Mushroom mycelium can facilitate the transport of phytohormones like MeJA through phytohormone receptors. According to Hérivaux et al. [32], studies on fungal phytohormone receptors have identified fungal histidine kinases that exhibit similarities to plant hormone receptors. These fungal receptors respond to MeJA by inducing changes in growth patterns. Phytohormones are known to significantly influence mushroom growth, and recent research highlights the role of MeJA in regulating biosynthetic and metabolic processes [33]. MeJA's mechanism of action in mushroom development involves a cascade of biochemical and molecular events that modulate physiological processes such as growth, development, secondary metabolite synthesis, and stress responses.

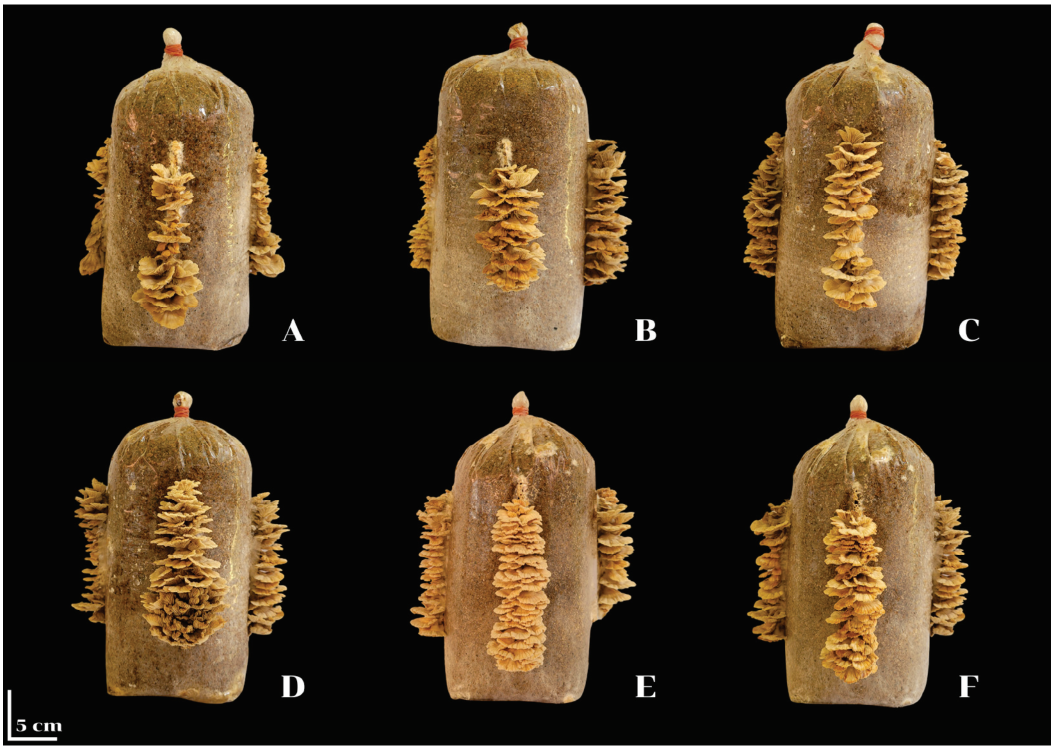

Figure 2. The densities of the fruiting bodies of *S. commune:* (**A**) 0 μM (control), (**B**) 4 μM, (**C**) 13 μM, (**D**) 22 μM, (**E**) 31 μM, and (**F**) 40 μM. The fruiting body density is categorized; + is low density, ++ is medium density, and +++ is high density.

Table 2. The growth and yield of the *S. commune* were evaluated under the influence of various concentrations of MeJA.

Concentration of MeJA (μM)	Cap Diameter (cm)	Fresh Mushroom Weight (g)	Dry Mushroom Weight (g)	Biological Efficiency (%)
0 (control)	1.65 ± 0.23 ^{b}	15.30 ± 2.71 ^{bc}	5.63 ± 0.75	6.59 ± 1.73 ^{d}
4	1.46 ± 0.07 ^{b}	16.62 ± 2.68 ^{bc}	5.78 ± 0.80	10.05 ± 1.01 ^{bc}
13	1.53 ± 0.12 ^{b}	14.95 ± 3.48 ^{bc}	5.66 ± 0.78	11.25 ± 1.20 ^{b}
22	2.01 ± 0.20 ^{a}	24.10 ± 4.99 ^{a}	7.44 ± 1.49	15.21 ± 1.52 ^{a}
31	1.76 ± 0.24 ^{ab}	19.88 ± 3.10 ^{ab}	7.02 ± 1.92	12.04 ± 1.47 ^{b}
40	1.58 ± 0.09 ^{b}	13.81 ± 0.88 ^{c}	5.67 ± 0.57	8.12 ± 0.67 ^{cd}
F-test	*	**	ns	**
C.V.%	11.88	22.19	13.07	12.88

The data are presented as mean ± standard deviation (SD) ($n = 5$). Distinct letters within the same column indicate significant differences between treatments, as determined by Duncan's multiple range test (DMRT) at $p < 0.05$. Asterisks (** and *) indicate significant differences at $p < 0.01$ and $p < 0.05$, respectively, while "ns" denotes no significant differences.

The results of the application of MeJA on *S. commune* yield indicate that adding MeJA to the substrate increased the yield compared to the control treatment. When MeJA was added to the substrate, it enhanced the yield performance of the *S. commune* fruiting body. For mushroom production, the application of 22 μM MeJA resulted in the highest fresh weight, with the *S. commune* reaching 18.79 g. The dry weight, which represents the organic mass of the mushrooms after complete dehydration, is also correlated with the fresh weight. MeJA concentrations ranging from 4 to 40 μM produced a dry weight between 5.66 and 7.44 g. Additionally, the biological efficiency of the *S. commune* varied significantly with different concentrations of MeJA. The highest biological efficiency of 15.21% was observed at a 22 μM concentration, whereas the control treatment showed the lowest biological efficiency at 6.59% (Table 2). Biological efficiency serves as an important indicator of substrate conversion effectiveness in mushroom cultivation. It is calculated as the ratio of the fresh weight of harvested mushrooms to the dry weight of the cultivation substrate. A higher BE value signifies more efficient utilization of the substrate for mushroom growth and development [34]. In this study, it was found that using MeJA resulted in a higher biological efficiency for *S. commune* compared to the control treatment. However, the biological efficiency in the result may be slightly lower than that in general production. Nonetheless, these findings indicate that MeJA effectively stimulates growth, thereby enhancing both the yield and biological efficiency of *S. commune*. Additionally, MeJA plays a role in regulating vital activities such as cell division and meristem formation, which influence the growth of the *S. commune*. The experimental findings are in line with the notion that the presence of MeJA could be another significant element influencing growth and productivity. The study provides evidence that MeJA has a crucial impact on the structural changes in fungi by stimulating the formation of tissues and the division of cells. This stimulation of mycelial growth leads to the development of fruiting bodies [1]. Thus, the application of MeJA and its effect on stimulating phytohormone production within the mushroom mycelium is a key factor in regulating various developmental processes in mushrooms, contributing to the sustainable cultivation and optimization of *S. commune* as a renewable natural resource.

3.3. Mineral Content and Proximate Composition of the Fruiting Body of S. commune

3.3.1. Analysis of Mineral Content of the *S. commune*

The mineral content in the powdered dried fruiting body of *S. commune* treated with varying concentrations of MeJA was analyzed. Specifically, the study focuses on total nitrogen, phosphorus, and potassium, measured as percentages, to assess the influence of MeJA on the mineral content of the *S. commune*. Treatments were applied at MeJA concentrations of 0, 4, 13, 22, 31, and 40 μM. The results reveal that total nitrogen content ranged between 3.43% and 4.47%, with the highest value observed at 4 μM MeJA. Total phosphorus was recorded between 0.06% and 0.12%, while total potassium ranged from 0.98% to 1.24%. Furthermore, the treatment with MeJA led to *S. commune* containing calcium, magnesium, and zinc in the ranges of 0.08 to 0.09%, 0.06 to 0.08%, and 0.010 to 0.014%, respectively (Figure 3 and Table S1). The experimental results are consistent with the findings of Singh et al. [7]. Their study reported that the mineral content of *S. commune* collected from the wild consisted of nitrogen, phosphorus, and potassium at levels of 3.25%, 0.79%, and 1.12%, respectively. However, the mineral content in mushrooms largely depends on the composition of the growth substrate. Mushrooms absorb minerals through their mycelium from the substrate, so altering external factors like MeJA application may not impact this process if the substrate's mineral content remains unchanged [35]. Also, MeJA is known for modulating secondary metabolite production and stress response rather than directly affecting the absorption or assimilation of minerals. If MeJA is applied at a stage when mineral uptake has already stabilized or completed, it may have no observable impact on mineral content.

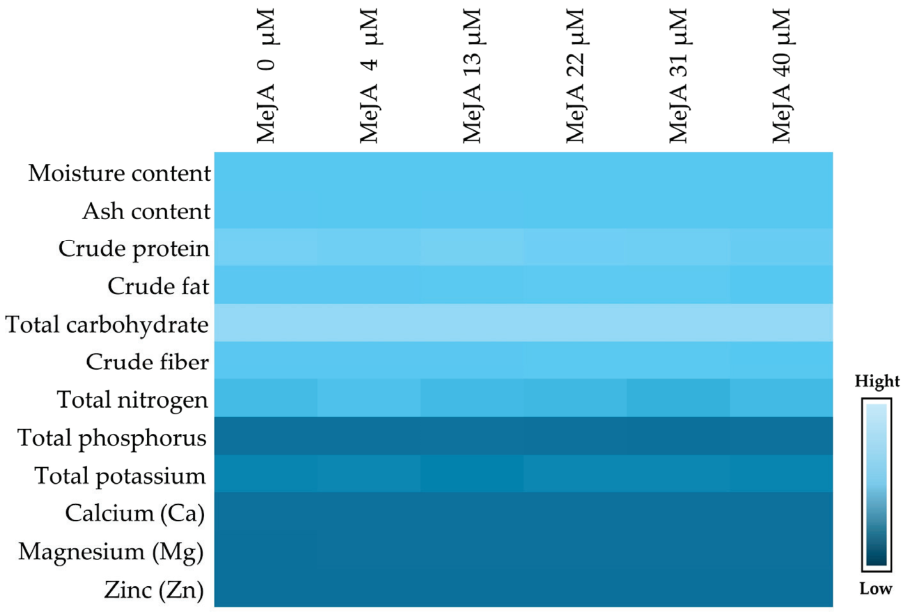

Figure 3. This heat map illustrates the proximate composition and mineral content of *S. commune* after the exogenous application of MeJA at varying concentrations. The color gradient denotes the relative values, with light shades representing higher concentrations of the respective components.

3.3.2. Analysis of Proximate Composition of the *S. commune*

The *S. commune* studied showed moisture contents ranging from 5.28% to 6.06% after MeJA application, with no statistically significant differences. This suggests that the application of MeJA, a growth regulator known to influence cell proliferation and differentiation, does not have any impact on the moisture content of *S. commune*. The ash content of *S. commune* was not significantly different, with the MeJA application showing ash contents ranging from 6.36% to 7.02% at concentrations of 4 to 40 μM. From the above experimental results, it is concluded that ash content is primarily a measure of the total mineral content in a sample after the organic material has been burned off. As mineral content in mushrooms is largely determined by the nutrients in the growth substrate, external application of MeJA is unlikely to impact it unless it alters substrate properties or nutrient uptake [35]. In summary, ash content is a reflection of the inherent mineral composition of the substrate and the mushroom's ability to assimilate these minerals. Since MeJA does not alter the substrate's mineral content or the mycelium's absorption process, it has little to no impact on the ash content of mushrooms [36]. In addition, the use of MeJA also affected the crude protein content of *S. commune*. The application of MeJA at a concentration of 13 μM resulted in the highest crude protein content of *S. commune*, equal to 25.54%, whereas the control treatment yielded a protein content of 23.76%, according to the report of Singh et al. [7] it was found that *S. commune* had a crude protein content of 24.51%, which was similar to what was analyzed. In the same way, *S. commune* crude fat levels, following exposure to MeJA concentrations from 4 to 31 μM, exhibited fat percentages ranging from 7.37% to 7.92%. Meanwhile, the application of 40 μM of MeJA resulted in the fat content being reduced to 5.97% (Figure 3 and Table S2). The production of proteins and fats in *S. commune* was suppressed due to MeJA's significant involvement in the breakdown of organic material by microorganisms. As previously reported by Chutimanukul et al. [1], the decomposition process breaks down organic matter into smaller molecules that cells use as energy and nitrogen sources for synthesizing proteins and fats. The study highlighted that phytohormones act as signaling molecules, transmitting information about environmental factors to the cell genome, thereby activating pathways involved in protein and fat synthesis [37]. Therefore, the application of higher concentrations of MeJA appears to interfere with cellular signaling pathways, potentially disrupting the normal regulatory mechanisms involved in protein and fat synthesis. This inhibition may alter key molecular processes, including gene expression and enzyme activity, which are critical for maintaining the balance of metabolic systems. As a result, the synthesis of proteins and lipids may be negatively affected, leading to changes in the biochemical composition and overall metabolic response of the organism. These findings suggest that while MeJA can serve as an elicitor, excessive concentrations may trigger stress responses that hinder its beneficial effects on metabolic pathways.

Interestingly, carbohydrates were the most abundant macronutrient resulting from MeJA applications at 4 to 40 μM concentrations, resulting in *S. commune* having the highest levels with applications between 47.11 and 56.03%. The *S. commune* carbohydrate content aligns with its protein and ash content. During the inoculated mushroom process, the degradation of carbohydrates is caused by the crude protein and ash content. This research revealed that the application of MeJA causes a decrease in the amount of protein and ash in *S. commune*, which results in an increased accumulation of carbohydrates. However, the experimental results showed that the application of MeJA did not affect the increase in the crude fiber and energy contents of *S. commune*, which ranged from 6.35 to 7.51% and 344.75 to 365.53 kcal, respectively (Figure 3 and Table S2). The energy content of *S. commune* is determined by its energy-yielding components, including carbohydrates, fats, and proteins. These macronutrients serve as the primary contributors to the mushroom's overall energy value. When combined, these elements determine the overall nutritional energy value of the mushrooms. The findings of this study are unique because this is the first time that the effects of MeJA on the nutritional composition of *S. commune* have been investigated, to the best of our knowledge. The results challenge the existing literature, offering new insights into how MeJA influences the nutritional profile of this mushroom species.

3.4. Measurement of Bioactive Compounds and Antioxidant Activity of *S. commune*

Mushrooms, as natural resources, provide a wealth of bioactive compounds that contribute significantly to human health and the environment. These compounds are often responsible for the medicinal, nutritional, and ecological benefits of mushrooms. The presence of bioactive compounds in mushrooms enhances their value as renewable natural resources, supporting both sustainable agriculture and therapeutic applications.

3.4.1. Total Triterpenoid Content

The total triterpenoid content in *S. commune* was analyzed to examine the effect of MeJA on triterpenoid biosynthesis. Different MeJA concentrations were tested, revealing a significant increase in total triterpenoid content with MeJA treatment. The highest triterpenoid levels, ranging from 66.40 to 78.27 mg Urs/g DW, were observed at MeJA concentrations between 22 and 40 μM. In contrast, the control treatments showed a triterpenoid content of 47.51 mg Urs/g DW (Figure 4 and Table S2). These findings highlight a significant difference in triterpenoid levels between treated and control groups, indicating that MeJA effectively stimulates triterpenoid biosynthesis. Previous studies have demonstrated the physiological impacts of MeJA as a plant hormone on *S. commune*. Hypotheses suggest potential trade-offs in secondary metabolite synthesis, as supported by research from Xu et al. [38], which showed a 53.6% increase in triterpenoid production in *Inonotus obliquus* upon MeJA treatment. Similarly, Ren et al. [12] reported that MeJA significantly enhanced ganoderic acid production in *Ganoderma lucidum*. This aligns with findings from Meng et al. [39], which demonstrate that MeJA, as a naturally occurring plant growth regulator and inductor of gene expression, is involved in the biosynthesis of secondary metabolites. Additionally, the presence of phytohormone receptors in fungi, such as fungal histidine kinases, enables the effective stimulation of secondary metabolite biosynthesis through phytohormones like MeJA for mushroom cultivation [40]. These results provide valuable insights into the role of MeJA as a phytohormone in enhancing the production of bioactive compounds, such as triterpenoids, in *S. commune*.

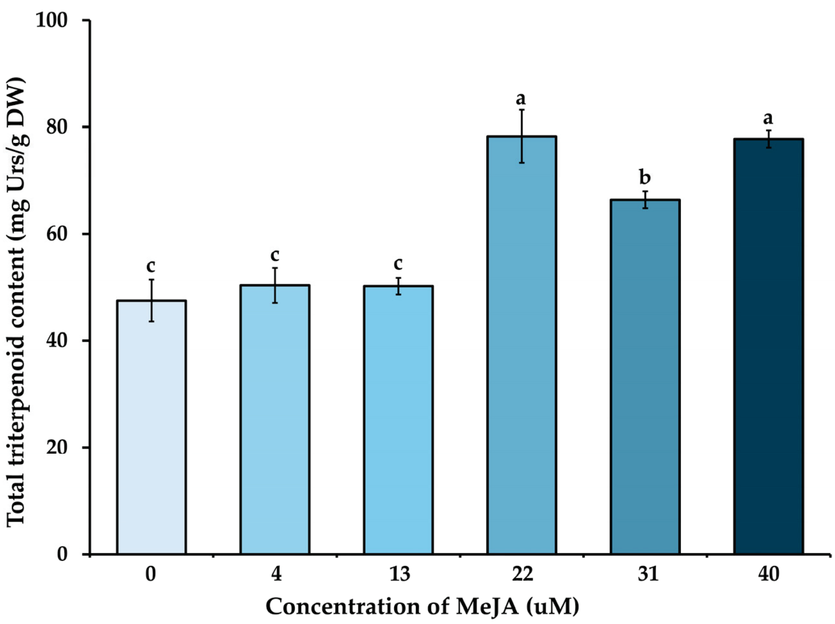

Figure 4. The total triterpenoid content in *S. commune* was assessed following the exogenous application of MeJA at varying concentrations. The findings, presented as mean values with standard deviations ($n = 5$), revealed statistically significant differences among treatments. These differences are denoted by distinct letters displayed above the bars, determined using Duncan's multiple range test at a significance level of ($p < 0.05$).

This finding is significant for the sustainable utilization of *S. commune* as a natural resource, as it highlights the potential to optimize the production of valuable bioactive metabolites through controlled cultivation practices. MeJA is a well-known plant hormone that is involved in plant stress responses and secondary metabolite production. When applied to mushroom cultures, MeJA can significantly increase the production of triterpenoids. In addition, MeJA is one of the most studied plant hormones in mushroom cultivation due to its ability to increase the production of triterpenoids and other secondary metabolites. MeJA is known to regulate gene expression and stimulate defense-related enzymes in fungi, leading to enhanced secondary metabolite production [41]. In mushrooms such as *G. lucidum* (reishi) and *Lentinula edodes* (shiitake), the application of MeJA has been shown to boost triterpenoid content significantly [42].

3.4.2. Total Phenolic Content

To examine the impact of MeJA on the biosynthesis of phenolic compounds in *S. commune*, the total phenolic content was analyzed following treatment with varying concentrations of MeJA. The results demonstrated a notable increase in total phenolic content after the MeJA application. Specifically, MeJA concentrations ranging from 4 to 40 μM enhanced phenolic compound synthesis, resulting in total phenolic contents ranging from 15.86 to 20.04 mg GAE/g DW, compared to 13.81 mg GAE/g DW in the control group (Table 3). These findings indicate that MeJA serves as an effective elicitor for enhancing the production of bioactive compounds in *S. commune*. As a plant hormone and signaling molecule, MeJA primarily facilitates plant defense responses to various biotic and abiotic stressors. When applied to fungi, including mushrooms, MeJA acts as an elicitor by activating pathways that promote growth and increase the synthesis of bioactive compounds such as phenolics and triterpenoids. This aligns with the findings of Lin et al. [43] that demonstrate the application of MeJA to enhance the production of bioactive components in the fruit body of *Cordyceps militaris*. Results showed that the effect of MeJA could increase the content of polyphenol. The phenylpropanoid pathway in fungi is typically responsible for producing secondary metabolites as a defense mechanism against environmental stimuli [44–46]. Signal molecules activate this pathway, triggering cellular defense mechanisms at the plasma membrane, which then initiate the transcription of defense-related genes [46,47]. This process leads to the accumulation of secondary metabolites through oxidative catabolism during fungal interactions or elicitor treatments [16,46]. Furthermore, Dai et al. [20] found that MeJA supplementation significantly increased secondary metabolite production, such as ergosterol, in *Hericium erinaceus*. This increase was associated with elevated enzyme activities and related defense proteins. MeJA application also stimulated the production of other secondary metabolites, such as alkaloids and phenolic acids, and regulated the release of volatile signaling compounds [48].

MeJA is involved in regulating gene expression in fungi by activating specific signaling pathways. MeJA binds to receptors in the cell membrane or cytoplasm, leading to the activation of jasmonic acid (JA) responsive transcription factors. These transcription factors then initiate the expression of genes that regulate the production of secondary metabolites and other growth-related factors [49]. One of the most significant effects of MeJA on mushroom growth is its role in the induction of secondary metabolites. In many mushrooms, including medicinal species like *G. lucidum* and *L. edodes*, MeJA stimulates the synthesis of bioactive compounds such as triterpenoids, phenolics, and polysaccharides (e.g., β-glucans). These metabolites play crucial roles in the medicinal properties of mushrooms, including antioxidant, anticancer, and anti-inflammatory activities. MeJA enhances the production of these compounds by activating biosynthetic enzymes involved in their pathways [42].

Table 3. The total phenolic content and antioxidant activity of *S. commune* were evaluated across various concentrations of MeJA treatment.

Concentration of MeJA (μM)	Total Phenolic Content (mg GAE/g DW)	Antioxidant Activity (IC_{50}, mg/mL)
0	13.81 ± 1.15^{d}	3.50 ± 0.58^{b}
4	15.86 ± 1.33^{c}	2.93 ± 0.07^{a}
13	16.09 ± 0.59^{c}	2.89 ± 0.12^{a}
22	17.18 ± 0.53^{bc}	2.67 ± 0.03^{a}
31	18.56 ± 0.50^{ab}	2.70 ± 0.09^{a}
40	20.04 ± 1.20^{a}	2.70 ± 0.20^{a}
F-test	**	*
C.V.%	5.35	5.83

The data are presented as mean ± standard deviation (SD) ($n = 5$). Distinct letters within the same column indicate significant differences between treatments, as determined by Duncan's multiple range test (DMRT) at $p < 0.05$. Asterisks (** and *) indicate significant differences at $p < 0.01$ and $p < 0.05$, respectively.

3.4.3. Antioxidant Activity

The DPPH radical scavenging ability of *S. commune* extracts was assessed, and the results were compared to the standardized antioxidant butylated hydroxytoluene (BHT), which exhibited an IC_{50} value of 13.33 ± 0.89 μg/mL. The assays, conducted in methanol, presented the findings as IC_{50} values, which indicate the concentration of antioxidants required to reduce the initial DPPH concentration by 50%. Generally, lower IC_{50} values correspond to stronger antioxidant properties. The results revealed that the DPPH radical scavenging ability of *S. commune* extracts treated with MeJA was significantly higher compared to the control treatment. MeJA treatments at concentrations ranging from 4 to 40 μM exhibited the strongest antioxidant activity, with IC_{50} values ranging from 2.70 to 2.93 mg/mL. In contrast, the control treatment demonstrated a higher IC_{50} value of 3.50 mg/mL, indicating lower antioxidant activity (Table 3). The improved antioxidant activity in MeJA-treated extracts is likely due to the stimulatory effects of MeJA on phenolic compound synthesis in *S. commune*. The control treatment displayed reduced antioxidant activity, which could be attributed to limited phenolic compound production. This aligns with findings by Yuan et al. [46], which reported that total polyphenols from *Sanghuangporus vaninii* cultured with MeJA supplementation exhibited strong free radical scavenging capacities. Similarly, Zeng et al. [50] found that MeJA treatment enhanced the ability of *Flammulina velutipes* to scavenge reactive oxygen species. Furthermore, phenolic compounds are well documented for their direct relationship with antioxidant activity and other biological functions [51–53]. The data from this study support the hypothesis that the application of exogenous MeJA stimulates the production of secondary metabolites, such as phenolic compounds, thereby enhancing the antioxidant activity of *S. commune*.

The mechanism of action of MeJA on antioxidant activity in mushrooms and other organisms involves activating signaling pathways that stimulate the production of antioxidant enzymes and secondary metabolites with antioxidant properties. This process enhances the organism's ability to neutralize reactive oxygen species (ROS) and protect against oxidative damage. MeJA functions as an elicitor, triggering antioxidant defense mechanisms in mushrooms by upregulating genes responsible for the synthesis of key antioxidant enzymes. These include Superoxide Dismutase (SOD), Catalase (CAT), and Glutathione Peroxidase (GPX), which collectively play a vital role in mitigating oxidative stress. They achieve this by scavenging free radicals and maintaining the cellular redox balance [54]. Additionally, MeJA stimulates the biosynthesis of secondary metabolites, such as phenolic compounds, flavonoids, and triterpenoids, all of which exhibit potent antioxidant properties [42].

4. Conclusions

This study revealed the effects of elicitors on the production of bioactive compounds in *S. commune*, highlighting the potential of MeJA application as a sustainable strategy to enhance natural resources. The application of MeJA at a concentration of 22 μM significantly improved the growth, yield, and nutritional value of *S. commune*, including crude protein, crude fat, and total carbohydrates, compared to the control treatment. Furthermore, higher concentrations of MeJA, particularly 40 μM, stimulated the production of triterpenoids and phenolic compounds, resulting in enhanced antioxidant activity. MeJA acts as an elicitor that mimics environmental stress, thereby activating metabolic pathways that lead to the production of secondary metabolites, including phenolic compounds, triterpenoids, and other antioxidants. These findings underscore the feasibility of incorporating MeJA into mushroom cultivation systems as an eco-friendly strategy to enhance productivity and the synthesis of bioactive compounds. Such advancements promote the efficient utilization of mushrooms as natural resources for food, pharmaceuticals, and nutraceuticals. Furthermore, this study lays a foundation for future research into the growth mechanisms and metabolic synthesis processes of *S. commune* under elicitor applications, contributing to the sustainable management and optimization of biological resources.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/resources14010003/s1, Table S1: The mineral content of *S. commune* from the exogenous application of MeJA at various concentrations; Table S2: Proximate composition of *S. commune* from the exogenous application of MeJA at various concentrations; Table S3. Total triterpenoid content of *S. commune* from the exogenous application of MeJA at various concentrations.

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Assessing the Impact of External Shocks on Prices in the Live Pig Industry Chain: Evidence from China

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Abstract: Analyzing the influence of external shocks on the pricing dynamics of the live pig industry chain is essential for effective macroeconomic control. Utilizing monthly data spanning from January 2010 to August 2023, this study employs the TVP-SV-VAR (Time-Varying Parameter—Stochastic Volatility—Vector Autoregression) model to analyze the effects of EPU (Economic Policy Uncertainty) and INU (Live Pig Industry News Uncertainty) on industry pricing. The findings are as follows: Firstly, the impacts of EPU and INU on industry prices exhibit time variability and distinct characteristics. Specifically, the impact magnitude of EPU ranges between [−0.025, 0.025], and that of INU between [−0.01, 0.01]. These differences in impact magnitude elicit varied responses from manufacturers and consumers to the indices. Secondly, uncertainty shocks at particular time points show high consistency, suggesting a patterned influence of external shocks on industry pricing that aligns with historical trends. Thirdly, robustness tests with alternative explanatory variables confirm the reliability of the findings. An uncertainty index, crafted from more comprehensive information sources, more accurately captures the effects of external shocks on industry pricing. Additionally, the volume of live pig slaughters illustrates the potential interaction between external shocks and pricing dynamics. In an era marked by increasingly frequent external shocks, this research offers valuable insights for policymakers to implement macro-control and foster high-quality industrial development.

Keywords: external shock; economic policy uncertainty; industrial news uncertainty; pig industry chain

1. Introduction

China is the world's largest producer and consumer of pork [1]. The price dynamics of the live pig industry chain has become an important consideration basis for the government to formulate relevant agricultural policies and carry out international trade. The stability of pig prices are closely related to key economic indicators, such as the consumer price index (CPI), inflation, and commodity market prices [2–6], and their fluctuation has consistently attracted attention across various sectors [7,8]. However, recent global uncertainties have significantly disrupted the stability of pig industry prices, presenting new challenges for producers, consumers, and government market interventions. Consequently, studying the impact of external shocks on the live pig industry chain is of considerable practical significance.

With increasing specialization and vertical integration, a well-structured pig chain has emerged, linking upstream and downstream segments of production. Similar to other agricultural chains, the pig industry is highly susceptible to external shocks, such as disease outbreaks [9]. After absorbing external shocks, prices adjust, accompanied by cyclical and persistent fluctuations [10]. Due to the imbalance between supply and demand, the cyclical fluctuation phenomenon of pork price and output alternating peaks is called the "pig cycle". The concept of the "pig cycle," first introduced by Benner in 1895 [11], has been observed globally [12–14]. The rising frequency of uncertain events, coupled with external shocks with market structural changes, has contributed to significant price fluctuations within the "pig cycle" [15,16].

External shocks originate from various sources, including economic and society factors, necessitating the establishment of a systematic analysis framework. In this study, external shocks are defined as factors that arise either randomly or non-randomly from outside the system, disrupting the stable fluctuations of prices within the live pig industry chain. These shocks influence key stages of the industry, including production, distribution, and consumption, and can be systematically observed and recorded. On a macro level, uncertainties arising from global economic conditions and government fiscal and monetary policies can affect all sectors within the system [17–19]. At the micro level, factors such as pig diseases, food safety concerns, and technological innovations have a profound impact on the price dynamics and the structure of the live pig chain industry [20–24]. The existing literature has typically relied on newspaper data to identify external shocks, constructing uncertainty indices related to economic policy, geopolitics, and trade, yielding positive results [25–27]. The impact of external shocks on prices is often analyzed using VAR models, such as the TVP-VAR model, which effectively explains price fluctuations and their time-varying characteristics [17,28]. However, research on external shocks in the pig industry remains insufficient, especially in terms of identifying and measuring the impact of specific events (such as epidemics and food safety), and there is a lack of specific categorization and quantification methods. In addition, the discussion of external shocks is limited to a specific event, and it is impossible to obtain enough historical experience from the impact of the same type of external shocks. Furthermore, the dynamic impact of external shocks on the price of the live pig industry chain remains unclear and requires further in-depth exploration.

This paper addresses two core issues: first, the identifying and measuring of external shocks affecting the live pig industry chain, and second, analyzing the time-varying characteristics and underlying mechanisms through which external shocks influence pig industry chain prices. The study makes several marginal contributions. First, the study defines and classifies the external shocks affecting the live pig industry, effectively identifying and measuring these shocks across different levels. This framework is critical for investigating how external shocks influence industrial prices at both macro and micro levels. Second, by creating indices based on news and disease data related to the pig industry, the study examines the dynamic effects of these uncertainties on industry chain prices over time using the TVP-SV-VAR model. This approach not only validates prior research on the direct impacts of animal diseases and food safety concerns on prices [29,30] but also provides valuable insights into price fluctuations in other industries. Third, the study establishes and analyzes the transmission mechanism linking external shocks to industry chain prices. It tests the "external shocks—market supply and demand—industry chain price" pathway through robustness checks [31,32], confirming both the validity and effectiveness of this mechanism.

The structural framework of this study can be outlined as follows: Section 2 reviews relevant literature and establishes a theoretical framework for understanding the impact of external shocks on the live pig industry chain's prices. Section 3 details the data sources, processing methods, and fluctuation characteristics considered in this paper and introduces the TVP-SV-VAR model. Section 4 analyzes and discusses the empirical results. Section 5 further discusses the results, including robustness tests and potential mechanism analysis. Finally, the study concludes with a summary and suggestions in Section 6.

2. Literature Review and Theoretical Framework

2.1. Literature Review

2.1.1. Influencing Factors of Price Fluctuations in the Live Pig Industry Chain

Price volatility in the hog market is characterized by high variability and general contraction, distinguishing it from other types of meat [33]. The causes of price fluctuations in the live pig industry have been analyzed extensively in the existing literature. Early studies primarily focused on the dynamic transmission relationships between different segments of the industry chain. For example, feed costs, which constitute the largest component of pig production, and breeding expenses directly influence market prices [34]. Consequently, upstream and midstream segments of the chain typically exert the greatest impact [35]. Other scholars have highlighted the long-term co-integration between retail pork prices and live pig prices, facilitating price transmission between these two levels [36]. In recent years, with increasing uncertainty, external factors affecting the industry chain—such as policies, epidemics, and public opinion—have garnered growing attention. These external shocks indirectly impact prices by influencing the behaviors and expectations of stakeholders [37]. Following the dissemination of information about African swine fever, consumer preferences changed dramatically and began to pay more attention to safety attributes. Furthermore, when belief in the occurrence of African swine fever in the future was strong, the frequency of consumers' purchasing behavior decreased significantly [38].

2.1.2. The Impact of Economic Policies on Price Fluctuations in the Live Pig Industry Chain

Macro-level factors, such as economic events, policies and regulations, are a focal point in studies of external shocks. Economic policies can disrupt the production and transportation of the live pig industry chain, restrict market supply, and cause short-term price surges [39,40]. For instance, tight monetary policies increase the capital costs for producers, compelling them to curtail production plans, which exacerbates price volatility [41]. Simultaneously, reduced consumption expectations amplify market uncertainty [42]. Some scholars advocate active price regulation policies to stabilize short-term fluctuations in the hog market [43]. Conversely, others argue that most external shocks do not fundamentally alter the structure of the live pig market; supply and prices often revert to expected levels in a relatively short time [44]. They propose minimizing government intervention and allowing market mechanisms to regulate prices to avoid potential policy distortions [45,46].

2.1.3. The Impact of Industry News on Price Fluctuations in the Live Pig Industry Chain

Industry news has become a key focus in studies of external shocks, particularly regarding animal diseases and food safety. For example, during the outbreak of African swine fever in China in 2018, the large-scale culling of infected pigs led to a significant reduction in hog numbers and a sharp rise in prices [47]. The dissemination of this news intensified market panic, creating an asymmetry between production and consumption adjustments. Retail price increases far outpaced production price increases [48]. Wang et al. (2023) observed that following the swine fever outbreak, incomplete public information hindered the spatial integration of the industry chain and slowed the recovery of inter-provincial price linkages [49]. While regional differences in food culture influence purchasing behavior [50], there is a growing consensus on food safety issues, which directly affect consumer decisions [51,52]. Negative news reports about food safety significantly deter consumers' purchasing intentions and behaviors [53,54]. Some studies have also noted that media reports amplify emotional responses, potentially triggering panic buying or selling, which further drives price volatility [55,56].

Price fluctuations in the live pig industry chain have been a long-standing research focus. The influence of external shocks on price volatility in this sector has been widely studied. However, effective methods for identifying the external impacts of industry news remain unclear. Furthermore, empirical tests are necessary to validate the potential mechanisms of these external shocks, particularly in terms of market supply and demand and stakeholder decision-making.

2.2. Theoretical Framework

2.2.1. Static Theoretical Framework

External shocks encompass various factors, such as the economic environment, policy regulation, and news events, generating uncertainties that directly impact the supply and demand functions of the live pig industry chain [57]. Producers adjust production and operation modes based on market conditions and economic policy orientation, while factors like purchasing power, risk appetite, and external information interventions influence consumer behavior. In theory, market adjustments ideally lead to a dynamic equilibrium between supply and demand in response to external shocks. However, achieving complete balance requires the exchange of supply, demand, and price information. Price is generally considered the key determinant of the live pig supply–demand relationship [58]. The existence of information asymmetry may aggravate price fluctuations, manufacturers cannot accurately obtain the changing trend of the market, and will become blind and uncertain in decision-making, thus aggravating the instability of prices. At the same time, in the case of incomplete information, the decrease of market efficiency will make the allocation of resources unable to reach the optimal state, resulting in the delay in reaching the balance of supply and demand. However, imbalances in supply and demand caused by external shocks such as economic policies and animal epidemics indirectly lead to abnormal price fluctuations in the live pig industry chain [59].

2.2.2. Dynamic Theoretical Framework

The static supply and demand model is inadequate for explaining the shift of the pig market from one equilibrium to another. Therefore, to effectively illustrate the dynamic process of price fluctuations and market behavior, we employ graphical techniques to depict the stable condition prior to and following market alterations, as depicted in Figure 1.

From a dynamic analysis perspective, we examine both ends of the live pig industry chain. On the supply side, changes in economic policy and industrial news influence live pig supply by affecting production cost factors, market expectations, and commodity support plans. Favorable external impacts typically lead farmers and enterprises to expand production, increasing market supply [60], while negative shocks result in production capacity reductions [61]. Strong market interventions, such as government reserve meat delivery or pig purchases, can directly alter market structures, causing sharp supply fluctuations [62,63].

On the demand side, the demand for pork is influenced by consumers' income levels, alternative commodity prices, and willingness to consume. While consumer income accounts for an important proportion, it generally does not change easily in the short term. Changes in the price of substitute commodities such as chicken, cattle and sheep will affect pork consumption, but the Chinese people's eating habits for meat greatly limit this substitution effect [64]. Therefore, consumer willingness to consume plays an important role, and negative news impacts consumer willingness to buy pork products, reducing market demand for live pigs [65]. As consumer confidence is restored, market demand tends to recover over time [66].

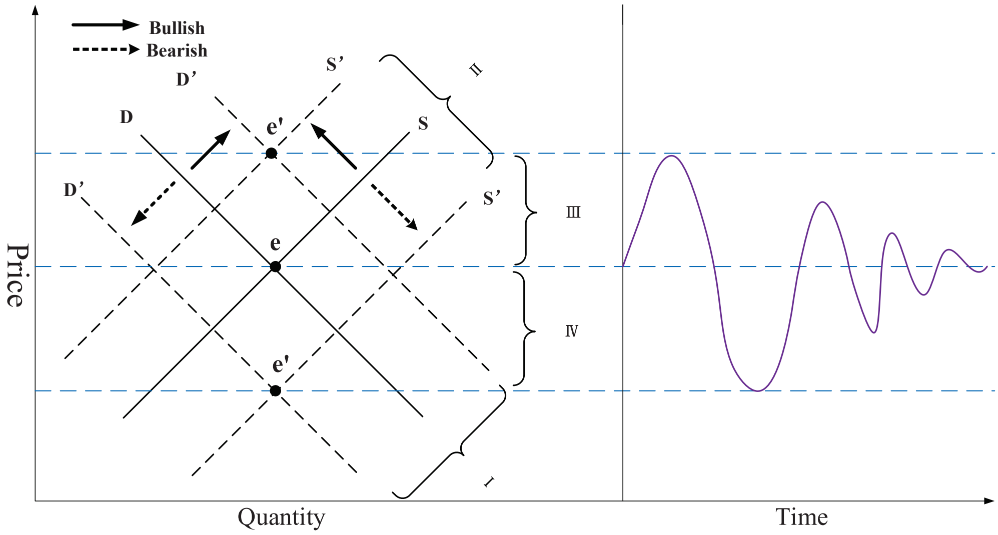

Figure 1. Dynamic price model of live pig industry chain. Notes: The purple line shows the iterative process where the price reaches an equilibrium state. Source: Author drawing.

However, the simple movement of supply and demand curves cannot fully capture the continuous fluctuation of the pork market. The dynamic transmission process of supply and demand relationships in the pork market is ongoing. As new price points are formed in the live pig industry chain, they are communicated back to producers and consumers, leading to further adjustments in supply and demand curves. This iterative process continues as both sides of the transaction adjust their activities based on industry information and new policies, ultimately leading to price convergence to a new stable state in the short term. Specifically, positive information in the external shock increases the demand for consumption, driving up pork prices, and the enthusiasm of producers to compensate the column leads to the gradual saturation of supply, and the price begins to fall back to the equilibrium state. Conversely, negative external shocks dampen producers' willingness to expand supply, resulting in insufficient market supply, which initially pushes prices higher. But the decline in consumer demand finally allows the market price to return to normal. The fluctuation of this equilibrium state is characterized by rapid changes in the equilibrium point, gradually stabilizing over time.

2.2.3. Potential Mechanism Analysis

Our theoretical framework posits that external shocks ultimately shape the equilibrium price in the pig industry chain through dynamic adjustments in market supply and demand. We hypothesize that certain mechanism variables mediate these adjustments, such as logistics and structural configurations. These variables influence the impact of external uncertainties on pricing within the live pig industry chain. To illustrate this, we use pig slaughter volume as a representative mechanism variable.

Pig slaughter serves as a pivotal mechanism for two main reasons: Firstly, it acts as an indicator of market supply and demand balance. The hog slaughtering industry in China, which possesses market influence, can significantly affect the industry's overall hog demand [62]. A reduced supply in the hog market typically results in lower slaughtering activity, leading to higher pork prices in the consumer market. In contrast, an abundant supply tends to stabilize or lower prices by increasing slaughtering. Secondly, pig slaughter volume serves as a regulatory indicator of supply. Manufacturers may adjust slaughter volumes in response to reduced supply or shifts in demand, aiming either to maintain high prices or to clear inventory based on market conditions. Similarly, governmental interventions in slaughter volumes can help stabilize market dynamics.

The interaction between external shocks and pricing, mediated by pig slaughter volumes, unfolds as follows: External uncertainties, such as epidemic outbreaks, reduce production incentives for manufacturers, while temporary government policies on environmental protection and land use can constrain farm expansion, indirectly leading to a supply shortage in pig production. Therefore, if market demand remains constant, this shortage leads to a decline in slaughter volume, driving pork prices upward [67]. This model assumes that changes in pig slaughter volumes precede and drive market price fluctuations.

3. Data and Model Construction

3.1. Data Source and Processing

The China Economic Policy Uncertainty (EPU) Index is utilized in this study to measure changes in economic policy. The EPU data is sourced from the official website of Policy Uncertainty (https://www.policyuncertainty.com/ (accessed on 1 December 2024)). Initially measured by scholars such as Baker [68], the index is calculated based on the frequency of keywords like "economy and finance", "uncertainty", and "policy" in news reports from the South China Morning Post.

To gauge changes in the pig industry news, this paper develops the Pig Industry News Uncertainty Index (INU) using the People's Daily newspaper as its primary source. The INU encompasses opinions and measures related to pig industry development within a specific period, along with news reports on public diseases and market prices. This index primarily reflects the uncertainty surrounding pig industry news during the specified period. People's Daily was chosen as the newspaper source due to its status as the most authoritative media outlet in China. Reports published by People's Daily are indicative of the government's attention to news events and play a crucial role in shaping public opinion across various sectors of society. Alternative news sources also considered Guangming Daily and Economic Daily, but because they had relatively little information about pigs, the index they compiled was not sufficiently convincing.

In this study, the keywords "pig" and "live pig" were identified in news reports from People's Daily spanning January 2010 to August 2023. Duplicate results were eliminated, and articles relevant to the live pig market were retained, resulting in a total of 1,137 articles. Following the optimization algorithm proposed by Baker et al. for uncertainty index measurement [69].

The Pig Industry News Uncertainty Index (INU) is calculated as follows: the frequency of hog-related news reports in People's Daily each month is tallied, multiplied by the number of months, and expanded by 100 times compared to the cumulative sum number. This yields the current Pig Industry News Uncertainty Index (INU_i). The formula is shown in Equation (1):

$$INU_i = \frac{N \times M_i}{\sum\limits_{i=1}^{n} M_i} \times 100 \tag{1}$$

where M_i represents the frequency of news uncertainty (the number of times of news reports related to the pig industry in People's Daily), N represents the monthly count of the sample interval (a total of 164), $\sum_{i=1}^{n} M_i$ represents the total number of occurrences of news reports in People's Daily. On this basis, the uncertainty index INU_i of pig industry news in each period is calculated.

The independent variables in this study are the Economic Policy Uncertainty Index and the Industrial News Uncertainty Index, while the dependent variables are the average prices of piglets, pigs, and pork across 22 provinces and cities in China. All variables cover monthly data from January 2010 to August 2023. The statistics mentioned are sourced from the official website of Policy Uncertainty and the National Bureau of Statistics of China.

3.2. Analysis of Data Fluctuation Characteristics

Table 1 summarizes the statistical indicators of various variables. The mean and standard deviation of the Economic Policy Uncertainty (EPU) index are 207.0847 and 123.425, respectively. These figures surpass those of the Live Pig Industry News Uncertainty (INU) index, which are 99.9998 and 71.5722, indicating a more pronounced fluctuation in EPU over time. The calculation base period of the two indexes is different, and the calculation time of INU is relatively late, which is of more reference value for the business decision of manufacturers. Among the piglet price, hog price, and pork price in the pig industry chain, the standard deviation of the piglet price is the highest at 25.3819, suggesting that it is the most volatile component, followed by pork price and hog price. The skewness values for all time series are positive, illustrating characteristics of a right-skewed distribution. All series exhibit kurtosis values greater than 3, indicating peaked distributions. Moreover, the Jarque–Bera test results for EPU, hog, piglet, and pork prices confirm non-normal distributions at the 1% significance level. To normalize scale differences across datasets, the empirical analysis employs the natural logarithm of the variables.

Table 1. Statistical description of time series variables.

Variable	Mean	SD	Min	Max	Skewness	Kurtosis	J-B
EPU	207.0847	123.4125	58.8992	661.8280	1.1095	3.8948	39.1155 ***
INU	99.9998	71.5722	12.2024	439.2846	1.9747	8.5779	319.1866 ***
Piglet	41.6433	25.3819	16.8400	125.0400	1.7894	5.3934	126.6678 ***
Hogp	17.4283	6.6048	9.7000	37.6600	1.7446	5.1994	116.2483 ***
Porkp	25.9491	8.675918	15.21000	52.2500	1.7581	5.1930	117.3520 ***

Note: SD denotes the standard deviation, J-B denotes the Jarque–Bera test for normality. *** denotes significance at 0.01 levels.

Figure 2 shows the trend characteristics of the uncertainty index. The Economic Policy Uncertainty Index exhibited a relatively stable trend before 2017, but sharp fluctuations occurred after 2017, particularly peaking during the Sino-US trade war and the COVID-19 epidemic. These fluctuations indicate significant changes in China's economic operating environment, with the impact of uncertainty on the economy becoming more pronounced. Three specific time nodes highlight these trends: (1) In 2017, China's agricultural supply-side reform emphasized high-quality production in animal husbandry, guiding efforts to stabilize pig production, optimize breeding structures, and upgrade the industry. (2) During the Sino-US trade war from 2018 to 2019, China implemented tariff measures in response to trade frictions. The resulting increase in trade tariffs led to rising commodity prices, significantly impacting the domestic agricultural economy. (3) In early 2020, the COVID-19 epidemic caused a global economic downturn, disrupting agricultural production and causing large fluctuations in agricultural product prices. China responded with various monetary and fiscal policies to promote economic recovery.

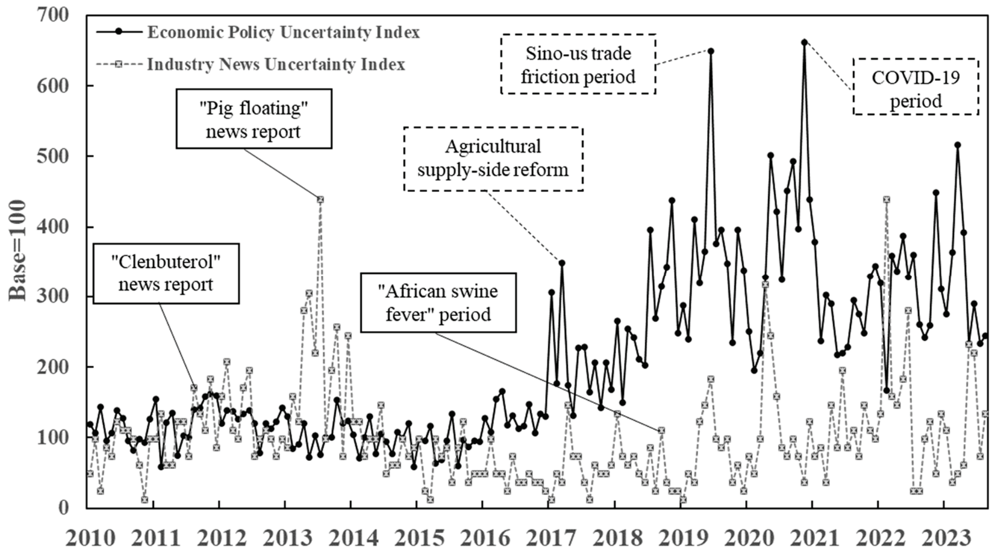

Figure 2. Trends of the Economic Policy Uncertainty Index and Pig Industry News Uncertainty Index. Source: Policy Uncertainty official website (https://www.policyuncertainty.com/ (accessed on 1 September 2024)), People's Daily statistics (http://paper.people.com.cn/rmrb/pc/layout/202502/24/node_01.html (accessed on 1 September 2024)).

The uncertainty index of the pig industry policy news exhibits peak volatility during major news or policy regulation periods, with notable mentions of pigs in the Chinese government's work report in March. Information from specific historical periods revealed the following: (1) The "clenbuterol incident" in 2011 raised widespread concerns about food safety (http://www.moa.gov.cn/ztzl/ncpzlaq/gzjb/201106/t20110630_2042621.htm (accessed on 1 December 2024)), significantly affecting short-term pork consumption. Consumers willingness to purchase dropped sharply, leading to continuous reductions in pork prices. (2) In 2013, improper disposal of sick and dead pigs by pig farmers in Zhejiang caused a large-scale "pig floating" phenomenon in the Huangpu River waters (http://www.moa.gov.cn/xw/zwdt/201303/t20130315_3273689.htm (accessed on 1 December 2024)), impacting water quality safety. This incident prompted the issuance of policies and regulations to address environmental issues in livestock and poultry breeding. (3) The 2018 outbreak of African swine fever resulted in the culling of more than one million pigs, leading to a significant decline in pig stocks. Cross-provincial embargoes due to supply shortages exacerbated soaring pork prices. The government implemented policy measures to contain the spread of swine fever and gradually restore production capacity.

In this study, piglet, pig, and pork prices are used to depict the pig industry chain, representing different positions within the chain with good representation. Figure 3 illustrates the price fluctuation trend of the pig industry chain. The prices of piglets, pigs, and pork exhibit a high degree of consistency in their trends, with relatively stable fluctuations before 2018. However, there was a significant change after 2018, showing a marked difference in fluctuation intensity. Their independence from one another leads to a significant variation in the extent of fluctuation. Given the close connection between the live pig and pork markets, the price of pork tends to be higher than that of live pigs, maintaining a reasonable price spread. Both prices demonstrate a trend of simultaneous rise and fall. The price fluctuation trend of piglets and pigs, which belong to the supply side, is consistent.

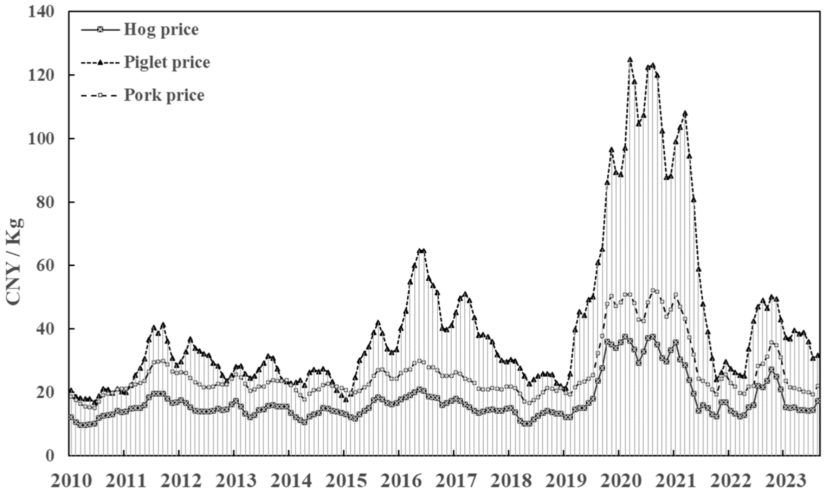

Figure 3. Price fluctuation trend of live pig industry chain. Source: National Bureau of Statistics of China (https://data.stats.gov.cn/index.htm (accessed on 1 September 2024)).

From a demand perspective, farmers typically purchase piglets in advance to ensure sustainable production and operation. However, the growth of piglets requires a certain amount of time and cannot be quickly converted into supply. During disease outbreaks such as African swine fever, the growth environment of piglets faces greater risks, leading to unusually volatile piglet prices. Despite these factors, when the supply and demand sides of the pig industry chain encounter external shocks, the overall trend tends to display a high degree of consistency.

3.3. Model Construction

The TVP-VAR model is characterized by its ability to adjust the analysis of each time point in the time series based on the time variability of the parameters. This allows for the dynamic depiction of the time-varying relationship between variables. The model was first proposed by Primiceri [70] and further applied and improved by Nakajima [71].

First, the general VAR model coefficients and covariance are constant [72]:

$$Ay_t = B_{1,t}y_{t-1} + \cdots + B_{k,t-k}y_{t-k} + \mu_t \cdot t = 1, 2, \ldots, n \tag{2}$$

In Equation (2), y_t is an observable endogenous vector of $k \times 1$; $B_{k,t-k}$ is the coefficient vector of $k \times k$; μ_t is an unobservable shock vector with a covariance matrix Ω_t, expressed by the following equation:

$$A_t \Omega_t A_t' = \Sigma_t \Sigma_t' \tag{3}$$

In Equation (3), the matrices A_t and Σ_t are expressed as follows:

$$A_t = \begin{bmatrix} 1 & 0 & \ldots 0 \\ a_{21} & 1 & \ldots 0 \\ \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \ldots 1 \end{bmatrix} \Sigma_t = \begin{bmatrix} \sigma_{1,t} & 0 & \ldots 0 \\ 0 & \sigma_{2,t} & \ldots 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & \ldots \sigma_{n,t} \end{bmatrix} \tag{4}$$

Combining Equations (3) and (4), Equation (2) can be written as Equation (5):

$$y_t = X_t' \beta_t + A_t^{-1}{}_t \Sigma_t \varepsilon_t \tag{5}$$

Among them, $B_{i,t}$ is converted to vector β_t, $V(\varepsilon_t) = I_n$, $X_t' = I_n \otimes \left[1, y_{t-1}', \ldots, y_{t-k}'\right]$, $\otimes$ is kronecker product.

Let a_t be the vector of the matrix A_t of non-0 and 1, and σ_t be the vector of the symmetric matrix Σ_t, the concrete expression of the TVP-VAR model is as Equations (6)–(8):

$$\beta_t = \beta_{t-1} + \mu_{\beta_t} \tag{6}$$

$$a_t = a_{t-1} + \mu_{\alpha_t} \tag{7}$$

$$h_t = log\sigma_{t-1} + \mu_{h_t} \tag{8}$$

The parameters B_t and A_t are assumed to follow the random walk process. Suppose σ_t follows a geometric random walk, and suppose that $\varepsilon_t,\ \mu_{\beta_t},\ \mu_{\alpha_t}, \mu_{h_t}$ obey the following:

$$\begin{pmatrix} \varepsilon_t \\ \mu_{\beta_t} \\ \mu_{\alpha_t} \\ \mu_{h_t} \end{pmatrix} \sim N(0, V)V = \begin{pmatrix} I_3 & 0 & 0 & 0 \\ 0 & \Sigma_\beta & 0 & 0 \\ 0 & 0 & \Sigma_\alpha & 0 \\ 0 & 0 & 0 & \Sigma_h \end{pmatrix} \tag{9}$$

In Equation (9), I_3 is a 3-dimensional identity matrix, and $\Sigma_\beta,\ \Sigma_\alpha,\ \Sigma_h$ are positive definite matrices. The Bayesian method is employed to estimate the model, and the Markov chain Monte Carlo method is used to estimate the posterior values of the parameters. The initial setting of model parameters in this paper is adopted from Nakajima [73], as shown in Equations (10) and (11):

$$\mu_{\beta_0} = \mu_{\alpha_0} = \mu_{h_0}, \varphi_{\beta_0} = \varphi_{\alpha_0} = 10I, \varphi_{h_0} = 100I \tag{10}$$

$$(\varphi_\beta)_i^{-2} \sim Gamma(40, 0.02), (\varphi_\alpha)_i^{-2} \sim Gamma(4, 0.02), (\varphi_h)_i^{-2} \sim Gamma(4, 0.02) \tag{11}$$

The total number of MCMC sampling is set to 10,000 times, and the samples from the first 1000 times are considered pre-burned values and discarded.

4. Empirical Results and Analyses

4.1. Stationarity Test and Parameter Setting

To ensure data stability and avoid "pseudo-regression," the Augmented Dickey–Fuller (ADF) test is first applied [74]. Additionally, the Phillips–Perron (PP) test [75] and the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test [76] are used to determine whether EPU, INU, Hogp, Piglet, and Porkp contain unit roots. As shown in Table 2, the results indicate that these variables are nonstationary, but become stationary after first-order differencing, with significance at the 1% level. Therefore, the first-differenced sequences are deemed suitable for further analysis, including MCMC sampling and TVP-SV-VAR model construction.

Table 2. The result of the unit root test of the variables.

Variable	ADF	PP	KPSS	Verdict
EPU	−0.2605(3)	−0.2508(15)	0.2639(8) ***	Nonstationary
INU	0.0121(1)	−0.0568(2)	0.4368(10) **	Nonstationary
Hogp	−0.0265(2)	−0.0877(4)	0.6224(10) *	Nonstationary
Piglet	−0.0217(1)	−0.0864(3)	0.3731(10) **	Nonstationary
Porkp	−0.1246(6)	−0.0724(24)	0.2686(8) ***	Nonstationary
Δ(EPU)	−13.1008(1) ***	−43.5993(22) ***	0.0933(22)	stationary
Δ(INU)	−8.6022(0) ***	−8.4833(4) ***	0.0425(2)	stationary
Δ(Hogp)	−7.5117(1) ***	−6.8130(9) ***	0.0781(4)	stationary
Δ(Piglet)	−7.6490(0) ***	−7.3132(7) ***	0.0645(3)	stationary
Δ(Porkp)	−9.0713(5) ***	−45.8966(31) ***	0.1068(32)	stationary

Notes: Δ represents the first-order lag of the variable. The number in parentheses indicates the lag order, which is selected based on the SIC. The number in the brackets indicates the bandwidth which uses Bartlett Kernel as suggested by the Newey–West test [77]. *, ** and *** refer to the significance at 10%, 5% and 1% levels.

The construction of the TVP-SV-VAR model requires consideration of the lag order. Too few lags may result in ineffective model estimation, while too many lags may lead to model equation redundancy. Therefore, determining the optimal lag order is crucial for the overall results. In this paper, the TVP-SV-VAR model, with lag periods ranging from 1 to 6, is evaluated based on the logarithmic likelihood estimate. A lag period of 2 is ultimately selected.

4.2. Model Estimation Results

Figure 4 presents the results of the MCMC estimation, including the sample autocorrelation, sample path, and posterior density distribution of the parameters (Σ_b), (Σ_a), (Σ_h), shown from top to bottom. The sample autocorrelation decreases rapidly as the number of samples increases, indicating that MCMC sampling effectively reduces autocorrelation. The sample path fluctuates around the mean, demonstrating relative stability without any discernible trend. The sample density converges to the posterior density of the parameter, indicating good convergence. Therefore, the results in Figure 4 further validate the parameters of the TVP-SV-VAR model constructed by EPU, INU, Hogp, Piglet, and Porkp, enabling the study of their dynamic relationship through the TVP-SV-VAR model.

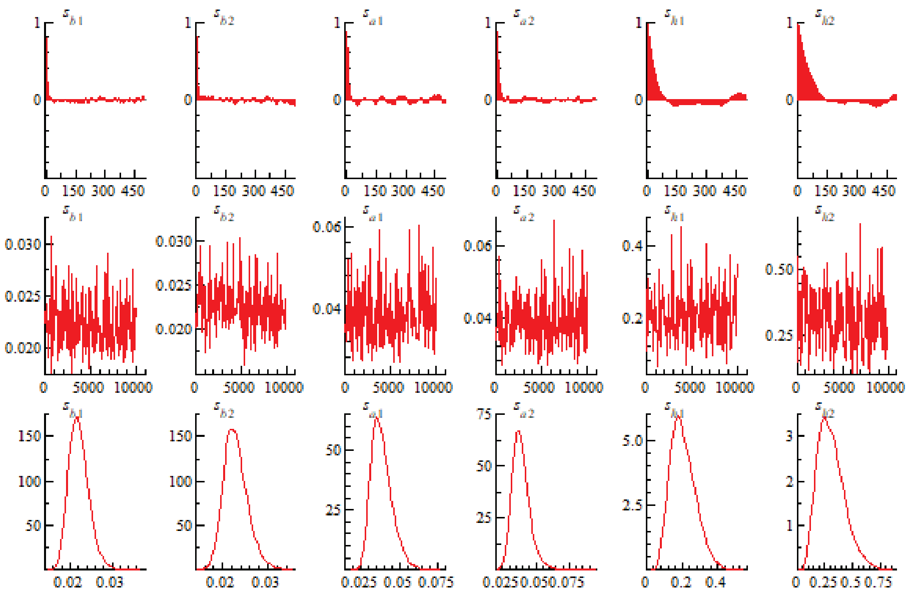

Figure 4. Sample autocorrelation, path, and posterior density estimated by MCMC. Notes: the six columns from left to right reveal the sample auto-correlation, path and posterior density of $(\Sigma_b)_1$, $(\Sigma_b)_2$, $(\Sigma_\alpha)_1$, $(\Sigma_\alpha)_2$, $(\Sigma_h)_1$, $(\Sigma_h)_2$.

The numerical characteristics of parameters estimated by MCMC are summarized in Table 3, which includes the mean value, standard deviation, confidence interval, Geweke value, and inefficiency factor. The mean values of the parameters fall within the 95% confidence interval, and the standard deviations are low, indicating parameter stability. The Geweke values are all below 1.96, suggesting that the null hypothesis of backward density convergence of parameters cannot be rejected [78]. The inefficiency factors are all below 100, meaning that at least 113 samples (10,000/88.49) can be obtained from 10,000 samples, indicating the effectiveness of the MCMC sampling process and parameter estimation of the TVP-SV-VAR model.

Table 3. Parameter estimation results in the TVP-SV-VAR model.

Parameter	Mean	Std.Dev.	95%L	95%U	Geweke	Inefficiency
$(\Sigma_b)_1$	0.0221	0.0024	0.0181	0.0275	1.000	5.52
$(\Sigma_b)_2$	0.0229	0.0026	0.0185	0.0288	0.030	13.48
$(\Sigma_\alpha)_1$	0.0384	0.0067	0.0278	0.0536	0.412	10.32
$(\Sigma_\alpha)_2$	0.0388	0.0067	0.0281	0.0545	0.345	15.74
$(\Sigma_h)_1$	0.2053	0.0693	0.0919	0.3585	0.728	47.89
$(\Sigma_h)_2$	0.3103	0.1194	0.1222	0.5884	0.349	88.49

4.3. Time-Varying Impulse and Response Results

This chapter examines the dynamic effects of Economic Policy Uncertainty (EPU) and Live Pig Industry News Uncertainty (INU) on the prices within the pig industry chain. The analysis includes impulse responses over various lag periods and specific historical points. In equidistant lagged impulse responses, lag periods are fixed at three, six, and nine intervals to evaluate the persistence of the impacts from EPU and INU. For impulse responses at specific historical points, three periods with significant fluctuations in the uncertainty indices were selected to explore whether the impacts of EPU and INU on the prices of the live pig industry chain differ across distinct historical contexts.

4.3.1. Impulse Response of Pig Industry Chain Price to Economic Policy Uncertainty

The impulse response results of the live pig industry chain prices to Economic Policy Uncertainty (EPU) are depicted in Figure 5. The response curves at lag periods of six and nine are nearly zero, indicating that EPU's fluctuations do not sustainably impact the prices within the live pig industry chain. Hence, analyzing the impulse responses at a lag of three periods provides insight into how the supply and demand sides of the live pig industry chain react to EPU.

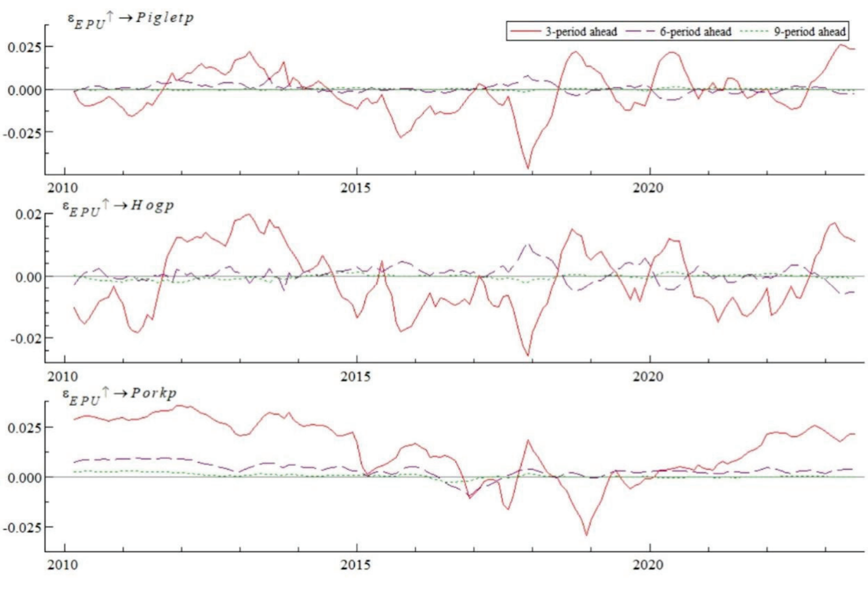

Figure 5. Equal-interval impulse response of pig industry chain price to economic policy uncertainty.

1. EPU and Supply-Side Prices: Across the entire interval, a standard deviation's positive shock from EPU on supply-side prices exhibits a cyclic pattern of positive to negative to positive shifts, with impact intensity fluctuating between [−0.02, 0.02]. The impulse response trends for piglet and hog prices are consistent, although the impact on hog prices is generally more pronounced than on piglet prices. This is mainly due to the different life-cycle stages of piglets and hogs; fluctuations in hog market prices are more complex. For instance, the surge in live pig prices in 2019 was primarily

due to a significant reduction in live pig stocks earlier, leading to insufficient market supply. Under substantial profit margins and policies supporting production capacity recovery, farmers rapidly adjusted breeding scales and increased live pig stocks, only for subsequent overcapacity to drive prices down.

2. EPU and Demand-Side Prices: A standard deviation's positive EPU shock on the demand side also alternates between positive and negative impacts, with the overall trend shifting from positive to negative to positive again, and the intensity varying within [−0.025, 0.025]. These fluctuations display periodicity and stability, with positive responses from 2010 to 2017 and after 2020, and negative responses from 2017 to 2020. The predominance of positive impacts suggests that the market's demand for pork remains relatively stable, and minimally affected by economic policy changes. The main reasons are economic fluctuations that increase production costs and reduce capacity, leading to excessively high pork prices in the market. However, Chinese residents' dietary preferences strongly favor pork, and they are unlikely to switch to alternatives simply due to price changes.
3. Differences Between Supply and Demand Responses: While the overall trends of EPU's impact on prices at the supply and demand sides are consistent, the impulse response curves for pork prices on the demand side are more stable. This indicates that prices on the supply side of the live pig industry chain are more susceptible to economic policy uncertainty. In response to economic environmental changes and policy adjustments, pig farmers tend to adjust their production scales, thereby affecting production-end prices. For example, during the enactment of the "Pig Slaughter Regulation" policy, the government required farmers and enterprises to gradually phase out outdated pig production capacities to ensure the high-quality development of the pig industry. Additionally, economic pressures from Federal Reserve rate hikes led some pig farmers to voluntarily reduce their stocks, causing a market reduction in live pig stocks and an increase in prices.

The impulse response results of the live pig industry chain prices to Economic Policy Uncertainty (EPU) at specific historical points are illustrated in Figure 6. The selected historical points include February 2017, July 2019, and March 2021, corresponding to significant events such as China's agricultural supply-side reform, the US–China trade war, and the COVID-19 pandemic, respectively. The impact of EPU on the prices of the live pig industry chain at these specific points exhibits several distinctive features:

1. Direction of Impact: EPU has a negative impact on supply-side prices, but its effect on demand-side prices is initially positive and then turns negative. The main reasons for these varied impacts relate to the distinct historical contexts of the periods under consideration: the agricultural supply-side reforms in 2017, which eliminated much of the outdated pig production capacity; the rise in feed prices during the US–China trade war in 2019, which affected breeders' profit expectations; and the dampening of pig breeders' enthusiasm for production due to COVID-19 pandemic controls in 2021. These events illustrate how reductions in stock levels and breeding expectations can lead to negative price adjustments for piglets and live pigs.
2. Duration of Impact: The impact of EPU on supply-side prices lasts for six periods, whereas its impact on demand-side prices lasts only three periods. The changes in economic policy have a longer-lasting effect on supply-side prices than on demand-side prices, primarily because prices on the supply side are influenced by stock levels, and breeders need time to adjust their production capacities. In contrast, pork prices on the demand side are tied to the normal development of the national economy. When market prices fluctuate, the government often releases reserve meat to stabilize prices, making demand-side prices easier to control in the short term.

3. EPU and Demand Side: The impact of EPU on pork prices shows a pattern of initially positive followed by negative effects, with the response curves at all three points highly overlapping. The primary reason is that economic policy uncertainty predominantly leads to a shortage in supply, as pig stock levels are often reduced under the influence of EPU. Consumer demand for pork remains unchanged, but the insufficient supply leads to successive price increases. As market supply eventually increases, the price trend gradually shifts downward.

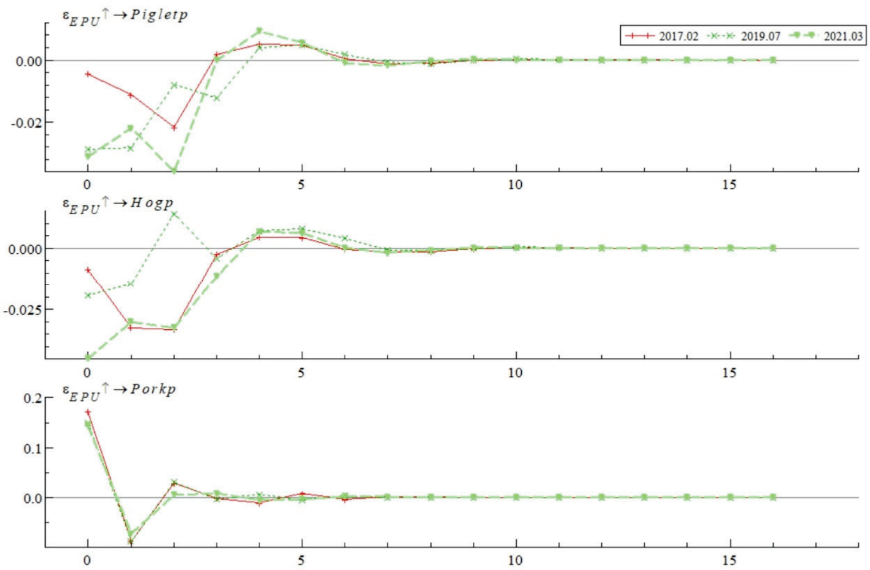

Figure 6. Impulse response of live pig industry chain price to economic policy uncertainty at specific time points.

4.3.2. Impulse Response of Pig Industry Chain Price to Industrial News Uncertainty

The impulse response results of the live pig industry chain prices to Live Pig Industry News Uncertainty (INU) are illustrated in Figure 7. The response curves at lag periods of six and nine tend towards zero, indicating that INU's fluctuations do not have a lasting impact on the prices within the live pig industry chain. Hence, analyzing the impulse responses at a lag of three periods provides insight into how the supply and demand sides of the live pig industry chain react to INU.

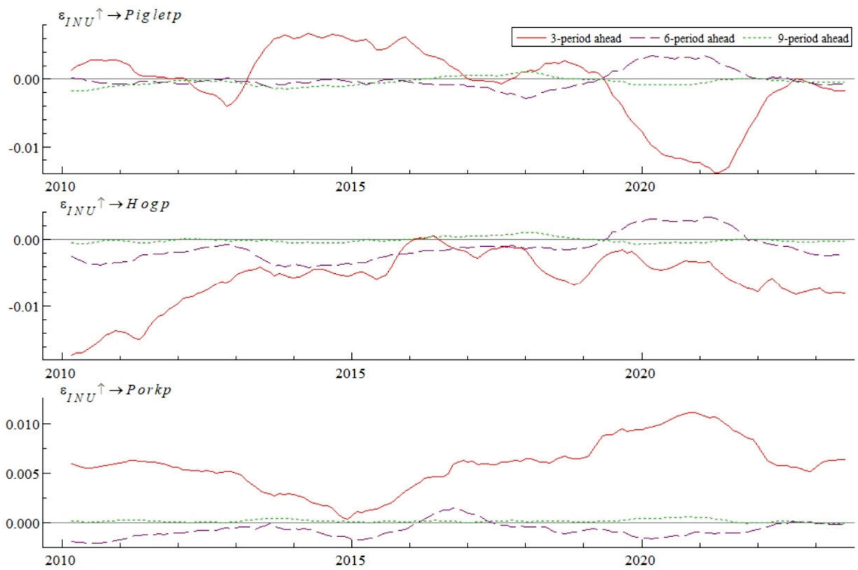

Figure 7. Equal-interval impulse response of pig industry chain price to industrial news uncertainty.

1. INU and Supply-Side Prices: Across the entire interval, a standard deviation's positive INU shock causes alternating positive and negative impacts on piglet prices, with the intensity fluctuating between [−0.01, 0.01]. In 2019, the impact shifted from positive to negative. INU consistently exerts a negative influence on hog prices, with the intensity ranging from [−0.016, 0], gradually weakening from 2010 to 2015. The primary reason for this pattern in piglet prices is their susceptibility to INU shocks, accentuated by changes in live pig stocks. The outbreak of negative news leads breeders to reduce their production capacities, decreasing the demand for piglets. As government measures such as the "Lean Meat Essence Special Rectification Plan" and the "Live Pig Production Capacity Control Implementation Plan" come into effect, increasing regulatory intensity gradually mitigates the negative impact of the news. This results in an increase in breeders' enthusiasm to expand their pens, boosting the demand for piglets.
2. INU and Demand-Side Prices: A standard deviation's positive INU shock has a positive impact on pork prices on the demand side, with the intensity fluctuating between [0, 0.01]. After 2015, the positive impact trends upwards, reaching its peak in 2021. Under the influence of INU, the prices on the demand side are also affected by the production side. Historical events related to food safety and epidemics show that when negative news about the pig industry arises, breeders typically adopt a pessimistic outlook on future market trends. As a result, they often reduce production capacity to mitigate losses from market price risks, which in turn leads to a rise in pork prices due to insufficient market supply.
3. Difference in Impact Between INU and EPU: The impact of INU on industry chain prices is less significant than that of EPU, mainly due to consumer behavior. Changes in the economic environment influence consumers' expectations for the future, their income, and their willingness to consume, and the extent of these influences determines the overall consumer demand for pork. However, industry-specific news, such as pig slaughtering standards and environmental regulations, has a more pronounced effect on pig breeders. We can reasonably infer that negative news related to live pigs is unlikely to structurally impact China's demand for pork, as consumers are unlikely to alter their long-established dietary culture and consumption preferences.

The impulse response results of the live pig industry chain prices to Industry News Uncertainty (INU) at specific historical points are shown in Figure 8. The selected points include March 2011, January 2013, and August 2018, corresponding to major news events such as the "Clenbuterol incident," "pig drifting incident," and the outbreak of "African swine fever," respectively. The impact of INU on the live pig industry chain prices at these points exhibits several notable characteristics:

1. Variability in Impact Magnitude: At these specific points, the impact of INU on supply-side prices is more significant than on the demand side. The impact on the prices of piglets and hogs exceeds 0.04, while the impact on pork prices is less than 0.01. The more substantial impact on the supply side might lead to structural adjustments within the industry chain. For instance, following the "pig drifting" and "African swine fever" incidents, the state intensified environmental regulations for pig breeding and slaughtering, leading to the elimination of numerous outdated capacities. This structural adjustment caused a severe short-term shortage in market production capacity, adversely affecting later market price fluctuations. The results are consistent with the conclusions of the above analysis.
2. Direction of Impact: INU impacts the prices of piglets and hogs positively, while its impact on demand-side pork prices alternates between positive and negative. Typically, following major pig news outbreaks, breeders cull diseased and unqualified

pigs, leading to a rapid decrease in supply-side capacity, which causes an initial rise in hog prices. On the demand side, pork prices also initially rise due to the supply shortage, but as consumers increasingly focus on the news and reduce their consumption out of concern for food safety, pork prices then decline. This alternating pattern of impact suggests a potential "intergenerational" effect of industry news uncertainty on pork prices, where changes in current market prices lead to subsequent adjustments in market supply and demand, thus adversely affecting price fluctuations.

3. Consistency Across Historical Points: The impulse responses of INU on live pig industry chain prices at these three historical points highly overlap, yet none exhibit long-term sustainability. This indicates that the impact of INU on industry chain prices follows a certain historical pattern during major pig industry news outbreaks, suggesting a high degree of consistency in its mechanism of action. The experiences from earlier events provide valuable insights. Additionally, the impact of INU on industry chain prices tends to approach zero after five periods, indicating that the effects of pig-related news do not sustainably influence prices over extended periods.

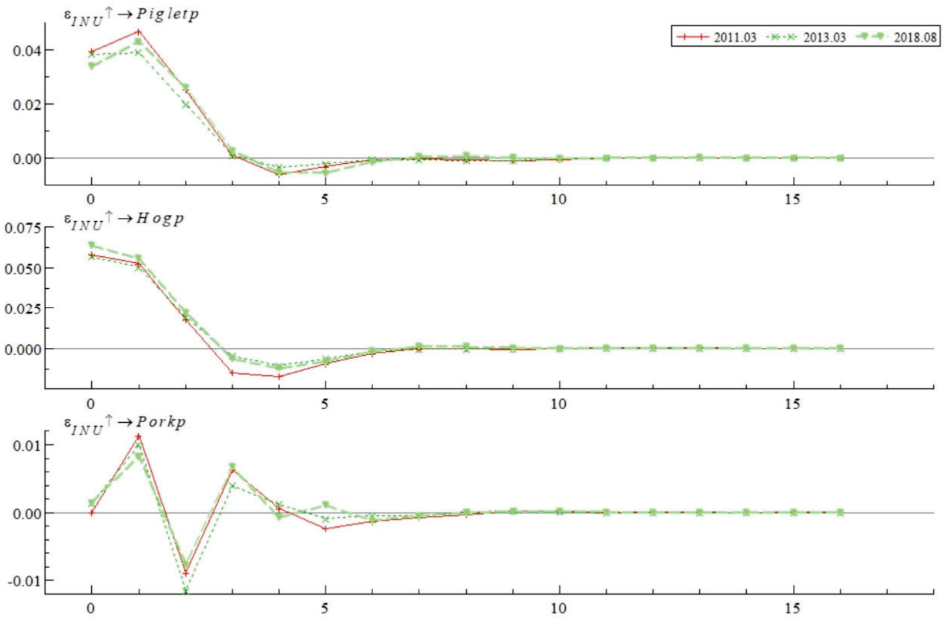

Figure 8. Impulse response of live pig industry chain price to industrial news uncertainty at specific time points.

5. Further Discussion

We build upon the initial empirical analysis by exploring three key dimensions: Firstly, we conduct a robustness test by replacing the source of the news uncertainty index compilation for the pig industry. This modification demonstrates that the findings regarding the impact of news uncertainty on the industry chain's pricing remain robust. Robustness is mainly reflected in two aspects. First, the model based on the uncertainty index compiled by Farmers Daily and the price of the live pig industry chain is stable. Second, the impact of the index compiled by Farmers Daily and People's Daily on the price of the live pig industry chain is consistent in the intensity of the impact, which is between $[-0.1, 0.1]$, and the trend of the impact curve is highly consistent in multiple time periods. Secondly, in order to verify whether the uncertainty impact of specific events is robust, the uncertainty index of a live pig epidemic is constructed to investigate its impact on the price of the industrial chain. Thirdly, we incorporate the variable of pig slaughter volume into our empirical analysis to elucidate the mechanisms through which uncertainty-induced shocks affect the industry chain's pricing.

5.1. Robustness Test

Firstly, in the robustness test segment of this research, we substituted the original source of the index from People's Daily to Farmers' Daily, aligning with the previously described method for compiling the Pig Industry News Uncertainty Index. Although Farmers' Daily is less prominent and well-known compared to People's Daily, its strong relevance to agricultural activities and significant coverage of pig-related news justify its selection as a more comprehensive source for compiling the uncertainty index of pig industry news. Over 152 months, from the inception of the digital edition of Farmers' Daily in December 2010 to August 2023, we crawled all the daily data following the electronic release of Farmers' Daily and manually screened 2,083 industry news reports related to "pig" and "live pig" through word frequency analysis. We utilized the measurement method established in Section 3 and constructed the Pig Industry News Uncertainty Index (INU_F) from Farmers' Daily.

Secondly, utilizing the newly compiled Pig Industry News Uncertainty Index (INU_F), we developed a Time-Varying Parameter—Stochastic Volatility—Vector Autoregression (TVP-SV-VAR) model to assess its impact on pig industry chain prices. According to the results detailed in Tables A1 and A2 and Figure A1 in the Appendix A, the log-difference series of INU_F has passed the Augmented Dickey–Fuller test, confirming its status as a stationary time series. Additionally, the Markov Chain Monte Carlo (MCMC) test results indicate that there are at least 153 valid samples out of 10,000 samples. At the same time, the Geweke convergence diagnosis is less than the critical value of 1.96 (Z-score) at the 95% significance level, so the null hypothesis that the parameters converge to a posterior distribution cannot be rejected. This result highlights the robustness of the TVP-SV-VAR model incorporating INU_F, Piglet, Hogp, and Porkp variables. Following this, we present the results of the impulse responses analyzed at equal intervals and at specific time points.

The equidistant impulse response results, depicted in Figure 9, illustrate the reaction of the live pig industry chain's pricing to INU_F, with impulse response curves at lag periods of 6 and 9 approaching zero. This suggests that the impact of the newly constructed INU_F on the industry's pricing lacks long-term sustainability. This result reflects that the impact of shocks such as general live pig news events can be quickly corrected in a relatively short period of time, and the government usually adopts policy measures (such as reserve meat release, import regulation, etc.) to smooth market price fluctuations and ensure market supply and price stability. These policy measures can effectively mitigate the continued impact of news events on pig prices. Hence, while the impulse responses lagged by three periods demonstrated a high degree of consistency with the original impacts on the supply and demand sides of the live pig industry chain, notable differences are observed: (1) The impact of INU_F on piglet prices alternates between positive and negative, with intensity fluctuating within the range of $[-0.005, 0.01]$. (2) A significant divergence is noted in the effect of INU_F on hog prices around 2018; the impact is positive prior to 2018 and transitions to negative thereafter. The main reason is that market expectation prior to the outbreak of African swine fever were relatively stable, which provided some support for prices. However, the media coverage following the outbreak intensified market panic, leading to a negative impact on prices. (3) The influence of INU_F on pork prices predominantly remains positive from 2013 to 2021 but shifts to negative during other periods.

The impulse response results of the pig industry chain prices to INU_F at specific time points are illustrated in Figure 10, focusing on March 2011, March 2013, and August 2018. The impulse responses reveal that INU_F exerts a positive influence on both piglet and hog prices, while its impact on pork prices alternates between positive and negative. Notably, the impact results for hog and pork prices in August 2018 exhibit opposite trends.

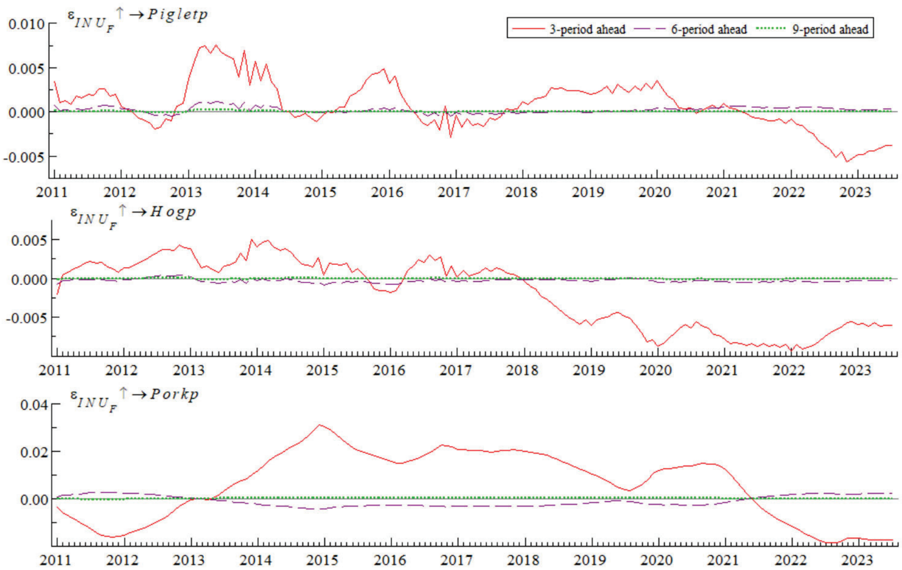

Figure 9. Equal-interval impulse response of pig industry chain price to industrial news uncertainty (INU_F).

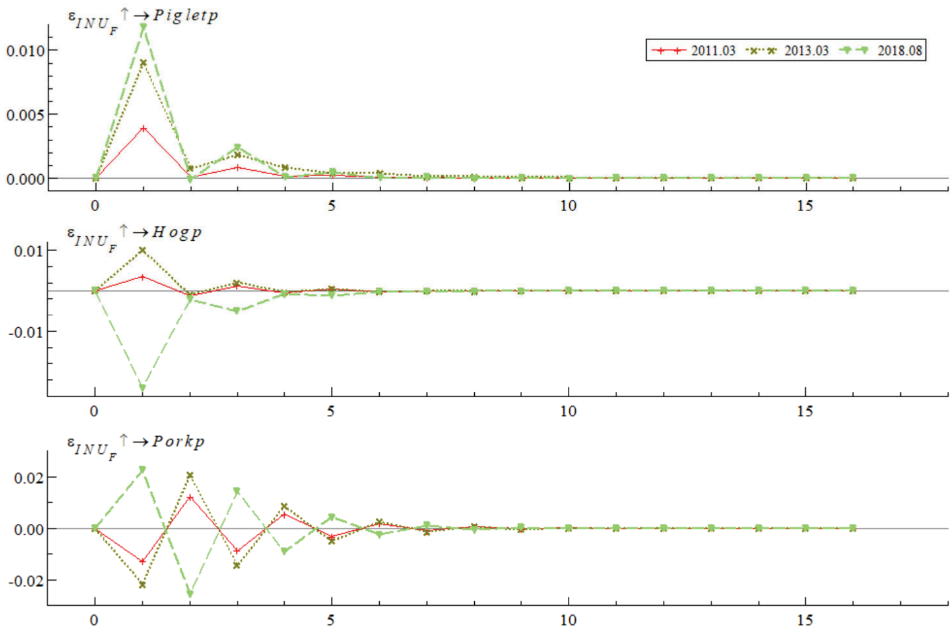

Figure 10. Impulse response of live pig industry chain price to industrial news uncertainty at specific time points (INU_F).

Employing the news uncertainty index of the pig industry compiled from Farmers' Daily, the TVP-SV-VAR model outputs for the pig industry chain prices show high consistency with those derived from the index compiled by People's Daily. This consistency underscores the robustness of the study's findings. Nonetheless, some nuanced differences in the impulse response results are observed, primarily attributable to variances in the reporting of pig-related events between People's Daily and Farmers' Daily, which serve as the sources for index compilation. Specifically, Farmers' Daily tends to include more detailed reports on pig production, management, and technology, resulting in slight discrepancies in the trends indicated by the indexes from the two newspapers. However, the trends reflected in the empirical results from both sources are relatively consistent. This outcome further demonstrated that indexes derived from more comprehensive information sources could consistently represent the impact on the industrial chain and offered more effective guidance.

5.2. Impact of Pig Epidemic on the Price of the Industrial Chain

Pig epidemic disease represents a significant component of the uncertainty surrounding the pig industry. Prior research has highlighted that outbreaks such as pig blight are crucial drivers of the cyclical fluctuations observed in pig prices. By concentrating on the impact of pig epidemic disease on the price dynamics within the industrial chain, this research not only narrows down the effects of uncertainty to specific critical points but also assesses the robustness of previous discussions concerning pig epidemic diseases.

For this purpose, we developed the Pig Disease Uncertainty Index (PDU) based on a compilation of statistical data covering deaths and culls from swine fever, porcine reproductive and respiratory syndrome, swine erysipelas, and other pig diseases. This data was collected by the Ministry of Agriculture and Rural Affairs of China over a period spanning 140 months, from January 2010 to August 2021. The method of compiling the uncertainty index of pig epidemic disease also referred to the content of Section 3.

A Time-Varying Parameter—Stochastic Volatility—Vector Autoregression (TVP-SV-VAR) model was then constructed to examine the relationship between pig epidemics and price fluctuations within the industrial chain. According to the results depicted in Tables A1 and A3 and Figure A2 in Appendix A, the log-difference series of the newly constructed PDU is stationary and passes the 1% significance test. Moreover, the Markov Chain Monte Carlo (MCMC) test results reveal that Geweke's value is less than 1.96, indicating at least 137 valid samples out of 10,000. These findings affirm the robustness of the TVP-SV-VAR model incorporating PDU, Piglet, Hogp, and Porkp. Below, we detail the outcomes of impulse responses analyzed at equal intervals and specific time points.

The equidistant impulse response results of the pig industry chain prices to the Pig Disease Uncertainty Index (PDU) are displayed in Figure 11. Here, the impulse response curves with lag periods of 6 and 9 approach zero, suggesting that the impact of the newly constructed PDU on the industry's pricing lacks long-term sustainability. From the results obtained with an impulse response lagged by three periods, it is evident that the impact of PDU on both the supply and demand sides of the live pig industry chain differs in positive and negative directions. However, the overall trend of these impacts remains highly consistent. Specifically:

1. The impact of PDU on the prices of piglets and hogs at the supply end shows a high consistency in trend and direction, indicating that the effects of pig epidemic disease are universally felt across all production stages. This may be attributed to the substantial impact that outbreaks have on the entire production and breeding chain, compelling farmers to adjust their overall production plans rather than targeting specific segments.
2. PDU exhibited a negative impact on pork prices on the demand side prior to 2018, with the most significant negative impact occurring in 2015. After 2018, the impact turned positive. This shift suggests that before 2018, outbreaks of pig disease tended to depress pork prices due to increasing concerns over pork food safety, which diminished consumer demand. Despite a short-term reduction in pig market supply, the drop in consumer demand was more pronounced, leading to lower prices. After 2018, however, the trend reversed, reflecting changes in market dynamics or consumer perceptions regarding food safety and supply stability.

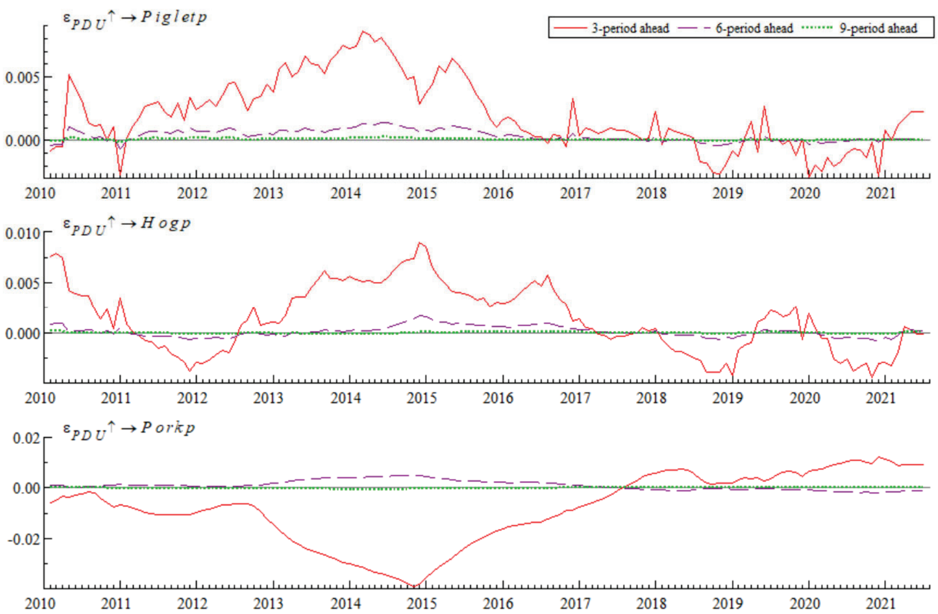

Figure 11. Equal-interval impulse response of pig industry chain price to swine disease uncertainty.

The impulse response results of the live pig industry chain prices to the Pig Disease Uncertainty Index (PDU) at specific time points are depicted in Figure 12, focusing on October 2010 and December 2015. These periods were selected due to the severity of swine fever in 2010 and porcine reproductive and respiratory syndrome in 2015, both of which significantly influenced the industrial chain. While other time points also experienced serious pig epidemics, they were accompanied by other unobservable factors that could lead to biased empirical results. The findings are as follows:

1. The pig epidemics in 2010 and 2015 demonstrated significant differences in the impacts on the prices at the supply side and demand side of the industrial chain, aligning with the results from the equally spaced impulse response analysis.
2. The impact of the pig epidemic on the prices of piglets and hogs at the supply end is initially positive but trends towards zero as the lag period increases. This indicates that the epidemic led to a decrease in the number of piglets and hogs at the supply end, consequently driving up the prices due to reduced supply.
3. The impact of the pig epidemic disease on the price of pork on the demand side initially shows a negative response, which then alternates but eventually trends to be positive. This pattern suggests that consumer concerns about food safety initially drove prices down. However, as the severity of the epidemic alleviated over time and the realities of market supply became apparent, the impact on prices turned positive and eventually stabilized.

The findings on the impact of the pig epidemic uncertainty index on the industrial chain's prices reveal that the constructed uncertainty index for this specific event, despite its relatively limited informational depth, can still reliably represent price fluctuations. This also validates the broad applicability of the uncertainty analysis framework for hogs that we have developed.

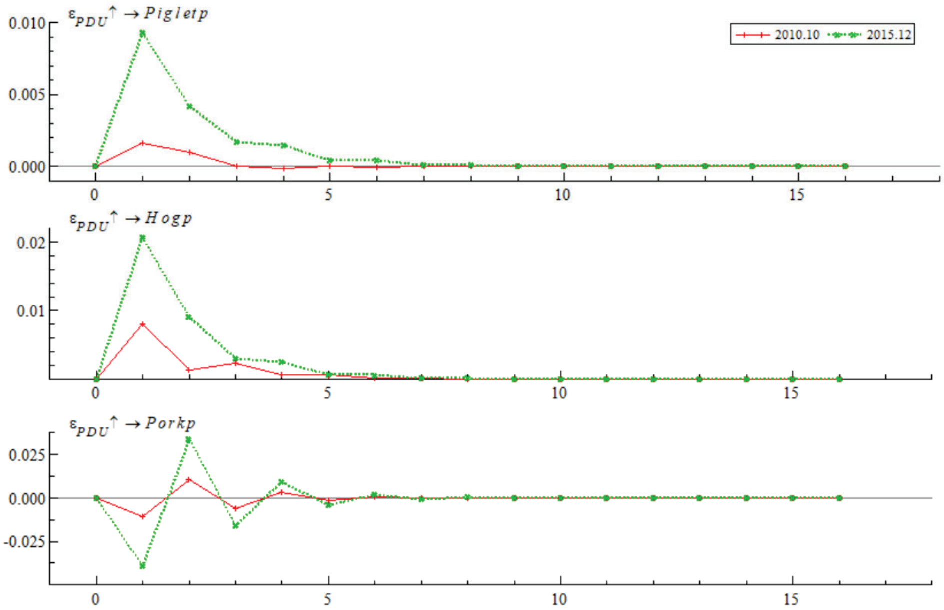

Figure 12. Impulse response of live pig industry chain price to swine disease uncertainty at specific time points.

5.3. Potential Mechanism

In our analysis, we conceptualize the impact of uncertainty on price fluctuations within the industrial chain as being mediated by the dual forces of supply and demand. To quantitatively elucidate this mechanism, we introduce pig slaughter volume as a mechanistic variable. By examining how uncertainty influences pig slaughter volumes, we elucidate the operational dynamics of the "uncertainty—pig slaughter volume—industry chain price" mechanism.

The data for the number of pigs slaughtered, sourced from the Ministry of Agriculture and Rural Affairs, is transformed into a time series denoted as NPS, achieved by taking the natural logarithm and then differencing the data. Utilizing this transformed data, we construct a Time-Varying Parameter—Stochastic Volatility—Vector Autoregression (TVP-SV-VAR) model incorporating Economic Policy Uncertainty (EPU), Live Pig Industry News Uncertainty (INU), and NPS to investigate the impact of uncertainty on the quantity of pig slaughters.

The test results for the variables and the model are presented in Tables A1 and A4, and Figure A3 in Appendix A. The analyses confirm that the time series data are stationary and that the Markov Chain Monte Carlo (MCMC) results uphold the reliability of the findings. This robust approach allows for a detailed understanding of how fluctuations in uncertainty metrics affect critical operational variables within the pig industry, providing insights into broader economic dynamics.

The impulse response results of pig slaughter quantity to uncertainty are depicted in Figure 13, which includes (a) results for equidistant impulse responses, and (b) results for impulse responses at specific time points. The findings are detailed as follows:

1. Equal-interval Impulse Responses: The response curves at lag 6 and lag 9 periods approach zero, suggesting that uncertainty does not exert a long-term sustainable impact on the quantity of pigs slaughtered. This indicates that the immediate effects of uncertainty are more pronounced than their prolonged influences.
2. Differential Impacts of EPU and INU: The effects of Economic Policy Uncertainty (EPU) and Live Pig Industry News Uncertainty (INU) on the slaughter quantity are markedly distinct. EPU had a positive impact on the number of pigs slaughtered from 2010 to 2015 and again after 2020, but a negative impact from 2015 to 2020. Conversely,

INU consistently had a negative impact on the number of pigs slaughtered throughout the period under review. Theoretically, the influence of uncertainty on slaughter volumes is expected to inversely correlate with its impact on the demand-side price of pork.

3. Specific Time Points Analysis: August 2018 and March 2021 were selected as specific time points to assess the impact of uncertainty on pig slaughter quantities, coinciding with the African swine fever epidemic (related to INU) and the COVID-19 pandemic (related to EPU), respectively. The findings reveal that the impact of EPU on pig slaughter quantities was initially negative and then turned positive, which contrasts with the impact of EPU on pork prices. On the other hand, the impact of INU on pig slaughter quantity remained negative, suggesting a corresponding rise in pork prices during this period, aligning with the empirical results observed for INU's impact on pork prices.

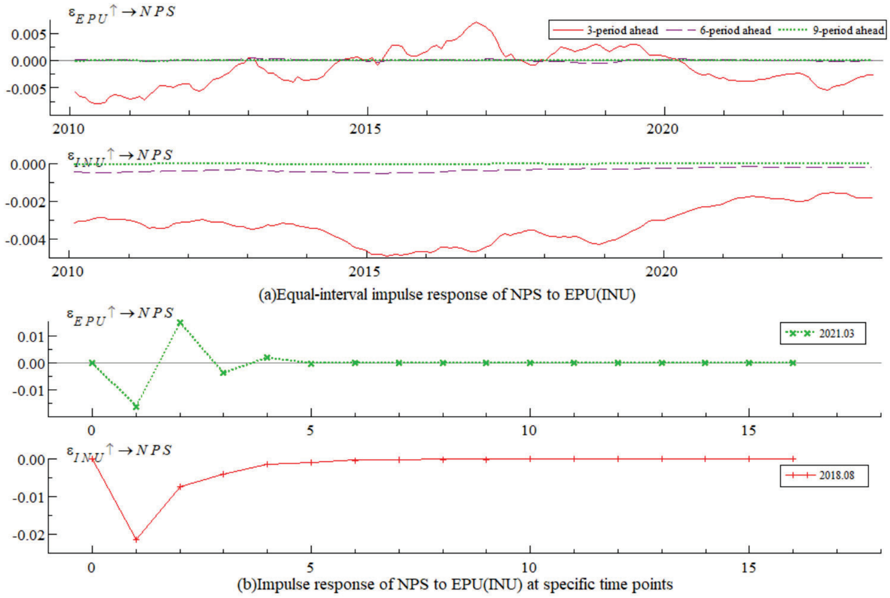

Figure 13. Results of the impulse response of pig slaughter quantity to uncertainty shock.

The empirical findings regarding pig slaughter volume and uncertainty demonstrate that the potential mechanism variable of pig slaughter volume effectively sustains the relationship between uncertainty and industry chain price. Concurrently, this evidence further corroborates the theory presented in Section 2.

6. Conclusions and Recommendations

6.1. Conclusions

This paper examines the dynamic impact of external shocks on the price of the live pig industry chain, and the main findings are as follows:

1. The impact of economic policy uncertainty on the supply side and demand side prices of the live pig industry chain shows obvious time-varying characteristics. The impact on the price of piglets and live pigs on the supply side is greater than that on the pork price on the demand side, which reflects that the manufacturers on the supply side are more vulnerable to the impact of economic policy changes and face greater risks. The main reason is that economic policy has a more direct impact on the supply side, including the adjustment of production costs and market expectations. In contrast, the impact on the demand-side price is more indirect, occurring through channels such as consumption behavior and competition in the commodity market, and thus

experiences a time lag. Additionally, Chinese consumers' dietary habits and low sensitivity to pork prices further support to the stability of pork prices.
2. The impact of industry news on the supply and demand sides of the live pig industry chain is quite different. The supply side is mainly affected negatively, while the demand side is mainly affected positively. Negative news in the industry reduces market expectations of farmers and forces manufacturers to reduce their willingness to expand scale, thus reducing capacity. However, news reports such as strict environmental policies are positive information for consumers, which can effectively enhance consumers' trust in pork and purchase intention. At the same time, the market demand is inelastic in the short term, and pork consumption is difficult to be replaced.
3. Impulse responses at specific time points reveal that different types of external shocks have different impacts on the price of the live pig industry chain, but at the same time, they all aggravate the original fluctuation degree. On the supply side, economic policy uncertainty negatively affects prices due to its varying ability to regulate market supply, while uncertainty in industry news has the opposite effect. On the demand side, external shocks initially drive prices up, but their impact turns negative over time.
4. The uncertainty indexes compiled from different information sources effectively reflect the impact on the price of the industrial chain, and confirm that the pig slaughter quantity is the key mechanism link. Whether it is the news uncertainty index compiled by Farmers' Daily or the uncertainty index focusing on the pig epidemic, it effectively measures the impact of external shocks on the price of the pig industry chain. In addition, pig slaughter volume is identified as a key mechanism linking external shocks to price fluctuations, a relationship supported both by the theoretical framework and the empirical results of the analysis.

6.2. Recommendations

1. Establish and improve the risk monitoring and early warning mechanism of the live pig market, and improve the ability of the industrial chain to resist external risks. Relevant agencies must strengthen monitoring and early warning of risks such as swine diseases and food safety problems. Big data and other technologies are used to regulate the market, and a characteristic and professional uncertainty index is constructed to promote the continuous assessment of potential external risks in the pig market.
2. The policies of relevant departments for the live pig market need to be targeted and appropriately adjusted around price and supply and demand. It is crucial to avoid excessive or mismatched policy implementations that could exacerbate market price fluctuations. Additionally, attention should be given to the sentiment of market participants, guiding the production behaviors of manufacturers, and adopting counter-cyclical measures to regulate production capacity effectively.
3. Strengthen the dynamic monitoring of public opinion within the live pig industry chain, and ease the impact of shocks on the consumer market with prudent policies. Agriculture, health and market supervision departments should establish a rapid reaction mechanism of public opinion to deal with the adverse impact of negative news on market consumption. Measures such as price support, subsidies, and other interventions should be implemented to restore consumer confidence and stimulate demand growth.

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Abbreviations

The following abbreviations are used in this manuscript:

TVP-SV-VAR	Time-Varying Parameter—Stochastic Volatility—Vector Autoregression
EPU	Economic Policy Uncertainty
INU	Live Pig Industry News Uncertainty

Appendix A

Table A1. The unit root test results of variables in the Section 5.

Variable	ADF	PP	KPSS	Verdict
INU_F	−11.4401(2) ***	−24.9629(3) ***	0.051379(6)	stationary
NPS	−3.0286(11) ***	−24.9331(23) ***	0.1488(26)	stationary
PDU	−16.8981(0) ***	−17.6459(5) ***	0.0514(14)	stationary

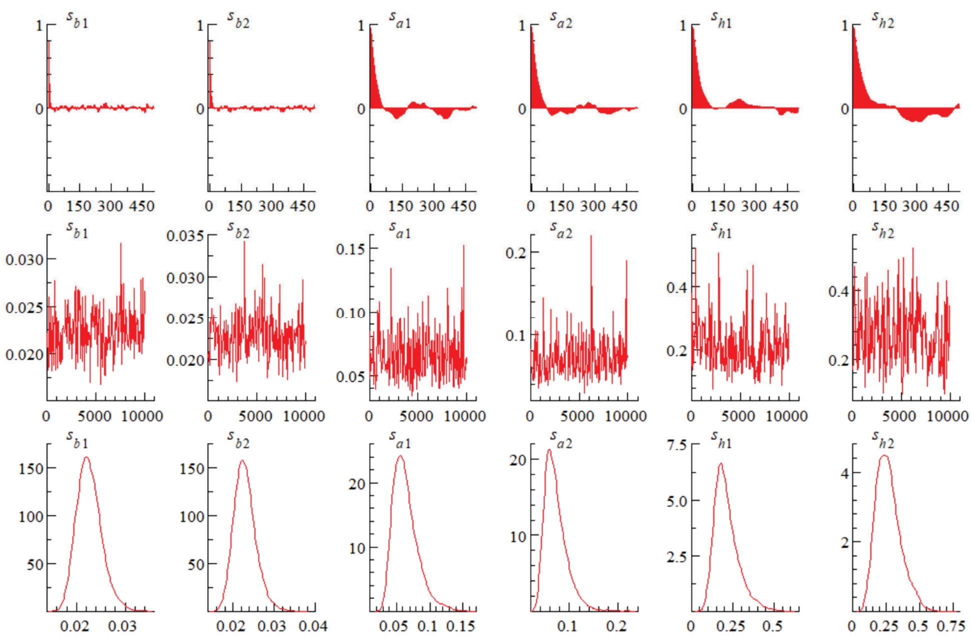

Figure A1. Sample autocorrelation, path, and posterior density estimated by MCMC in Section 5.1.

Table A2. Parameter estimation results in the TVP-SV-VAR model in Section 5.1.

Parameter	Mean	Std.Dev.	95%L	95%U	Geweke	Inefficiency
$(\Sigma_b)_1$	0.0226	0.0025	0.0182	0.0282	0.370	8.37
$(\Sigma_b)_2$	0.0229	0.0026	0.0184	0.0288	0.663	7.05
$(\Sigma_\alpha)_1$	0.0641	0.0186	0.0373	0.1110	0.541	32.88
$(\Sigma_\alpha)_2$	0.0718	0.0231	0.0402	0.1278	0.078	37.85
$(\Sigma_h)_1$	0.2123	0.0728	0.1054	0.3946	0.024	59.92
$(\Sigma_h)_2$	0.2670	0.0902	0.1212	0.4741	0.054	65.14

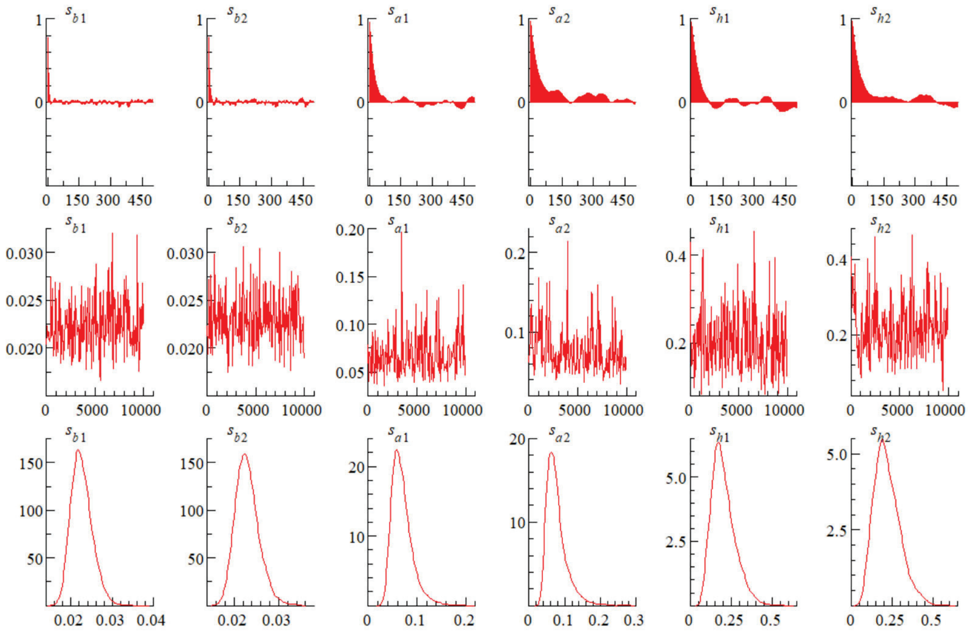

Figure A2. Sample autocorrelation, path, and posterior density estimated by MCMC in Section 5.2.

Table A3. Parameter estimation results in the TVP-SV-VAR model in Section 5.2.

Parameter	Mean	Std.Dev.	95%L	95%U	Geweke	Inefficiency
$(\Sigma_b)_1$	0.0226	0.0025	0.0184	0.0281	0.343	8.97
$(\Sigma_b)_2$	0.0229	0.0026	0.0185	0.0287	0.568	8.58
$(\Sigma_\alpha)_1$	0.0695	0.0212	0.0399	0.1230	0.045	44.39
$(\Sigma_\alpha)_2$	0.0770	0.0291	0.0408	0.1510	0.018	83.15
$(\Sigma_h)_1$	0.2033	0.0709	0.0947	0.3697	0.962	52.71
$(\Sigma_h)_2$	0.2198	0.0783	0.0939	0.4012	0.766	72.66

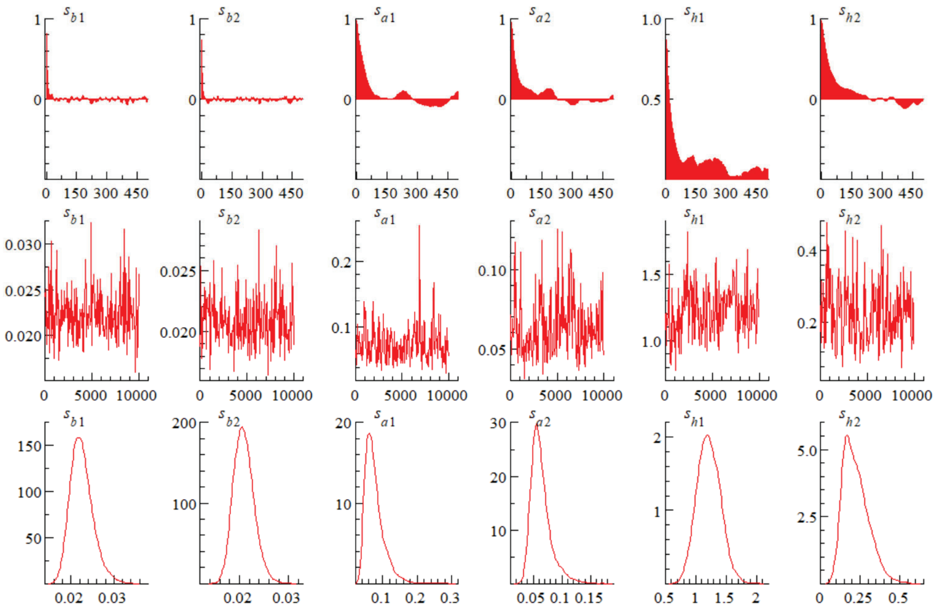

Figure A3. Sample autocorrelation, path, and posterior density estimated by MCMC in Section 5.3.

Table A4. Parameter estimation results in the TVP-SV-VAR model in Section 5.3.

Parameter	Mean	Sth.Dev.	95%L	95%U	Geweke	Inefficiency
$(\Sigma_b)_1$	0.0225	0.0026	0.0181	0.0285	0.254	9.96
$(\Sigma_b)_2$	0.0209	0.0021	0.0173	0.0253	0.554	4.23
$(\Sigma_\alpha)_1$	0.0762	0.0294	0.0409	0.1496	0.548	70.97
$(\Sigma_\alpha)_2$	0.0634	0.0178	0.0390	0.1097	0.826	65.63
$(\Sigma_h)_1$	1.2152	0.1901	0.8614	1.5978	0.001	71.79
$(\Sigma_h)_2$	0.2237	0.0793	0.1066	0.4033	0.134	88.84

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Nutrient Management Under Good Agricultural Practices for Sustainable Cassava Production in Northeastern Thailand

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Abstract: Emphasis on sustainable cassava production is increasing, with aims to increase the net income of cassava farmers in an ecologically friendly way. This study examined the optimization of soil fertilizer management at two research locations (Nampong and Seungsang) in northeastern Thailand. The experiment was conducted as a randomized complete block design with five replications. Eight different fertilizer management protocols consisted of (1) no fertilizer application (control), (2) the recommended dosage of chemical fertilizer (RDCF), (3) 3.12 t ha^{-1} of chicken manure (CM), (4) 937.5 L ha^{-1} of swine manure extract (SME), (5) CM + SME, (6) ½ RDCF + ½ CM, (7) ½ RDCF + ½ SME, and (8) CM + PGPR (stake soaking with PGPR solution). At the Nampong site, the application of CM + PGPR has the most potential for increasing the cassava yield in terms of the fresh tuber yield when compared with no fertilizer and RDCF applications. At the Seungsang site, the application of CM gave the high fresh tuber yield, without significant differences from RDCF applications. Furthermore, compared to the RDCF treatment, both soil fertilizer management protocols produced positive marginal rate of return values, showing clear potential for contributing to sustainable cassava production.

Keywords: cassava; sustainable production; marginal rate of return; microbiome; fresh storage root yield

1. Introduction

Sustainable cassava (*Manihot esculenta* Crantz) production is increasingly becoming a priority for tropical climate farmers worldwide [1]. The development of production models that help to maintain ecosystem functioning while generating worthwhile profits can be challenging because of the many factors involved in agroecosystem management. Farmers are faced with the need to maintain or improve yields on soils that are being degraded from cultivation practices and the overuse of synthetic fertilizers and pesticides [2,3]. Increasing synthetic fertilizer costs are making such a task continually more important as they often increase at rates faster than those of cassava crop selling prices, making synthetic fertilizer use less profitable than before [4].

Farmers often put little significance on overall soil health and the use of ecosystem services from soil microbes, microinvertebrates, macroinvertebrates, and other members of the soil food web [5]. This may be due to the fact that the benefits of these ecosystem services often take long periods to observe and do not always result in direct yield increases. Indirect benefits may include pest and disease suppression through competition, beneficial metabolite production, phytohormone modulation, and increases in soil nutrient availability [6]. The sustainability of cassava production going into the future will depend on more holistic approaches, which need to be studied to gain more understanding of how to apply them in real farm situations [7].

Thailand cassava production scored very well on the Social Life Cycle Assessment (SLCA) scale, an internationally recognized social sustainability assessment tool used to inform decisions on sustainable development [8]. Current trends in Thailand crop growth patterns suggest that cassava farming is becoming more popular in Thailand, partly due to the plant's ability to grow in poor soils and relatively low susceptibility to drought, an effect of climate change and unsustainable land use practices [9]. Climate change analysis predicts that the northeastern part of Thailand will have the greatest increase in cassava-growing season temperatures, and the cassava yield is projected to drop in this region [10]. Like any crop, when cultivated on the same land for long periods, cassava can deplete available nutrients, and production practices tend to erode soils, a fact that hinders its potential for ecological sustainability [11–13]. More ecologically friendly soil management practices may be used to mitigate the negative effects that these upcoming climate changes will have on northeastern Thailand cassava production.

Several studies have demonstrated yield advantages from incorporating farm wastes, organic fertilizers, and other amendments into cassava field soils [14,15]. Nutrients and organisms in manures can be beneficial for cassava production, both used solely and in combination with synthetic fertilizer [4,16–19]. Incorporation of both animal and green manures into soil can increase soil organic matter (SOM), which has been shown to buffer the adverse effects of extreme weather events, including those causing both excess water and drought [20,21]. Manure application can also improve soil fertility maintenance, an important aspect of farm sustainability [22]. While the nutrients in field soils and manures can be easily assessed, the microorganisms involved in these agroecosystems exist in dynamic symbiotic relationships that take place in extremely complex soil food webs [23]. Although the exact biochemical mechanisms controlling microbial–plant interactions are difficult to pinpoint, they can still be used in efforts to make cassava production more economically and ecologically sustainable. This can be conducted by limiting expensive off-farm inputs and improving overall agroecosystem functioning [24].

Many studies that involve limiting synthetic fertilizer and pesticide use have been conducted on organic cassava production, due to the strict organic production requirements and the higher selling price of cassava products when compared with those of non-organic cassava, making the endeavor financially more worthwhile [25,26]. Good agricultural practice (GAP) guidelines are based on many of the same sustainability principles as organic guidelines but are more lenient. While smallholding non-organic cassava farmers, who manage areas less than 10 ha [27] may not see organic production as feasible for their farming systems, GAPs may be adopted more if their profitability can be communicated to farmers.

Problems with cassava production profitability in Thailand have been linked to factors like volatile market prices, disease outbreaks, and increases in the costs of off-farm inputs, particularly synthetic fertilizer and pesticide products [25]. The presence of intensive livestock farming in many regions of Thailand provides an opportunity to replace synthetic fertilizer use with that of manure, without many additional transport costs. Farmyard manure (FYM) and other agricultural byproducts, like green manure, also tend to have less price fluctuations. Some of the literature has reported popular organic amendments used in cassava production. In northeastern Thailand, chicken manure, cassava starch production waste [28], and liquid swine manure extract [29] have been particularly useful and their application has been observed to promote a greater fresh tuber yield, with values that were not significantly different from those resulting from synthetic fertilizer application at recommended doses. In some trials, the use of these organic amendments in combination with synthetic fertilizer application allowed for synthetic fertilizer rates to be reduced by half. Therefore, the promotion of using FYM or locally derived agricultural byproducts for amending cassava system soils may benefit farm profitability and the overall sustainability of cassava-based cropping systems.

Efforts are also underway to enhance cassava growth via the pre-planting treatment of stem cuttings by soaking with rhizobacteria that are known to be plant growth-promoting rhizobacteria, or PGPRs [30]. Even after decades of study, research teams from different regions continue to search for PGPR strains that are appropriate for use in their respective local environmental conditions [31–33]. Since cassava is the third most important source of calories in tropical and subtropical regions, after rice and corn, many government agencies have been employed to increase its productivity through improved farming methods in order to meet the rising demand for this root tuber crop. Yields have increased over time, mainly due to improved varieties and better agricultural practices. The average cassava yield in Thailand from 2014 to 2024 was estimated to be 19.4–22.6 t ha^{-1} [34–36]. This yield has been exceeded in studies that provided suitable growth conditions. For instance, in Thailand, optimal irrigation resulted in a yield of 56.9 t ha^{-1} from the Rayong 9 variety [37].

Better economic opportunities for farmers can be provided by formulating suitable efficient nutrient management practices to maximize production to input cost rations. This is exemplified by the study of Aravind et al. [38] in India which reported that an optimal nutrient application (25 t ha^{-1} of farmyard manure + 100% recommended dose of chemical fertilizer + cassava booster spray) produced 33.27 t ha^{-1} from the Vellayani Hraswa variety, which could be harvested in 6–7 months instead of the typical 9–24 months. These simple adjustments in crop management, using strategies that are suitable for each region under cultivation, have great potential for increasing production while also improving the livelihood of cassava farmers.

Given this background, and with the overall goal of developing guidelines for increasing cassava production's economic, ecological, and social sustainability, an integrative study was conducted to compare the use of chemical, chicken manure, swine manure, and PGPR-strain biological fertilizers in eight nutrient management treatments to determine their effects on cassava growth, yield components, and profitability, while also testing for correlations with nutrient uptake in an attempt to identify mechanisms by which growth and yield are affected by these different treatments. These eight management protocols were conducted at both of the two different field sites in Seungsang district, Nakhon Ratchasima province, and Nampong district, Khon Kaen province, two regions in northeastern Thailand. The findings of the current study will add to a bank of applicable knowledge that can be further tested and used for increasing the efficiency of cassava production.

2. Materials and Methods

2.1. Research Location and Soil Characteristics

Field trials were conducted at two locations in northeastern Thailand, the current dominant cassava-growing region of the country. The first field site is located in Nampong district, Khon Kaen province (Latitude: 16.823750, Longitude: 102.979556). The soil type belongs to the Nam Phong soil series (Loamy, siliceous, isohyperthermic Grossarenic

Haplustalfs). The soil of the experimental field has a sandy texture [21]. The chemical properties of the experimental plot's soil were as follows: pH 5.60 (moderately acidic), EC 0.12 dS m^{-1} (non-saline), 0.46% organic matter (very low), 0.02% total N (very low), 9.00 mg kg^{-1} available P (low), and 34.00 mg kg^{-1} available K (low). Throughout the experimental period, the study site's growth season temperatures averaged 27.1 °C, with a normal range of 23.0 °C to 30.5 °C.

The second field site is located in Seungsang district, Nakhon Ratchasima province (Latitude: 14.490722, Longitude: 102.508167). The soil type belongs to the Chokchai soil series (very fine, kaolinitic, isohyperthermic Rhodic Kandiustox). The soil of the experimental field has a silty clay texture [39]. The chemical properties of the experimental plot's soil were as follows: pH 6.15 (slightly acidic), EC 0.14 dS m^{-1} (non-saline), 2.98% organic matter (medium), 0.15% total N (low), 25.33 mg kg^{-1} available P (high), and 40.65 mg kg^{-1} available K (low). The temperatures of the study site during the growing season typically ranged from 23.5 °C to 29.5 °C, with an average of 26.8 °C throughout the experimental period.

Both locations are owned by smallholder farmers (less than 10 ha) who have been growing cassava for more than 5 years. The Nam Phong soil series in Nampong district and the Chokchai soil series in Seungsang district are two of the most studied soil series in Thailand for cassava cultivation [21,40–42].

The organic soil amendments used in this experiment were chicken and swine manure. The chemical properties of the chicken manure were as follows: pH 7.69, EC 7.29 dS m^{-1}, 41.88% organic matter, 2.67% total N, 0.97% total P, 2.24% total K, and a C/N ratio of 8.38. The swine manure chemical properties were as follows: pH 7.22, EC 4.99 dS m^{-1}, 44.79% organic matter, 1.22% total N, 1.25% total P, 1.05% total K, and a C/N ratio of 21.16 [43].

2.2. Plant Materials and Experimental Design

The commercial Rayong 72 cassava variety, which is well known for its high yield, high starch quality, good stem quality, and resistance to drought [44], was utilized because planting was planned for March, which is considered part of the dry season in Thailand. This variety is also known to perform well in the early rainy season (in May) and has been reported to have drought tolerance during a 4-month drought period in the mid-growth stage, as shown by the high storage root yield and high leaf retention [45].

The experiment was arranged as a randomized complete block design (RCBD) with five replicates. At the two study sites, namely Nampong and Seungsang, the eight different fertilizer management protocols conducted were as follows: (1) no fertilizer application (control), (2) recommended dosage of chemical fertilizer based on soil analysis (RDCF) [46], (3) 3.12 t ha^{-1} of chicken manure (CM), (4) 937.5 L ha^{-1} of swine manure extract (SME), (5) 3.12 t ha^{-1} of chicken manure + 937.5 L ha^{-1} of swine manure extract (CM + SME), (6) 50% of the recommended dose of chemical fertilizers + 1.56 t ha^{-1} of chicken manure (½ RDCF + ½ CM), (7) 50% of the recommended dose of chemical fertilizers + 468.8 L ha^{-1} of swine manure extract (½ RDCF + ½ SME), and (8) 3.12 t ha^{-1} of chicken manure + stake soaking with plant-growth-promoting rhizobacteria (PGPR) solution (CM + PGPR). The description of the macronutrient contents from each fertilizer application is shown in Table 1.

After plowing using a 7-disc plough, 40 plots were prepared at both study sites, each having dimensions of 5 m wide by 6 m long (30 m^2). Rayong 72 cassava stakes, aged 12 months and 25 cm long, were planted at 1 m × 1 m standard inter- and intra-spacing (20 plants $plot^{-1}$). For the fertilizer application, chicken manure was produced from a mixture of chicken excrement, feathers, and rice husk bedding material, all of which was composted in sacks for one month before use. To limit erosion and volatilization, chicken manure compost was incorporated into the soil by digging holes to a depth of 10 cm and thoroughly mixing the chicken manure compost into the soil two weeks before planting. These positions were marked so that cassava stalks could be planted directly into them two weeks later. The swine manure compost extract was made by soaking dry manure compost in tap water at a ratio of manure compost to water of 1:10, by weight. This procedure was adapted from the work reported by Kanto et al. [28]. The compost was soaked for 24 h, after which the water was filtered twice using cheesecloth. The resulting solution was then applied manually by misting the underside of cassava plant leaves to maximize uptake by stomata. This treatment was conducted monthly, from 2 to 5 months after planting (MAP), for a total of 4 applications. A chemical fertilizer combination was used to fulfill the recommended soil nutrient requirements based on soil analysis. In a single application, the fertilizer was incorporated into soil on both sides of each cassava plant 1 MAP. The PGPR-3 biofertilizer product was used to soak cassava stalks for 30 min before planting. The powdered product was mixed with tap water at a ratio of 1 kg of product to 20 L of water per hectare of planting area. This product was applied only once. Plants were irrigated equally by drip irrigation in all plots, as required to maintain vigorous growth. Specifically, the crops were partially irrigated during the rainy season and fully irrigated during the dry season. Natural extracts were sprayed to eliminate both diseases and insects when needed, and mechanical methods eliminated weeds every month until harvesting.

Table 1. Proportion of primary elements when various fertilizers were applied for each treatment.

Fertilizer Treatment	**Application Rates**	**Soil Application**			**Foliar Application**		
		N (kg ha^{-1})	**P (kg ha^{-1})**	**K (kg ha^{-1})**	**N (kg ha^{-1})**	**P (kg ha^{-1})**	**K (kg ha^{-1})**
Control (no fertilizer)	-	-	-	-	-	-	-
RDCF	CF 16-8-8 at 312.5 kg ha^{-1} CF 0-0-60 at 43.8 kg ha^{-1}	50.00	25.00	50.00	-	-	-
CM	CM 3125.0 kg ha^{-1}	83.11	30.31	70.00	-	-	-
SME	SME 937.5 L ha^{-1} × 4 times	-	-	-	4.58	4.69	3.94
CM + SME	CM 3125.0 kg ha^{-1} SME 937.5 L ha^{-1} × 4 times	83.11	30.31	70.00	4.58	4.69	3.94
½ RDCF + ½ CM	CF 16-8-8 at 156.3 kg ha^{-1} CF 0-0-60 at 21.9 kg ha^{-1} CM 156.3 kg ha^{-1}	66.72	27.66	60.00	-	-	-
½ RDCF + ½ SME	CF 16-8-8 at 156.3 kg ha^{-1} CF 0-0-60 at 21.9 kg ha^{-1} SME 468.8 L ha^{-1} × 4 times	25.00	12.50	25.00	2.29	2.34	1.97
CM + PGPR	CM 3125.0 kg ha^{-1} Stake soaking with PGPR	83.11	30.31	70.00	-	-	-

RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria (with PGPR-3 containing two types of bacteria: *Azospirillum brasilense* and *Gluconacetobacter diazotrophicus*).

2.3. Data Collection and Analysis

2.3.1. Plant Growth

Five randomly selected samples from the middle rows per each experimental plot were collected to determine vegetative growth, including plant height, plant width, and leaf number at 2, 4, 6, and 8 MAP. The plant height was measured using measuring tape, from soil level at the base of the plant to the terminal bud, while the plant width was collected as the average width measured at the widest point 90° to the plant. In addition, the leaf chlorophyll was measured from the central lobe of the fourth expanded leaf from the top using a chlorophyll meter (SPAD 502Plus, Konica Minolta, Inc., Tokyo, Japan) every 2 months until 8 MAP.

2.3.2. Yield and Starch Content

Harvesting was conducted at 10 MAP, and the fresh tuber yield and starch content were recorded. After uprooting, the stumps were cut at 20 cm above the soil surface level, and then stumps and tubers were washed in running tap water to remove any adhering soil particles. The fresh mass of tubers was recorded in the field with a digital balance, and these values were used for the fresh tuber yield. The starch content of each sample was measured using the specific gravity method, which is based on the correlation between the starch content and the specific gravity of tubers using a Reimann scale balance according to Bainbridge et al. [47]. Briefly, the tubers were washed to remove excess soil, homogenized, and a 5 kg subsample per sample of fresh tubers was weighed in air and placed in water to obtain the specific gravity (SG), which is equal to 5 kg/(5 kg FWW) where FWW is the weight measured on a hydrostatic scale after submerging the tubers in water. Based on the obtained measurement results, the cassava density and the dry matter content are calculated. The cassava starch value is obtained by subtracting the content of non-starchy components from the dry matter content.

2.3.3. Sample Preparation and Nutrient Analysis

The leaf, stem, and tuber samples were chopped and dried in an oven (Thermotec 2000, Contherm Scientific Ltd., Lower Hutt, New Zealand) at 60 °C until constant sample weights were achieved. The samples were ground and then sieved through a 2 mm sieve before analysis of N, P, and K contents on a % dry weight basis. To determine the total N content, the Kjeldahl method was used, and for determining the P and K contents in the plant tissues, the standard protocol of the Association of Official Analytical Chemists (AOAC) [48] was followed with some modifications. Each sample, weighing 1.0 g, was digested in 15 mL of nitric-perchloric acid (HNO_3:$HClO_4$ at a ratio of 2:1 *v*/*v*). After digestion, the samples were diluted with distilled water until they reached a volume of 50 mL and were then stored in plastic tubes at room temperature. The P content in the diluted samples was analyzed by using a spectrophotometer (UV-1280, Shimadzu, Kyoto, Japan) at 420 nm. In contrast, the K quantification was analyzed using an atomic absorption spectrometer (PinAAcle900F, Perkin-ESMEer, Waltham, MA, USA).

2.3.4. Economic Analysis

Economic feasibility of the fertilizer management for cassava production in two study sites was determined by calculating net benefit and conducting an economic cost and benefit analysis, based on the partial budget techniques described by the International Maize and Wheat Improvement Center (CIMMYT) [49]. Prevailing market prices for inputs during planting time and outputs during harvesting time were used in calculations. All costs and benefits were converted to USD per hectare. The main equations used during the economic analysis by partial budgeting included the following:

$$\text{TVC} = \text{FFC} + \text{AC} + \text{HPTC} \tag{1}$$

$$\text{GFB} = \text{AAY} \times \text{CFP} \tag{2}$$

$$\text{NB} = (0.9 \times \text{GFB}) - (1.1 \times \text{TVC}) \tag{3}$$

where

TVC = total variable cost in USD ha^{-1};
FFC = fertilizer field cost in USD ha^{-1};

AC = fertilizer application cost in USD ha^{-1};
HPTC = harvesting, packing, and transport cost of fresh tubers in USD ha^{-1};
GFB = gross field benefit in USD ha^{-1};
AAY = adjusted average yield, which is 90% of the average yield in kg $plant^{-1}$ × planting rate (plant ha^{-1});
CFP = cassava field price in USD kg^{-1};
NB = net benefit in USD ha^{-1}.

After the TVC and GFB per ha were calculated for the treatments, dominance analysis was performed using the methods described by the CIMMYT [49]. Dominance analysis determined which treatments were dominated, meaning that they have net benefits that are less than or equal to those of treatments that have lower costs. The TVC and NB values of non-dominated treatments were then used for marginal rate of return (MRR) analysis to determine how much farmers would benefit when switching between economically beneficial treatments with a sequentially greater TVC. Non-dominated treatments were ranked from the lowest to highest TVC. MRR analysis was performed between treatment pairs, in order from treatments that had the lowest to highest TVC. The MRR calculation for each treatment pair was conducted with the following formula:

$$MRR = [(\Delta NB)/\Delta TVC] \times 100\% \quad (4)$$

where

MRR = marginal rate of return in percent;
NB = net benefit in USD ha^{-1};
TVC = total variable cost in USD ha^{-1}.

Using this method, a 100% MRR means that for every USD invested in switching between treatment pairs, there would be a USD 1 return on investment.

In order to make recommendations from economic analysis data, a minimum acceptable MRR value is required. In this study, a minimum acceptable MRR of 100% was chosen. This means that if a soil and plant management treatment results in an MRR of 100% or higher, that treatment would be recommended to farmers.

2.4. Statistical Analysis

Experimental treatment effects were analyzed using a randomized complete block design with five replications, and the statistical analysis of data collected was carried out using standard analysis of variance by using IBM SPSS Statistics, Version 26.0 software (IBM Crop., Armonk, NY, USA). To determine the significance of the difference between the means, Duncan's multiple range test was computed at the 0.05 probability level ($p \leq 0.05$). A correlation heatmap was made using Python visualization (version 3.11.7) to facilitate visual inspection for evaluating the relationships between different parameters at the two study sites.

3. Results

3.1. Plant Growth and Chlorophyll Content

At the two study sites, different soil management treatments were shown to affect traits related to cassava plant growth, including plant height and plant width, recorded at 2, 4, 6, and 8 MAP (Tables 2 and 3). At the Nampong site, different nutrient management treatments resulted in significantly different plant height at 4 MAP, with the plants from the ½ RDCF + ½ CM treatment having significantly greater height than those from the SME, ½ RDCF + ½ SME, and control treatments. At 2, 6, and 8 MAP, however, no significant differences in height were observed among the treatments. The plant height of cassava at 2, 6, and 8 MAP was shown to be between 62.80 and 74.02 cm, 191.80 and 225.68 cm, and 210.00 and 240.66 cm, respectively (Table 2). At the Seungsang site, there were no significant differences between the plant height resulting from different treatments during any of the data collection periods. The cassava height at 2, 4, 6, and 8 MAP was in the range of 48.66–56.66 cm, 123.72–138.46 cm, 178.12–194.16 cm, and 181.34–205.60 cm, respectively (Table 3).

Table 2. Plant height and plant width of cassava at different months after planting (MAP) exposed to different fertilizer applications at Nampong site.

Treatment	Plant Height (cm)				Plant Width (cm)			
	2 MAP	4 MAP	6 MAP	8 MAP	2 MAP	4 MAP	6 MAP	8 MAP
Control (no fertilizer)	66.78	156.98bcd [1]	202.34	232.66	87.14	100.32	79.32	58.64
RDCF	71.60	170.00ab	225.68	240.66	88.30	101.32	72.64	53.32
CM	65.58	167.34abc	219.98	236.68	89.54	102.14	73.34	62.64
SME	63.80	153.00d	191.80	222.00	82.74	94.32	75.34	70.68
CM + SME	68.46	166.66abc	216.12	231.34	89.76	102.00	72.00	51.36
½ RDCF + ½ CM	74.02	175.00a	210.66	239.00	94.26	101.34	75.02	59.32
½ RDCF + ½ SME	66.40	155.32cd	196.92	210.00	87.64	94.34	67.48	59.34
CM + PGPR	62.80	163.34a–d	217.32	234.66	85.26	98.32	77.30	65.34
Significance	ns	**	ns	ns	ns	ns	ns	ns
CV (%)	9.68	5.65	10.79	9.59	7.24	6.67	10.92	18.03

[1] Means with different letters in the same column indicate a significant difference according to Duncan's multiple range test at $p \leq 0.05$. ns = no significant difference; ** = statistical different at 99% level of confidence. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

Table 3. Plant height and plant width of cassava at different months after planting (MAP) exposed to different fertilizer applications at Seungsang site.

Treatment	Plant Height (cm)				Plant Width (cm)			
	2 MAP	4 MAP	6 MAP	8 MAP	2 MAP	4 MAP	6 MAP	8 MAP
Control (no fertilizer)	50.94	128.54	186.92	197.00	100.48	157.92	161.78	134.92
RDCF	55.26	138.46	194.16	205.60	113.54	163.20	157.86	137.40
CM	54.72	137.00	188.48	197.28	107.26	160.06	151.40	126.18
SME	48.66	123.72	178.12	181.34	93.52	146.34	147.44	117.16
CM + SME	53.68	132.80	184.78	191.48	114.08	160.94	157.06	132.80
½ RDCF + ½ CM	53.00	130.26	177.94	184.06	105.14	149.26	139.92	108.74
½ RDCF + ½ SME	53.52	132.34	182.00	189.68	109.60	152.80	153.66	123.66
CM + PGPR	56.66	133.00	185.20	197.00	99.26	149.92	156.12	129.52
Significance	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	11.12	8.82	7.21	7.79	11.77	8.11	7.82	13.23

ns = no significant difference. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

For the plant width at both study sites, different soil management treatments did not significantly affect the plant width recorded at 2, 4, 6, and 8 MAP. At the Nampong site, the SME treatment resulted in the greatest plant width at 8 MAP (70.68 cm), while the CM + SME treatment resulted in the lowest width (51.36 cm) (Table 2). At the Seungsang site, cassava at 8 MAP grown under the RDCF treatment tended to result in the greatest plant width (137.40 cm), while the ½ RDCF + ½ CM treatment resulted in the lowest (108.74 cm) width (Table 3).

The leaf number of cassava plants at both sites tended to increase at 4 MAP and gradually decrease with plant age (Tables 4 and 5). At the Nampong site, the CM + PGPR treatment resulted in significantly greater leaf number than the ½ RDCF + ½ CM, CM, and control treatments at 4 MAP. The CM + PGPR treatment also resulted in significantly greater leaf number than the CM + SME, ½ RDCF + ½ SME, ½ RDCF + ½ CM, CM, and control treatments at 8 MAP (Table 4). At the Seungsang site, the control and RDCF treatments resulted in the greatest leaf number at 6 MAP, both with an average value of 76.40 leaves, significantly higher than that resulting from the ½ RDCF + ½ CM treatment (Table 5). At 8 MAP, the RDCF treatment also resulted in the greatest leaf number (48.06 leaves), which was not significantly different from that resulting from the control and CM + PGPR treatments, while the lowest leaf number of cassava was observed in the SME treatment (Table 5).

Table 4. Leaf number and SPAD values of cassava at different months after planting (MAP) exposed to different fertilizer applications at the Nampong site.

Treatment	Leaf Number				SPAD			
	2 MAP	4 MAP	6 MAP	8 MAP	2 MAP	4 MAP	6 MAP	8 MAP
Control (no fertilizer)	38.88	57.88c [1]	35.20	28.36cd	38.88b	57.88b	35.20b	28.36d
RDCF	45.56	64.70ab	30.68	32.60abc	45.56a	64.70a	30.68c	32.60bcd
CM	40.42	63.06bc	30.00	29.42bcd	40.42b	63.06a	30.00c	29.42cd
SME	45.08	68.22ab	31.34	35.06ab	48.22a	47.54c	46.72a	35.82abc
CM + SME	44.72	63.66ab	30.14	24.54d	47.04a	46.98c	47.98a	35.20abc
½ RDCF + ½ CM	38.52	57.74c	28.94	27.40cd	46.76a	46.36c	44.40a	38.98ab
½ RDCF + ½ SME	45.18	64.88ab	29.74	26.40d	47.74a	46.00c	46.72a	40.58a
CM + PGPR	40.94	69.00a	34.82	35.68a	45.84a	47.92c	44.28a	36.50ab
Significance	ns	**	ns	**	**	**	**	**
CV (%)	16.13	6.36	13.05	14.02	8.20	7.34	7.32	12.41

[1] Means with different letters in the same column indicate a significant difference according to Duncan's multiple range test at $p \leq 0.05$. ns = no significant difference; ** = statistical different at 99% level of confidence. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

Table 5. Leaf number and SPAD values of cassava at different months after planting (MAP) exposed to different fertilizer applications at the Seungsang site.

Treatment	Leaf Number				SPAD			
	2 MAP	4 MAP	6 MAP	8 MAP	2 MAP	4 MAP	6 MAP	8 MAP
Control (no fertilizer)	47.54	107.06	76.40a [1]	46.34ab	44.44	42.80bc	41.08ab	35.50bc
RDCF	50.66	111.58	76.40a	48.06a	43.56	45.44a	42.70a	38.42ab
CM	49.86	108.86	64.00ab	34.06cd	43.44	41.64c	39.18b	33.98c
SME	45.94	102.86	68.26ab	28.54d	39.86	42.92bc	43.20a	38.90a
CM + SME	52.40	114.52	69.46ab	40.68bc	42.76	42.42bc	40.70ab	37.80ab
½ RDCF + ½ CM	49.20	107.42	57.00b	35.14cd	40.56	41.64c	41.94a	35.64abc
½ RDCF + ½ SME	50.00	107.54	67.60ab	40.12bc	41.68	44.66ab	42.22a	37.04abc
CM + PGPR	47.68	104.82	67.80ab	44.28ab	39.92	42.84bc	40.90ab	38.66ab
Significance	ns	ns	*	**	ns	**	*	*
CV (%)	9.95	6.35	13.03	12.74	9.37	3.79	4.26	6.06

[1] Means with different letters in the same column indicate a significant difference according to Duncan's multiple range test at $p \leq 0.05$. ns = no significant difference; *, ** = statistically different at 95% and 99% level of confidence, respectively. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

Nutrient management significantly affected chlorophyll content at both study sites (Tables 4 and 5). At the Nampong site, the control and CM treatments resulted in the lowest SPAD values at 2 MAP, with SPAD values of 38.88 and 40.42, respectively. During the other two times measured, 4 and 6 MAP, the highest SPAD values resulted from the

RDCF and CM treatments at 4 MAP, while the lowest SPAD values resulted from the RDCF and CM treatments at 6 MAP. In addition, at 8 MAP, the lowest SPAD value was observed in the control treatment (Table 4). At the Seungsang site, the RDCF treatments resulted in the highest SPAD value (45.44) at 4 MAP, but it was not significantly different from the ½ RDCF + ½ SME treatment (44.66). The SME treatment resulted in the highest SPAD values at 6 and 8 MAP, with SPAD values of 43.2 and 48.9, respectively, which were significantly higher than those resulting from the CM treatment at 6 MAP and the CM and control treatments at 8 MAP, respectively (Table 5).

3.2. Yield and Starch Content

Cassava tubers from both the Seungsang and Nampong study sites were harvested 10 MAP, and it seems that the cassava tubers at the Nampong site tended to be longer than those at the Seungsang site, (Figure 1).

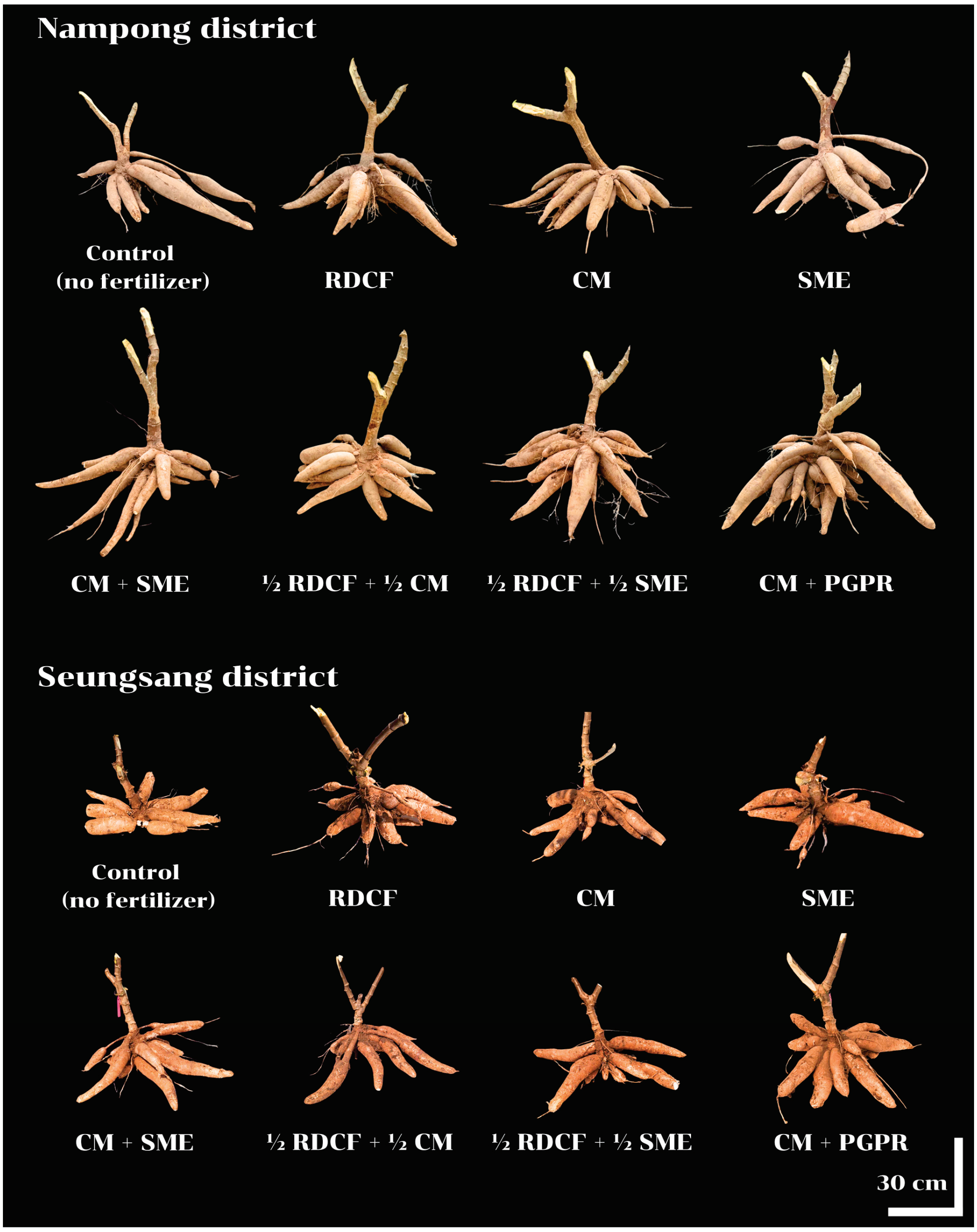

Figure 1. Tuber characteristics of cassava at 10 months after planting (MAP), when exposed to different fertilizer applications at two sites in northeastern Thailand. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

At the Nampong site, different fertilizer management had an influence ($p \leq 0.05$) on the fresh tuber yield. The highest fresh tuber yield was observed resulting from the CM + PGPR treatment (6.22 kg plant^{-1}) and was significantly greater than that resulting from all the other treatments. The CM and CM + SME treatments resulted in the next greatest average fresh tuber yield increase (4.79 kg plant^{-1}), but these values were not significantly different from the lowest fresh tuber yield, which resulted from the control treatment (4.25 kg plant^{-1}) (Table 6). At the Seungsang site as well, different fertilizer management had an influence ($p \leq 0.05$) on the fresh tuber yield. The highest fresh tuber yield was observed resulting from the CM treatment (5.19 kg plant^{-1}), followed by that resulting from the CM + SME treatment (5.11 kg plant^{-1}). These top two yield values were not significantly different, and they also were not significantly different from the yield values resulting from the RDCF, ½ RDCF + ½ SME, and CM + PGPR treatments, which were 4.66, 4.66, and 4.53 kg plant^{-1}, respectively (Table 6). The starch content of cassava grown at both study sites was revealed to not be influenced significantly by fertilizer management ($p > 0.05$). Starch content resulting from the different fertilizer management treatments at the Seungsang and Nampong sites was between 28.23–29.93% and 26.10–29.47%, respectively (Table 6).

Table 6. Fresh tuber yield and starch content of cassava exposed to different fertilizer applications at two sites in northeastern Thailand.

Treatment	Nampong		Seungsang	
	Fresh Tuber Yield (kg plant^{-1})	Starch Content (%)	Fresh Tuber Yield (kg plant^{-1})	Starch Content (%)
Control (no fertilizer)	4.25b [1]	28.23	3.70b	29.47
RDCF	4.72b	28.50	4.66ab	26.13
CM	4.79b	29.23	5.19a	26.40
SME	4.56b	28.47	4.02b	27.00
CM + SME	4.79b	29.93	5.11a	26.10
½ RDCF + ½ CM	4.65b	28.43	4.04b	29.25
½ RDCF + ½ SME	4.61b	28.80	4.66ab	29.47
CM + PGPR	6.22a	29.63	4.53ab	29.07
Significance	**	ns	*	ns
CV (%)	11.90	2.80	16.21	6.28

[1] Means with different letters in the same column indicate significant differences according to Duncan's multiple range test at $p \leq 0.05$. ns = no significant different; *, ** = statistically different at 95% and 99% level of confidence, respectively. RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

3.3. Macronutrient Concentrations in Plant Parts

Significant effects of soil nutrient management on the macronutrients in the leaf, stem, tuber (root), and whole-plant tissue of cassava at both study sites were observed (Tables 7 and 8). At the Nampong site, different nutrient management treatments had significant effects ($p \leq 0.05$) on the N, P, and K accumulation in cassava plants. The CM + SME, CM + PGPR, and CM treatments resulted in the top three total N values in leaves, with averages of 3.67%, 3.57%, and 3.53%. This was significantly greater than the total N resulting from the control, RDCF, ½ RDCF + ½ CM, and SME treatments. In whole-plant tissues, the CM + PGPR, CM, and CM + SME treatments resulted in the top three N concentrations, with 1.69%, 1.65%, and 1.63%, respectively (Table 7).

Total P concentrations in leaf tissues were highest in plants resulting from the CM (0.110%) and SME (0.107%) treatments, followed by plants resulting from the RDCF (0.100%) and CM + PGPR (0.100%) treatments. The lowest total P concentrations in leaves resulted from the control treatment (0.057%). In stem tissues, the highest total P concentrations resulted from the RDCF (0.077%) and CM (0.073%) treatments, without any significant difference between these values and those resulting from the SME treatment (0.060%). In tuber tissues, the highest total P concentrations resulted from the ½ RDCF + ½ CM (0.027%), ½ RDCF + ½ SME (0.030%), and CM + PGPR (0.030%) treatments, which were significantly higher than those from all other treatments. In the whole plant, the highest total P concentrations resulted from the RDCF (0.063%) and CM (0.070%) treatments, without any significant difference between these values and those resulting from the SME, ½ RDCF + ½ SME, and CM + PGPR treatments (0.060%) (Table 7).

Table 7. Macronutrient content in different plant parts of cassava exposed to different fertilizer applications at the Nampong site.

Treatment	Total N (%)				Total P (%)				Total K (%)			
	Leaf	Stem	Tuber	Whole Plant	Leaf	Stem	Tuber	Whole Plant	Leaf	Stem	Tuber	Whole Plant
Control	2.97d [1]	0.93	0.23	1.38f	0.057d	0.047b	0.020b	0.040c	0.41d	0.28d	0.34bc	0.34d
RDCF	3.27c	1.00	0.33	1.54cde	0.100ab	0.077a	0.020b	0.063a	0.37d	0.61a	0.37b	0.45c
CM	3.53ab	1.20	0.20	1.65ab	0.110a	0.073a	0.020b	0.070a	0.58b	0.53ab	0.45a	0.52b
SME	3.23c	1.00	0.30	1.51de	0.107a	0.060ab	0.020b	0.060ab	0.42cd	0.59ab	0.32c	0.44c
CM + SME	3.67a	0.97	0.27	1.63abc	0.087bc	0.050b	0.020b	0.050b	0.47c	0.50b	0.25de	0.41c
½ RDCF + ½ CM	3.27c	0.90	0.27	1.49e	0.083c	0.040b	0.027a	0.050b	0.41d	0.23d	0.23e	0.29e
½ RDCF + ½ SME	3.43b	1.00	0.27	1.58bcd	0.097abc	0.050b	0.030a	0.060ab	0.58b	0.40c	0.27de	0.41c
CM + PGPR	3.57ab	1.17	0.30	1.69a	0.100ab	0.050b	0.030a	0.060ab	0.92a	0.54ab	0.30cd	0.59a
Significance	**	ns	ns	**	**	*	**	**	**	**	**	**
CV (%)	2.63	12.30	17.56	3.06	9.08	20.17	8.88	9.48	5.86	11.05	7.84	5.85

[1] Mean with different letters in the same column indicate a significant difference according to Dun-can's multiple range test at $p \leq 0.05$. ns = no significant different; *, ** = statistical different at 95% and 99% level of confidence, respectively. Control: no fertilizer; RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

Table 8. Macronutrient content in different plant parts of cassava exposed to different fertilizer applications at the Seungsang site.

Treatment	Total N (%)				Total P (%)				Total K (%)			
	Leaf	Stem	Tuber	Whole Plant	Leaf	Stem	Tuber	Whole Plant	Leaf	Stem	Tuber	Whole Plant
Control	2.93e [1]	0.90c	0.30a	1.39d	0.043cd	0.027bc	0.023	0.030b	0.40c	0.23cd	0.33c	0.32d
RDCF	3.50b	1.00a	0.30a	1.60a	0.040d	0.030b	0.030	0.030b	0.57ab	0.40b	0.36bc	0.45b
CM	3.83a	0.80d	0.23bc	1.61a	0.050b	0.040a	0.030	0.040a	0.42c	0.56a	0.37bc	0.45b
SME	3.30c	0.93bc	0.20cd	1.48b	0.047bc	0.020c	0.030	0.030b	0.63a	0.44b	0.48a	0.52a
CM + SME	3.20d	0.90c	0.27ab	1.45c	0.060a	0.040a	0.030	0.043a	0.38c	0.28c	0.33c	0.33cd
½ RDCF + ½ CM	2.87e	0.80d	0.20cd	1.28e	0.050b	0.030b	0.030	0.040a	0.64a	0.20d	0.42ab	0.42b
½ RDCF + ½ SME	2.93e	0.70e	0.17d	1.25e	0.050b	0.030b	0.027	0.040a	0.38c	0.27c	0.37bc	0.34cd
CM + PGPR	3.53b	0.97ab	0.27ab	1.59a	0.060a	0.047a	0.030	0.040a	0.52b	0.26c	0.32c	0.36c
Significance	**	**	**	**	**	**	ns	**	**	**	**	**
CV (%)	1.44	3.24	14.13	1.43	5.51	13.44	9.96	5.49	8.80	9.21	11.29	5.06

[1] Mean with different letters in the same column indicate a significant difference according to Duncan's multiple range test at $p \leq 0.05$. ns = no significant different; ** = statistical different at 99% level of confidence. Control: no fertilizer; RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria.

The highest total K concentrations in leaves resulted from CM + PGPR (0.92%), which caused significantly greater K concentrations than all other treatments. The highest total K concentrations in stems resulted from the RDCF (0.61%), SME (0.59%), CM +PGPR (0.54%), and CM (0.53%) treatments. These four treatments resulted in significantly greater total K than the ½ RDCF + ½ SME (0.40%), control (0.28%), and ½ RDCF + ½ CM (0.23%) treatments. The highest total K concentrations in tubers resulted from CM (0.45%), which was significantly higher than those from all other treatments. Contrarily, the ½ RDCF + ½ CM (0.23%) treatment resulted in the lowest total K concentration in tubers, without any significant difference from those resulting from the CM +SME (0.25%) and ½ RDCF + ½ SME (0.27%) treatments. The highest total K concentrations in the whole plant resulted from the CM + PGPR (0.59%) treatment, whereas the lowest total K concentrations in the whole plant resulted from the ½ RDCF + ½ CM (0.29%) treatment (Table 7).

At the Seungsang site, total N concentrations in leaf tissues resulting from the CM treatment (3.83%) were significantly greater than those resulting from all other treatments. The lowest total N concentrations resulted from the ½ RDCF + ½ CM (2.87%), ½ RDCF + ½ SME (2.93%), and control (2.93%) treatments. In stem tissues, the significantly greatest total N concentrations resulted from RDCF treatment (1.00%) and were not significant different from those resulting from the CM + PGPR treatment (0.97%). In the tuber tissue, the greatest total N concentrations resulted from the control (0.30%), RDCF (0.30%), CM + SME (0.27%), and CM + PGPR (0.27) treatments, while the lowest N in tubers resulted from the ½ RDCF + ½ SME (0.17) treatment. In the whole plant, the highest N concentrations resulted from the CM (1.61%), RDCF (1.60%), and CM + PGPR (1.59%) treatments. These were all significantly greater than the lowest total N concentrations, which were observed in plants resulting from the ½ RDCF + ½ CM (1.28%) and ½ RDCF + ½ SME (1.25%) treatments (Table 8).

The greatest total P concentrations in leaves resulted from the CM + SME (0.060%) and CM + PGPR (0.060%) treatments, while the lowest leaf P concentrations resulted from the RDCF (0.040%) and control (0.043%) treatments. The greatest P concentrations in stem tissues resulted from the CM + PGPR (0.047%), CM (0.040%), and CM + SME (0.040%) treatments. Contrarily, the lowest total P concentrations in stem tissues resulted from the SME (0.020%) and control (0.027%) treatments. In tuber tissues, there were no significant differences between total P concentrations resulting from different fertilizer treatments. In whole-plant tissues, the lowest total P concentrations resulted from the control (0.030%), RDCF (0.030%), and SME (0.030%) treatments (Table 8).

Total K concentrations in leaves were highest in plants under the ½ RDCF + ½ CM (0.64%), SME (0.63%), and RDCF (0.57%) treatments. In stem tissues, total K concentrations were significantly highest in plants resulting from the CM (0.56%) treatment. In tuber tissues, the highest total K concentrations resulted from the SME treatment (0.48%), which were not significantly different from those resulting from the ½ RDCF + ½ CM (0.42%) treatment. In whole-plant tissues, the total K concentration was significantly greatest in plants under the SME treatment (0.52%), while the lowest total K concentration in the whole plant was observed in the control treatment (0.32%) plants, without any significant difference between values resulting from the CM + SME (0.33%) and ½ RDCF + ½ SME treatments (0.34%) (Table 8).

3.4. Correlations Between Macronutrient Concentration and Plant Productivity

To understand the relationships between the different traits recorded under different fertilizer management protocols at each study site, the correlations between the collected parameters were investigated and are shown in Figures 2 and 3. A positive relationship between parameters was assumed when the correlation coefficient (r^2) was 0.60 or higher. The total N concentration in the whole plant (r^2 = 0.64) and total K concentration in leaf tissues (r^2 = 0.67) displayed a higher positive correlation with the fresh tuber yield than other parameters. The starch content was positively correlated with the total N content in leaf tissues (r^2 = 0.60). However, these correlations were only observed at the Nampong site (Figure 2). Among the macronutrients in different plant parts and the whole plant in both study sites, the macronutrient concentrations in leaf tissues have the highest positive correlation (r^2 > 0.75) with the total macronutrient concentrations in the whole plant, compared with the stem and tuber tissue concentrations (Figures 2 and 3).

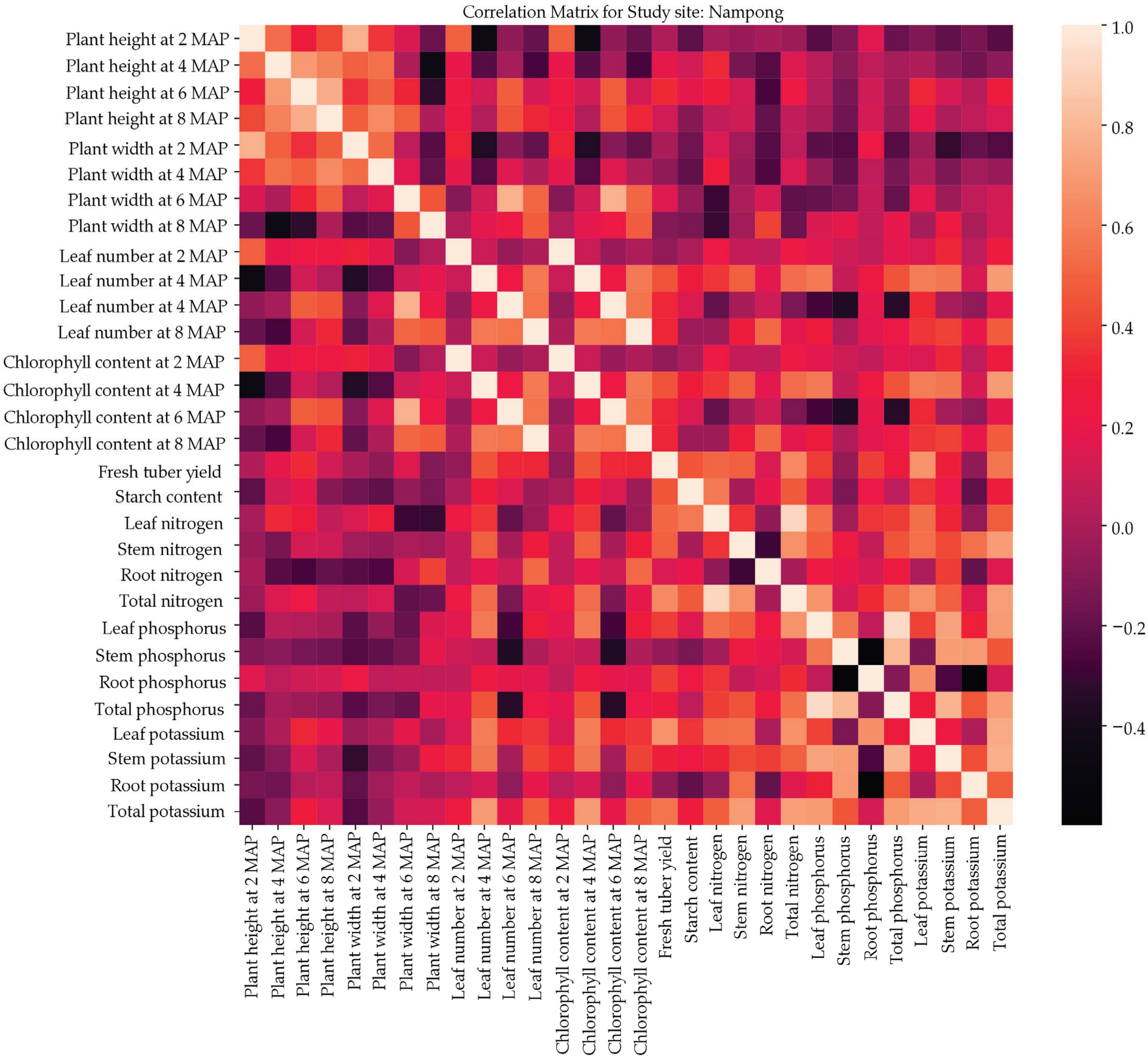

Figure 2. A correlational plot from 30 parameters recorded from cassava grown at the Nampong Site. MAP: months after planting.

3.5. Economic Analysis

Since cassava plants were planted with 1 × 1 m spacing, 10,000 plants can be planted in 1 ha. Therefore, the average fresh tuber yield per plant was multiplied by this 10,000-plant ha^{-1} rate to obtain the average fresh tuber yield that would be harvested per ha using this same spacing. Tables 9 and 10 show the results of the partial budget, dominance, and MRR analysis for each of the fertilizer management treatments. At the Nampong site, the treatments of CM and CM + PGPR both resulted in positive MRR values. The control, CM, and CM + PGPR treatments resulted in net benefits of 2376.31, 2461.74, and 3237.07 USD ha^{-1}, respectively. The MRR when changing from the control (no fertilizer) to CM would be 30.97%. This means that for every USD invested in changing from the control treatment to the application of chicken manure at the recommended rate of 3125 kg ha^{-1}, local farmers would recover that dollar and make, approximately, an additional

USD 0.31. The MRR when changing from the application of CM to CM + PGPR would be 355.97%, meaning that the local farmers who already manage cassava field fertility by applying chicken manure compost at recommended rates (3125 kg ha^{-1}) would earn, approximately, an additional USD 3.56 for every USD that is invested in applying the PGPR product along with chicken manure compost (Table 10).

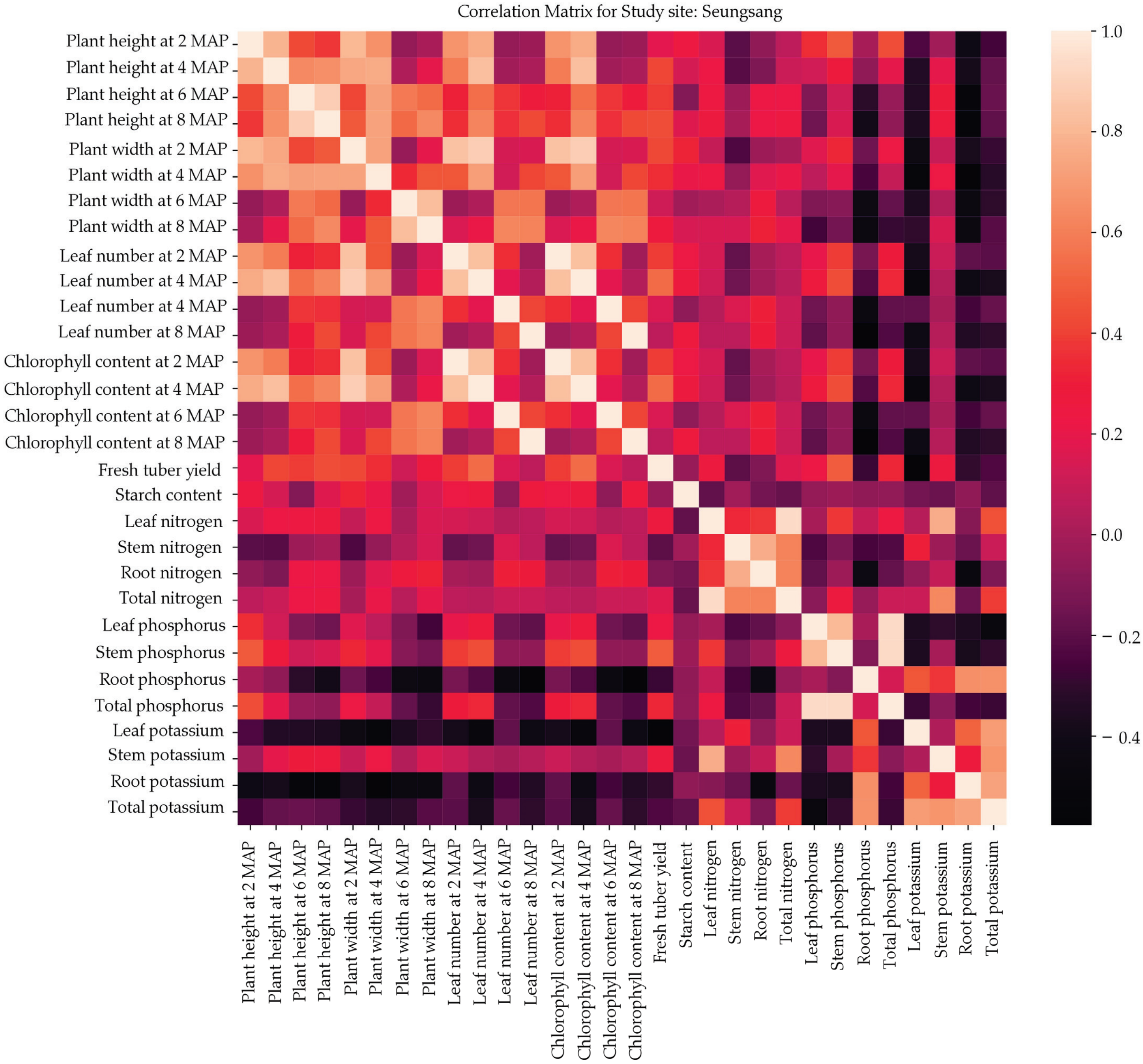

Figure 3. A correlational plot from 30 parameters recorded from cassava grown at the Seungsang Site. MAP: months after planting.

At the Seungsang site, the treatments of CM + PGPR, RDCF, and CM resulted in positive MRR values. The net benefits resulting from the control, CM + PGPR, RDCF, and CM treatments were 2070.40, 2291.41, 2375.65, and 2683.72 USD ha^{-1}, respectively. The MRR when changing from the control treatment to CM + PGPR would be 499.72%, meaning that for every USD invested in soil and plant management that utilizes chicken manure (3125 kg ha^{-1}) along with the inoculation of stakes with PGPR solution, there would be an around USD 4.99 return on investment. The MRR when changing from the application of

CM + PGPR to RDCF would be 1125.36% (Table 10), meaning that for every USD invested in changing from chicken manure treatment (3125 kg ha^{-1}) along with PGPR inoculation to the recommended dose of inorganic fertilizer (RDCF), there would be a USD 11.25 return for every USD invested. The MRR when changing from the application of the RDCF to CM would be 491.42%, which means that for every USD invested in changing from the RDCF to CM treatments, there would be a USD 4.91 return on investment (Table 10).

Table 9. Partial budget and net benefit of different fertilizer management treatments for cassava production at two sites in northeastern Thailand.

Study Site	Data	Control	RDCF	CM	SME	CM + SME	½ RDCF + ½ CM	½ RDCF + ½ SME	CM + PGPR
	Fertilizer field price (USD ha^{-1})	0.00	184.71	174.25	32.41	206.67	179.48	108.56	195.17
	Fertilizer application labor costs (USD ha^{-1})	0.00	26.14	26.14	139.40	165.54	52.28	165.54	26.14
Nampong	Total variable costs (USD ha^{-1})	586.09	862.25	861.92	801.14	1033.73	873.96	909.87	1079.73
	Average yield (kg plant^{-1})	4.25	4.72	4.79	4.56	4.79	4.65	4.61	6.22
	Average yield (kg ha^{-1})	42,467.00	47,200.00	47,933.00	45,600.00	47,933.00	46,533.00	46,067.00	62,200.00
	Adjusted average yield (kg ha^{-1}) *	38,220.30	42,480.00	43,139.70	41,040.00	43,139.70	41,879.70	41,460.30	55,980.00
	Gross field benefits (USD ha^{-1}) **	3356.68	3730.78	3788.72	3604.32	3788.72	3678.06	3641.23	4916.41
	Net benefit (USD ha^{-1}) **	2376.31	2409.22	2461.74	2362.63	2272.74	2348.90	2276.25	3237.07
Seungsang	Total variable costs (USD ha^{-1})	510.64	853.97	916.66	726.61	1077.44	789.32	917.23	846.49
	Average yield (kg plant^{-1})	3.70	4.66	5.19	4.02	5.11	4.04	4.66	4.53
	Average yield (kg ha^{-1})	37,000.00	46,600.00	51,900.00	40,200.00	51,100.00	40,400.00	46,600.00	45,300.00
	Adjusted average yield (kg ha^{-1}) *	33,300.00	41,940.00	46,710.00	36,180.00	45,990.00	36,360.00	41,940.00	40,770.00
	Gross field benefits (USD ha^{-1}) **	2924.55	3683.36	4102.28	3177.49	4039.05	3193.30	3683.36	3580.60
	Net benefit (USD ha^{-1}) **	2070.40	2375.65	2683.72	2060.46	2449.96	2005.72	2306.07	2291.41

Control: no fertilizer; RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria. * Adjusted average yield is 90% of average yield in kg plant^{-1} × planting rate (10,000 plant ha^{-1}). ** The price of cassava was 0.0878 USD kg^{-1} (USD 1 = THB 35.8670 on 15 March 2024).

Table 10. Dominance analysis and marginal rate of return for different fertilizer management treatments for cassava production at two sites in northeastern Thailand.

Fertilizer Management	Nampong			
	TVC (USD ha^{-1})	NB (USD ha^{-1})	Dominance Analysis	MRR (%) *
Control	586.09	2376.31		
SME	801.14	2362.63	Dominated	
CM	861.92	2461.74		30.97
RDCF	862.25	2409.22	Dominated	
½ RDCF + ½ CM	873.96	2348.90	Dominated	
½ RDCF + ½ SME	909.87	2276.25	Dominated	
CM + SME	1033.73	2272.74	Dominated	
CM + PGPR	1079.73	3237.07		355.97
Fertilizer Management	**Seungsang**			
	TVC (USD ha^{-1})	**NB (USD ha^{-1})**	**Dominance Analysis**	**MRR (%) ***
Control	510.64	2070.40		
SME	726.61	2060.46	Dominated	
½ RDCF + ½ CM	789.32	2005.72	Dominated	
CM + PGPR	846.49	2291.41		499.72
RDCF	853.97	2375.65		1125.36
CM	916.66	2683.72		491.42
½ RDCF + ½ SME	917.23	2306.07	Dominated	
CM + SME	1077.44	2449.96	Dominated	

Control: no fertilizer; RDCF: recommended dose of chemical fertilizer; CM: chicken manure; SME: swine manure extract; PGPR: plant-growth-promoting bacteria. TVC: total variable cost in USD ha^{-1}; NB: net benefit in USD ha^{-1}; MRR: marginal rate of return in percent. * MRR will only be shown when the treatment is not dominated.

4. Discussion

Despite being a resilient crop that can be cultivated in areas with inconsistent or low rainfall and with no inputs other than labor to provide a reasonable return, cassava requires careful management and may require some outside assistance to obtain larger yields and more significant financial gains [50,51].

Based on the background soil chemical properties at both study sites, Seungsang (silty clay texture) has a comparatively higher amount of the various nutrients than Nampong (sandy texture), which has lower levels of N, P, and K as well as six times less organic matter. The lower amount of nutrients in Nampong's soil is a result of the background soil properties, with sandy soils having less nutrients than soils with more clay content, especially in tropical regions [52]. In this study, the poor performance of cassava recorded from the unamended plots (control) was probably due to their low soil organic matter and nutrient content. The yield results at both the Nampong and Seungsang sites suggest that the CM + PGPR and CM treatments have a greater effect on the cassava yield than the absence of fertilizer (control), RDCF, and SME treatments. It seems that fertilizer treatments that contain combinations with CM have the most potential for increasing cassava tuber yields. Several investigations have revealed the enhancement of cassava production with poultry manure, either solely or mixed with chemical fertilizer, via improved soil physical and chemical characteristics [4,28]. Chicken manure application is also known to increase soil organic matter in soils, and soil organic matter facilitates cation exchange in soils and can help increase macronutrient availability [52,53]. These findings are consistent with previous research, which found that the chemical composition and C/N ratio of organic matter determine its quality, and that a combination of low- and high-C/N organic residues has a greater effect on soil fertility [54–56]. Biratu et al. [55] also reported that chicken manure application, both alone and in combination with NPK synthetic fertilizer, increased organic carbon, total N, and available P levels in cassava field soils. Higher levels of these nutrients in soils may have contributed to more uptake by the cassava plants. This dynamic may have played a role in the current study. However, chemical analysis of soil resulting from each fertilizer treatment would be required to support this hypothesis.

At the Nampong site, PGPR inoculation along with chicken manure application at the full recommended rate significantly increased the fresh tuber yield by 26–42%, compared to all other treatments. Moreover, the CM + PGPR treatment also resulted in a greater leaf number (at 4 MAP and 8 MAP by 9% and 21%, respectively) than the CM application alone. This finding suggests that the organisms in the PGPR product may indeed be providing ecosystem services that help the aboveground and tuber growth in this location. This explanation is supported by previous work by Wongsuwan et al. [57] in Thailand, which showed 5.79% increases in fresh tuber weight resulting from the use of this same PGPR-3 product along with composted chicken manure, when compared with the application of composted chicken manure alone. The application of the PGPR-3 biofertilizer product alone, however, did not result in yield increases. According to Astuti and Mulyono [58], cassava stakes that were wounded and inoculated with PGPR and mycorrhizal fungus also produced more leaves. The mechanisms behind the growth and yield increases, therefore, may involve microbial interactions in the cassava rhizospheric region. The *Azospirillum brasilense* and *Gluconacetobacter diazotrophicus* bacteria strains present in the PGPR-3 product are thought to act by producing auxins, which stimulate root cell elongation, and by increasing water and nutrient uptake efficiency [59]. *Azospirillum brasilense* inoculation has also been shown to minimize the negative effects of excess N on cassava tuber development [60], a problem that some farmers face when applying soil amendments. Interestingly, based on the highest fresh tuber yield of cassava grown under the different fertilizer management of both study sites, the treatment with CM + PGPR produced the most significant fresh tuber yield increase at the Nampong site (6.22 kg plant^{-1}), while CM produced the most significant fresh tuber yield increase at the Seungsang site (5.19 kg plant^{-1}). From this, the response of soil to PGPR at Nampong was greater, possibly because of the sandy soil there, which has less background soil nutrients and SOM. Application of organic fertilizers together with biological fertilizers containing PGPR microorganisms may be suitable for growing cassava in areas with degraded soils. Although it is obvious that PGPR application has beneficial effects in helping crops against biotic and abiotic stresses [61,62], the effectiveness of introduced PGPR inoculants is hard to predict without having site-specific background information about the PGPR activity because native PGPR, which appear to be considerably more prevalent in areas with high soil organic matter, may alter the relative performance of introduced PGPR inoculants [63]. Further microbiome and proteomics analysis may shed more light on the mechanisms behind how PGPR inoculation and PGPR inoculation along with fertilizer application affect cassava plant growth.

A high cassava fresh tuber yield has been observed in northeastern Thailand when chicken manure [28] and liquid swine manure extract [29] are applied, with results that are not significantly different from those obtained when synthetic fertilizer is applied at recommended doses. In this study, when compared to both synthetic fertilizer and chicken manure, nutrients from the monthly foliar application of swine manure may not be available to the cassava plants consistently. Whereas the plants growing under soil-applied fertilizer treatments would have continual access to the nutrients through the roots, at least at the beginning period after fertilizer/manure application, swine manure foliar application may cause a discontinuation of access to the nutrients in the manure and hence less potential for growth. This possibility is supported by the work of Janket et al. [64], which highlighted a temporal pattern of nutrient uptake and accumulation by cassava plants, with maximum rates occurring during early growth stages, from 1 to 6 months after planting. Discontinuous access to nutrients during this time of maximum absorption might be responsible for the significantly lower height observed at 4 MAP in plants that were only exposed to swine manure extract (Tables 2 and 3). This hypothesis would have to be tested by the investigation of nutrient levels in cassava plants under the different nutrient management treatments throughout the growing season for confirmation.

Although no clear consistent trend was found with the total macronutrient contents in each plant part in this study, their contents in whole plants resulting from different fertilizer treatments showed some clear patterns when related to different treatments. For the total N contents in cassava at the Nampong site, the CM + PGPR, CM, and CM + SME treatments resulted in the highest N concentrations in the whole plant. For the total N contents in plants at the Seungsang site, the CM, RDCF, and CM + PGPR treatments resulted in the greatest N concentrations. At both locations, the CM + PGPR and CM treatments resulted in the greatest total N accumulation. In addition, the cassava plants resulting from the CM treatments had some of the greatest total P contents in whole plants (Tables 8 and 9). While the highest total K value at the Nampong site resulted from the CM + PGPR treatment, the highest K at the Seungsang site resulted from the SME treatment (Table 9). Interestingly, a pattern was observed in the order of the highest total K concentrations and the highest fresh tuber yields resulting from different fertility treatments at the Nampong site, with both parameters being in the order of CM + PGPR > CM > RDCF > SME (Table 8).

Correlation analysis was conducted to test the significance of these correlations. Indeed, the N concentrations in the whole plant and the K concentration in the leaf tissue at the Nampong site are positively correlated with the fresh tuber yield there (Figure 2). In general, N is one of the key elements influencing the cassava yield [65]. This is consistent with the findings of Suwarto et al. [66] who reported that cassava requires sufficient N, P, and K nutrients to generate good tuber growth and productivity. Potassium (K) is also widely known to be crucial for root growth. Janket et al. [64] reported that about half of all total K and 26–42% of P absorbed by cassava plants were sent to tubers. Lin et al. [67] also found the K application amount to have a significant positive correlation with the cassava yield. Furthermore, Prajapati and Madi [68] described K as being needed for sugar and starch translocation since it is a starch synthesis enzyme activator for tuber crops. This is why K almost always has to be supplemented in order to cultivate cassava long term, as the harvesting of tubers removes K from farms. Knowledge of these correlations could potentially be used to further develop the use of nutrient analysis and yield prediction techniques, such as the NIR technique, which could be used to predict the cassava yield from quick, noninvasive spectroscopy.

In the present study, at the Nampong site, the highest correlation between the starch content and the other data was observed with the total N accumulation in leaves (Figure 2). This result was consistent with the findings of other studies investigating the association between the level of leaf N content and starch accumulation in the tubers of other Thai cassava varieties, such as Huay Bong 80 [28,69]. However, the other literature demonstrated that very high rates of N fertilizer can be excessive and cause a reduction in tuberization and starch accumulation in cassava tubers. Omondi et al. [70] specified that excessive use of N would induce shoot (leaves and stems) vegetative growth but a poor tuber yield and a decrease in the tuber starch content. Nevertheless, our findings demonstrated that different nutrient management did not affect the tuber starch content at either study site. This was not surprising, as Pongsivapai et al. [14], Leitch et al. [15], Phun-Iam et al. [69], and Raksarikorn et al. [71] all reported that soil amendments, whether they were organic or inorganic fertilizers, had no clear influence on starch content. Previous studies have demonstrated that the starch content can vary according to varieties and environmental surroundings (temperature), harvest season (dry and raining seasons), storage time, or processing technology [72,73]. Generally, varieties that can provide high starch content accumulate starch quickly and maintain starch content as long as possible and are required for breeding and farming [74]. In this study, the Rayong 72 cultivar was utilized. This variety is renowned for its high yield, drought resistance, and high starch content, which ranges from 20 to 22% during the rainy season to 24% during the dry season [45]. Furthermore, this variety has been reported to have a starch content of 19.1% [75] and 24.8% [76] when grown in the same northeastern region of Thailand, or of 22.5% [77] and 22.9% [78] when grown in the northern region. Our results from the starch content in cassava tubers grown under different nutrient management at both study sites show up to 27% higher averages than those of the previous reports.

Although cassava can be planted in all months of the year, different planting dates result in different climatic conditions, such as temperature, relative humidity, and solar radiation, all of which are factors that cause yield differences of cassava [37]. The main planting times in Southeast Asia, including Thailand, are the early rainy season (May–June) and the late rainy season (October–December), with both having an optimal climate for cassava crop growth [45]. The current study used a drought-tolerant genotype (Rayong 72) and drip irrigation in an attempt to reduce the growth and yield differences that result from moisture levels. The findings in our study show that this strategy is useful for maintaining the cassava yield even though the crop was planted in the dry season. This is in agreement with the findings of Wongnoi et al. [79] who reported that an increase in soil moisture content by irrigation can increase the canopy size and leaf area, both important factors for photosynthesis and biomass accumulation, contributing to increases in the tuber yield due to optimal climate conditions during crop growth. Nonetheless, there is a 2–3-fold difference between the projected average yields from the current study and the Thai national average of roughly 21.3 t ha^{-1}. The highest projected yields were 62.2 t ha^{-1}

from the CM + PGPR treatment and 51.9 t ha^{-1} from the CM treatment at the Nampong and Seungsang sites, respectively.

Economic analysis from Nampong data shows that the marginal rate of return (MRR) when changing from the CM to CM + PGPR treatments would be greater than the minimum accepted value of 100%, meaning that this treatment may be recommended for local farmers to increase return on investment. The PGPR-3 product is relatively easy to apply and inexpensive. This option may be very attractive to local farmers if they knew about the economic possibilities that the product offers. All other experimental treatments resulted in greater fresh tuber yields than those of the control but only CM and CM + PGPR resulted in positive MRR values. For treatments that involved synthetic fertilizer, the cost of the fertilizer itself was high and the additional yield that resulted was not enough to make the treatment economically beneficial, due to the low field price of fresh cassava tubers. In treatments that involved the application of swine manure extract, the costs associated with the application of the swine manure were high and the resulting fresh tuber yields were relatively low. CM + SME, ½ RDCF + ½ CM, and ½ RDCF + ½ SME all involved more than one type of fertilizer application, which increased both the fertilizer costs and labor costs for those treatments (Table 10). The Nampong site results are similar to those of Bilong et al. [80] who found soil treatments with chicken manure to have greater benefit-to-cost ratios than treatment with synthetic fertilizer in two consecutive years in sandy clay soil. The authors attributed greater fresh tuber yields to improved soil quality index values, which resulted from improved soil physical and chemical properties, like porosity, bulk density, water holding capacity, OM, and cation exchange capacity.

At the Seungsang site, since the MRR when changing from the RDCF treatment to the CM treatment is greater than the minimum accepted value of 100%, it may be beneficial economically to recommend that local farmers who currently manage fertility by adding synthetic fertilizer alone change to using chicken manure at the rates used in this study. Like at the Nampong site, the additional costs associated with the application of SME and fertilizer combinations were high when compared with the change in net benefit (NB). However, at the Seungsang site, the difference between the NB resulting from the RDCF treatment and that resulting from the control treatments outweighed the additional costs required. Again, the low field price of fresh cassava tubers is a limiting factor in increasing gross field benefits.

At both research sites, the CM treatments resulted in a greater NB per ha than the RDCF treatments. This is an interesting result, in terms of both economic and ecological sustainability. Chicken manure is produced at local farms, making it very accessible. This would likely result in a lower carbon footprint, when considering the greater transport distance and manufacturing involved in synthetic fertilizer distribution. Locally produced manures also have less price fluctuations than synthetic fertilizer, and their purchase by local farmers benefits the local economy. For organic cassava production systems, protocols that focus more on using composted animal manures, farmyard wastes, and biofertilizers theoretically have relatively high gross field benefits because the cassava plant product selling prices are higher. However, the higher production costs for organic cassava systems, due to more strict soil amendment standard requirements and higher labor costs, may prohibit many smallholder farmers from organic cassava production [81]. While at the surface level it may seem that the soil and plant management treatments investigated in this study would be more applicable to organic cassava farmers, the marginal rates of return resulting from the CM treatments at the Seungsang study site and CM + PGPR treatments at the Nampong site may prove to be a powerful incentive for non-organic farmers in those regions to adopt these production protocols as well. In particular, farmers that are currently using production systems that only apply synthetic fertilizer may be convinced to rely more on locally sourced composted chicken manure. In addition to the financial incentives provided by the viable treatments involving chicken manure compost application, or chicken manure compost application along with PGPR inoculation, farmers may benefit from the maintenance or increases in soil organic matter that are known to result from the application of composted manure amendments that contain carbon-rich materials [82]. This attribute is crucial to long-term soil health and soil food web stability, which is a requirement for sustainable agriculture [83].

5. Conclusions

Several relationships were found between the nutrient management protocols and the resulting cassava growth, yield components, macronutrient concentrations, and marginal rate of return. These relationships can be put to use to better understand cassava agroecosystem functioning, particularly in terms of what farmers can do to increase yields and what mechanisms may be behind those yield increases. At the Nampong site, the application of chicken manure at a rate of 3125.0 kg ha^{-1} and stake soaking with PGPR resulted in a higher fresh tuber yield than no fertilizer and the RDCF application. At the Seungsang site, the application of chicken manure at a rate 3125.0 kg ha^{-1} resulted in a high fresh tuber yield, which was not significantly different from the yield resulting from the RDCF application. Furthermore, compared to the RDCF treatment, both soil fertilizer management treatments produced a positive marginal rate of return values. The findings could be further substantiated by conducting similar investigations at more sites with varying climates and soil structures. All of the data resulting from these efforts may be used to make real-world recommendations for successful and sustainable cassava production.

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Comparison of Growth, Yield, and Carbon Dioxide Emission After Cultivation of Five Edible Mushrooms

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Abstract: The increasing problem of carbon dioxide emissions has become a significant concern, with mushroom production identified as one of the contributing factors. This is because the mushroom production process emits carbon dioxide through respiration, and the carbon dioxide emitted by the mushrooms contributes to an increase in greenhouse gases. The carbon dioxide emitted by mushrooms can be utilized in various applications, such as supporting vegetable cultivation in greenhouses. However, the amount of carbon dioxide emitted by mushrooms varies. Thus, this study aimed to investigate the growth, yield, and carbon dioxide emissions in five edible mushrooms, namely *Pleurotus pulmonarius*, *Lentinus squarrosulus*, *P. ostreatus*, *P. citrinopileatus*, and *P. cystidiosus*. The experiment found that the fresh weight, dry weight, and biological efficiency percentage of *P. ostreatus* were the highest at 65.71, 11.18 g, and 28.22 percent, respectively. In contrast, the fresh weight, dry weight, and biological efficiency percentage of *L. squarrosulus* were the lowest, at 24.90, 3.80 g, and 9.90 percent, respectively. On the other hand, the carbon dioxide emitted from *L. squarrosulus* was the highest, ranging from 854.00 to 8369.67 ppm, while the carbon dioxide emitted from *P. cystidiosus* was the lowest, ranging from 606.00 to 861.00 ppm.

Keywords: edible mushrooms; growth; yield; carbon dioxide emission

1. Introduction

Mushrooms are widely regarded as a nutritious food choice, offering a rich source of essential nutrients and health-enhancing compounds. They are a highly nutritious food as they contain a lot of protein, vitamins, and minerals and are low in fat [1]. Additionally, they have bioactive compounds that can be used in medicine [2]. This has made mushrooms an increasingly popular food, as they are considered to be rich in beneficial nutrients and minerals. Currently, mushroom consumption is trending upward in line with the health food market. Recently, Thailand produced more than 600,000 mushroom bags, with an economic value of approximately 8.7 million dollars, cultivating various economically significant mushroom species, such as *Pleurotus pulmonarius* (Fr.) Quél., *Lentinus squarrosulus* (Mont.) Singer, *P. ostreatus* (Jacq. ex Fr.) P. kumm., *P. citrinopileatus* Singer., and *P. cystidiosus* O.K. Mill [3]. The growing demand for mushrooms has led to an increase in their cultivation, which, in turn, contributes to carbon dioxide emissions. Mushrooms emit carbon dioxide as a natural byproduct of their metabolic and respiratory processes during mushroom growth [4]. This is because mushrooms are fungi that use oxygen for respiration [5]. However, research studies have shown that mushroom cultivation has a lower carbon footprint than other agricultural systems, as the carbon dioxide emitted from the decomposition of substrate, but the carbon dioxide emitted by mushrooms is a by-product [6]. The amount of carbon dioxide emitted from different mushroom species varies [7]. However, the various rates of carbon dioxide emission will affect the yield of mushrooms, as high concentrations of carbon dioxide inhibit mushroom growth [8]. Therefore, it is necessary to sequester carbon dioxide for use in plant cultivation. Carbon dioxide enhances the photosynthesis process in plants [9]. There have been reports of using carbon dioxide emitted by mushrooms in plant cultivation, such as the carbon dioxide from *P. eryngii*. In the amount of 108.8 to 150.8 micrograms per kilogram with romaine lettuce [10]. Additionally, there has been a study on the carbon dioxide emission of *Lentinula edodes* [11]. However, there have been no reports on the carbon dioxide emission of five mushroom species: *P. pulmonarius*, *L. squarrosulus*, *P. ostreatus*, *P. citrinopileatus*, and *P. cystidiosus*. Therefore, this leads to the objective of comparison of growth, yield, and carbon dioxide emissions in five edible mushrooms.

2. Materials and Methods

2.1. Analyses of the Physicochemical Properties and Nutrient Content of Mushroom Substrate Before and After Cultivation

Prior to cultivation, the substrate's physicochemical properties and nutrient content were evaluated by oven-drying it for 72 h at 70 °C, using a pH meter PC950, Apera Instrument (Columbus, OH, USA), measuring its electrical conductivity (EC) with a conductivity meter Eutech CON 2700, Thermo Fisher Scientific (Waltham, MA, USA), determining its moisture content in accordance with Horwitz [12], and analyzing its organic carbon (OC) using a CHNS/O Analyzer model 628 series, Leco Corporation (St. Joseph, MI, USA), organic matter (OM) (calculated by organic carbon ×1.724), and the C:N ratio, which is determined by dividing the organic carbon value by nitrogen.

2.2. Substrate Preparation and Mushroom Cultivation

The cultivation substrate was prepared using commercial recipes, specifically rubber wood sawdust (8), rice husk (1.5), and limes (0.5), which were well mixed. The substrate's moisture content was adjusted to 80% with water. A total of 750 g of substrate was placed into plastic bags, autoclaved for 30 min at 121 °C and 15 pounds of pressure per square inch (psi), and then allowed to equilibrate at ambient temperature for a full day. The inoculum of five edible mushrooms from Saraburi province—*P. pulmonarius*, *L.squarrosulus*, *P. ostreatus*, *P. citrinopileatus*, and *P. cystidiosus*—consisting of 5 g of mycelium from commercial sources was then added to the substrate-containing container. The plastic bags holding the inoculated substrate were then placed in a greenhouse with regulated environmental conditions, maintaining a temperature of 20 ± 2 °C and a relative humidity of 80 ± 5%. Over 30 days, the mycelium was allowed to cover the entire substrate block. The experiment was conducted from March to May 2024.

2.3. Study of Growth and Yield in Five Mushroom Species

The first batch of mushrooms was harvested after the caps were left open for an additional 7 days. In the meantime, the temperature was maintained at 25 ± 2 °C, and the relative humidity was kept at 85 ± 5%. The mushrooms were also watered for 15 min at 9:00 AM, 1:00 PM, and 5:00 PM.

Then, the diameter of the fruit bodies of all mushroom species (in centimeters) was measured using a vernier caliper. To determine yield, the fruit bodies of all mushroom species were harvested, and the obtained yield was measured as the fresh weight and dry weight (in grams). The biological efficiency (%) was calculated using the following equation:

$$\text{Biological efficiency } (\%) = \frac{\text{Fresh weight of mushrooms (g)}}{\text{Dry weight of substrate after harvest (g)}} \times 100 \quad (1)$$

2.4. Carbon Dioxide Emission of Five Mushroom Species

The Extech CO260 device was utilized to record the amount of carbon dioxide (ppm) over 7 days, starting from the first day when the mycelium began growing into mushrooms. Simultaneously, the carbon dioxide levels were measured twice a day, once at 5:00 AM and again at 5:00 PM, with a 12 h interval between measurements.

2.5. Statistical Analysis

The study was conducted in a completely randomized design (CRD), with five mushroom species—*P. pulmonarius*, *L.squarrosulus*, *P. ostreatus*, *P. citrinopileatus*, and *P. cystidiosus*—and six biological replicates for each species. Each biological replicate consisted of five bags. The experimental data were analyzed using a one-way analysis of variance, followed by Duncan's multiple range test. Observed differences were deemed to have statistical significance when the *p*-value was less than 0.05. Statistical analyses were conducted using IBM SPSS Statistics 21.

3. Results and Discussion

3.1. Analyses of the Physicochemical Properties and Nutrient Content of Mushroom Substrate Before and After Cultivation

The study analyzed the physicochemical characteristics and nutrient composition of the substrate before cultivating all mushroom species using commercial substrate formulas. The substrate was found to contain nitrogen, phosphorus, and potassium at concentrations of 0.46%, 0.0034%, and 0.21%, respectively (Table 1). The substrate's physical and chemical properties included an electrical conductivity of 2.113 dS m^{-1}, a pH of 7.77, an organic carbon content of 34.86%, and an organic matter content of 60.10%. The carbon-to-nitrogen ratio was 78.44%. It has been reported that a pH value of 7.00 in mushroom cultivation materials is suitable for nutrient breakdown and mushroom growth [13], while values of electrical conductivity above 1.6 dS m^{-1} should be avoided, as they can adversely affect mycelium growth and mushroom yield [14]. The C/N ratio serves as a source of nutrients that mushrooms absorb from the substrate through the mycelium and transfer to the mushroom fruiting body [15]. Additionally, phosphorus and potassium are essential nutrients for mushroom growth. Although they are required in small amounts, they still significantly impact the growth of mushroom mycelium [16].

Table 1. Nutrient and physicochemical content in substrates before and after.

	Mushroom Species	Nutrient Content in Substrates			Physical—Chemical Content in Substrates				C/N Ratio
		N (%)	P (%)	K (%)	pH	EC (dS/m)	OC (%)	OM (%)	
Before		0.46 ± 0.07	0.0034 ± 0.00	0.21 ± 0.01	7.77 ± 0.10	2.113 ± 0.12	34.86 ± 0.33	60.10 ± 0.56	78.44 ± 2.95
After	*P. pulmonarius*	0.29 ± 0.03 d [1/]	0.0012 ± 0.00	0.22 ± 0.01	4.96 ± 0.04 c	1.959 ± 0.40 c	33.62 ± 0.82 a	57.97 ± 1.42 a	118.22 ± 0.87 a
	L. squarrosulus	0.40 ± 0.03 c	0.0011 ± 0.00	0.29 ± 0.01	4.78 ± 0.04 d	2.116 ± 0.25 b	35.24 ± 1.26 a	60.77 ± 2.17 a	88.50 ± 2.24 b
	P. ostreatus	0.46 ± 0.04 b	0.0012 ± 0.00	0.30 ± 0.02	5.05 ± 0.13 c	2.469 ± 0.18 a	35.69 ± 1.03 a	61.53 ± 1.78 a	77.26 ± 1.43 c
	P. citrinopileatus	0.48 ± 0.02 b	0.0012 ± 0.00	0.21 ± 0.03	5.20 ± 0.10 b	1.765 ± 0.20 d	31.44 ± 2.39 b	54.21 ± 4.12 b	65.93 ± 1.77 d
	P. cystidiosus	0.91 ± 0.06 a	0.0011 ± 0.00	0.25 ± 0.01	5.39 ± 0.17 a	2.004 ± 0.09 c	31.40 ± 1.42 b	54.14 ± 2.45 b	34.66 ± 0.55 e
	F-test	**	ns	**	**	**	**	**	**
	C.V. (%)	7.42	4.15	3.05	1.96	2.63	4.44	4.44	1.95

[1/] Values are expressed as means ± standard deviations (n = 5). Means with different letters in the same column are significantly different according to DMRT at $p \leq 0.05$. ** denotes significant differences at $p \leq 0.01$, while ns indicates non-significant differences.

The research also showed significant differences in nitrogen content, potassium content, pH, electrical conductivity, organic carbon content, organic matter content, and the C/N ratio across all experimental treatments (Table 1). The results ranged from 0.29% to 0.91%, 0.21% to 0.30%, 4.78 to 5.20, 1.765 to 2.469 dS m^{-1}, 31.40% to 35.69%, 54.14% to 61.53%, and 34.66 to 118.22, respectively. However, no significant differences were observed in phosphate content between the treatments, with values ranging from 0.0011% to 0.0012%.

The pH value of the post-cultivation material tends to decrease because, during mycelium incubation, the spawn releases organic acids due to the activity of microorganisms in the cultivation material. This microbial activity leads to fermentation processes that increase acidity [17]. Similarly, the electrical conductivity tends to decrease because the mushroom mycelium absorbs nutrients for growth, which reduces the nutrient concentration in the cultivation material. Additionally, microorganisms use organic matter and carbon to form new microbial cells during fermentation, releasing nutrients the mushrooms need for growth. The nitrogen content fluctuates, resulting in uncertain changes in the C/N ratio of the post-cultivation material, leading to variations in the C/N ratio [18]. On the other hand, the increase in the C/N ratio of *P. pulmonarius L. squarrosulus* is due to the breakdown of nitrogen in the growing material, which causes the rise in the C/N ratio after cultivation. This, in turn, impacts the growth of mycelium and the yield of the mushrooms [19]. Furthermore, microbial decomposition of organic matter releases additional nutrients that the mushrooms absorb for growth. The phosphorus content also decreases in the post-cultivation material, as nutrients are consumed by the mycelium during its incubation for mushroom growth [20].

3.2. Study of Growth and Yield in Five Mushroom Species

The research on the growth and yield of all mushroom species found significant differences in the number of caps, cap diameter, fresh weight, dry weight, and biological efficiency (%) (Table 2 and Figure 1). *P. citrinopileatus* produced the highest number of caps, with an average of 60.17, and *P. pulmonarius* exhibited the largest cap diameter, measuring 4.88 cm. Additionally, *P. ostreatus* achieved the highest fresh weight (65.71 g), dry weight (11.18 g), and biological efficiency (28.22).

Table 2. Growth and yield of five mushroom species.

Mushroom Species	Number of Caps	Diameter of Cap (cm)	Fresh Weight (g)	Dry Weight (g)	Biological Efficiency (%)
P. pulmonarius	10.23 ± 0.43 ^{c} [1/]	4.88 ± 0.18 ^{a}	51.53 ± 0.11 ^{d}	9.65 ± 0.30 ^{b}	19.89 ± 0.82 ^{b}
L. squarrosulus	3.67 ± 0.48 ^{d}	2.28 ± 0.81 ^{e}	24.90 ± 0.81 ^{e}	3.80 ± 0.46 ^{d}	9.90 ± 0.87 ^{d}
P. ostreatus	27.00 ± 0.59 ^{b}	3.84 ± 0.12 ^{c}	65.71 ± 0.82 ^{a}	11.18 ± 0.77 ^{a}	28.22 ± 0.90 ^{a}
P. citrinopileatus	60.17 ± 0.79 ^{a}	2.71 ± 0.30 ^{d}	53.37 ± 0.93 ^{c}	7.00 ± 0.57 ^{c}	19.41 ± 0.60 ^{b}
P. cystidiosus	3.92 ± 0.28 ^{d}	4.30 ± 0.10 ^{b}	55.95 ± 0.82 ^{b}	7.11 ± 0.49 ^{c}	17.80 ± 0.34 ^{c}
F-test	**	**	**	**	**
C.V. (%)	2.53	8.81	1.52	7.00	4.00

[1/] Values are expressed as means ± standard deviations (n = 5). Means with different letters in the same column are significantly different according to DMRT at $p \leq 0.05$. ** indicates significant differences at $p \leq 0.01$.

The yield and biological efficiency of mushrooms are the most important parameters for evaluation, as they are directly influenced by the efficiency of the substrates used for mushroom production [21]. Additionally, the researchers observe that the biological efficiency follows the same trend as fresh and dry weights. However, the differences in growth and yield can be attributed to internal factors, such as the unique fungal patterns and biomass characteristics, which vary significantly between species (Figure 1).

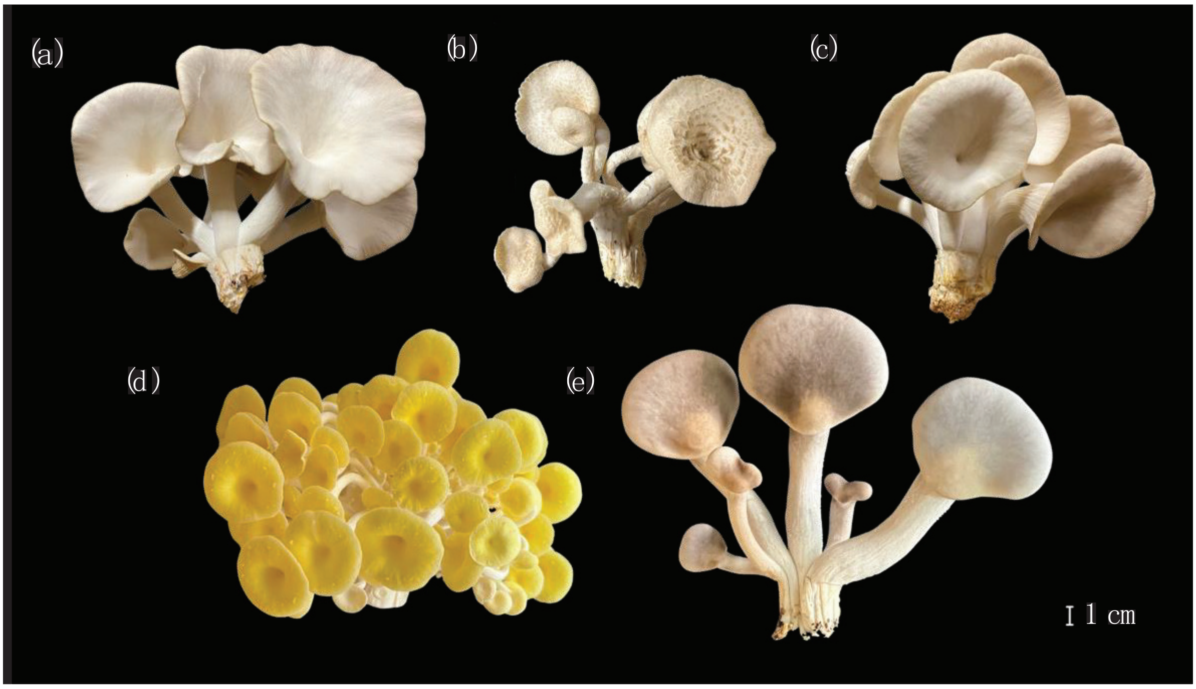

Figure 1. Growth and yield of five mushroom species: (**a**) *P. pulmonarius*; (**b**) *L. squarrosulus*; (**c**) = *P. ostreatus*; (**d**) = *P. citrinopileatus*, and (**e**) = *P. cystidiosus.*

3.3. Carbon Dioxide Emission of Five Mushroom Species

A one-week evaluation of the carbon dioxide emissions from all mushroom species showed significant differences across all mushroom species (Figure 2 and Table S1). From days 1 to 7, *P. pulmonarius*, *L. squarrosulus*, *P. ostreatus*, *P. citrinopileatus*, and *P. cystidiosus* emitted carbon dioxide at levels ranging from 787.33 to 1211.33, 854.00 to 8369.67, 753.33 to 1135.33, 518.33 to 1360.00, and 606.00 to 861.00 ppm, respectively. Based on these findings, we may conclude that *L. squarrosulus* produced the most emissions by 72, 108, and 132 h equal to 6864.67, 8369.67, and 6210.67 ppm, respectively, whereas *P. cystidiosus* produced the least. The experiment found that the *L. squarrosulus* exhibited low growth and yield, despite having the highest carbon dioxide emitted. In contrast, *P. ostreatus* showed high growth and yield, but its carbon dioxide emission was not the highest. This is because high concentrations of carbon dioxide can inhibit mushroom growth [8], which aligns with the findings of Jung and Son [10]. When mushrooms emit carbon dioxide, it is important to maintain the carbon dioxide concentration at an appropriate level, as high carbon dioxide levels can be more detrimental to mushroom growth than beneficial, potentially limiting yield [22]. Furthermore, the report by Qu et al. [11] states that when carbon dioxide is emitted in high amounts, it may reduce growth and yield because high levels of carbon dioxide hinder the respiration process of mushrooms and create an unsuitable environment for growth. If higher yields are desired, carbon dioxide must be removed from the greenhouse. Therefore, further research should focus on capturing carbon dioxide for use in plant cultivation and enhancing mushroom yield in the future. This study could also serve as a foundational reference for examining other greenhouse gas emissions from mushrooms in the future.

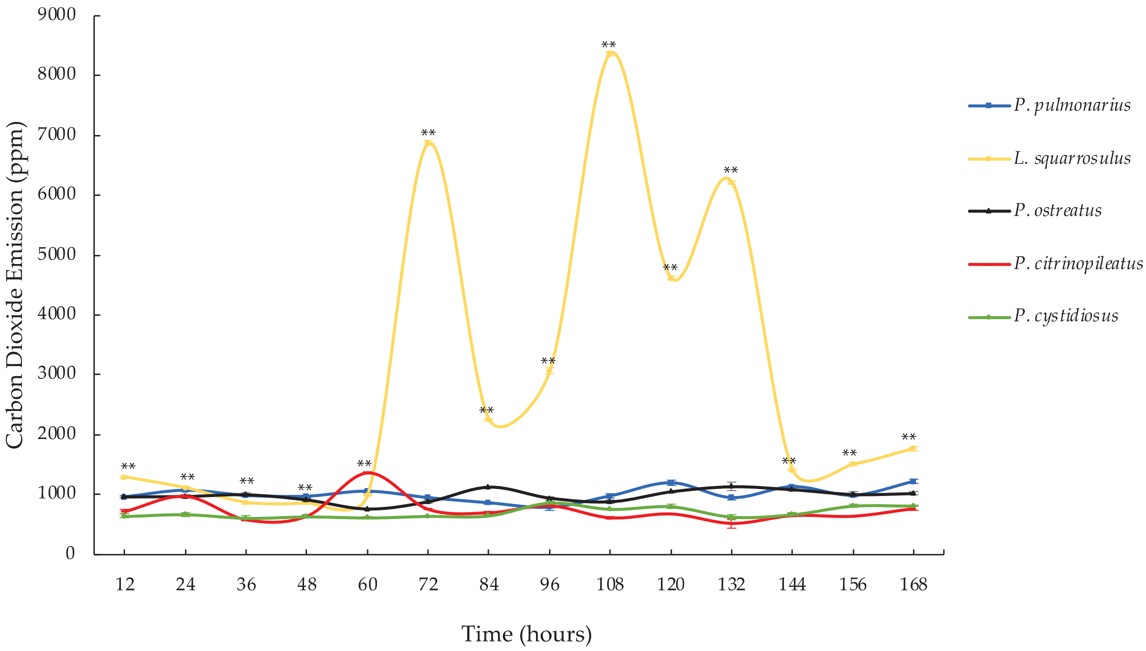

Figure 2. Carbon dioxide emissions from the five mushroom species over the course of one week. Data are represented as means ± standard deviation (n = 5). An asterisk (**) indicates statistically significant differences at $p \leq 0.01$.

4. Conclusions

This study identified notable differences in growth performance and yield across five mushroom species. Among these, *P. ostreatus* exhibited the highest productivity, achieving a fresh weight of 65.71 g, a dry weight of 11.18 g, and a biological efficiency of 28.22%. In contrast, *L. squarrosulus* emitted the highest levels of carbon dioxide, ranging from 854.00 to 8369.67 ppm during cultivation, but showed lower growth and yield. These findings underline the dual impact of mushroom farming on both agricultural productivity and environmental factors, particularly greenhouse gas emissions. This study provides foundational data on the relationship between mushroom farming and carbon dioxide emissions, contributing valuable insights for developing sustainable practices and future research aimed at mitigating environmental impacts associated with edible mushroom production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources14040055/s1. Table S1: Carbon dioxide emitted of five mushroom species in a week.

Author Contributions: Conceptualization, P.C.; methodology, P.C. and P.P.; validation, P.C., P.P. and S.S.; formal analysis, P.C., P.P. and S.S.; investigation, P.C., P.P. and S.S.; resources, P.C., P.P. and S.S.; data curation, P.C.; writing—original draft preparation, P.C., P.P.; writing—review and editing, P.C., O.T. and H.E.; supervision, P.C.; project administration, P.C.; funding acquisition, P.C. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data supporting the findings of this study are included in the article. Please contact the relevant authors for any questions.

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sustainability

Article

Integrating Lanthanide-Reclaimed Wastewater and Lanthanide Phosphate in Corn Cultivation: A Novel Approach for Sustainable Agriculture

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Abstract

With increasing global challenges related to water scarcity and phosphorus depletion, the recovery and reuse of wastewater-derived nutrients offer a sustainable path forward. This study evaluates the dual role of lanthanides (Ce^{3+} and La^{3+}) in recovering phosphorus from municipal wastewater and supporting corn (*Zea mays*) cultivation through lanthanide phosphate (Ln-P) and lanthanide-reclaimed wastewater (LRWW, wastewater spiked with lanthanide). High-purity precipitates of $CePO_4$ (98%) and $LaPO_4$ (92%) were successfully obtained without pH adjustment, as confirmed by X-ray photoelectron spectroscopy (XPS) and energy-dispersive spectroscopy (EDS). Germination assays revealed that lanthanides, even at concentrations up to 2000 mg/L, did not significantly alter germination rates compared to traditional coagulants, though root and shoot development declined above this threshold—likely due to reduced hydrogen peroxide (H_2O_2) production and elevated total dissolved solids (TDSs), which induced physiological drought. Greenhouse experiments using desert-like soil amended with Ln-P and irrigated with LRWW showed no statistically significant differences in corn growth parameters—including plant height, stem diameter, leaf number, leaf area, and biomass—when compared to control treatments. Photosynthetic performance, including stomatal conductance, quantum efficiency, and chlorophyll content, remained unaffected by lanthanide application. Metal uptake analysis indicated that lanthanides did not inhibit phosphorus absorption and even enhanced the uptake of calcium and magnesium. Minimal lanthanide accumulation was detected in plant tissues, with most retained in the root zone, highlighting their limited mobility. These findings suggest that lanthanides can be safely and effectively used for phosphorus recovery and agricultural reuse, contributing to sustainable nutrient cycling and aligning with the United Nations' Sustainable Development Goals of zero hunger and sustainable cities.

Keywords: rare earth elements; phosphorus; water reuse; drought; crop irrigation

1. Introduction

Water scarcity and food security remain among the most pressing global challenges of the 21st century. With climate change intensifying drought frequency and population growth increasing demand, the strain on freshwater resources is projected to worsen. According to the Food and Agriculture Organization (FAO), approximately 1.2 billion people already reside in water-stressed regions, and hunger continues to claim the lives of 17 people every minute [1,2]. Agriculture, which accounts for about 70% of global freshwater withdrawals, is particularly vulnerable to water shortages. At the same time, food production systems are under additional pressure due to the dwindling availability of essential nutrients, especially phosphorus.

Phosphorus (P) is a non-substitutable nutrient that is vital for plant development, yet it is primarily obtained from finite phosphate rock reserves. The extraction of phosphorus is energy-intensive and costly, ranging from $13 to $350 per metric ton depending on market and processing conditions [3–5]. Current estimates suggest that global phosphorus reserves may be exhausted within the next 80 years, especially under existing technological constraints and growing agricultural demand. Consequently, there is an urgent need to explore alternative and sustainable sources of phosphorus that can reduce dependence on mined fertilizers and mitigate environmental degradation associated with conventional fertilizer use.

One such promising strategy involves the recovery of phosphorus from municipal wastewater. Municipal wastewater is continuously generated and relatively stable in composition, making it a reliable resource for nutrient recovery. Unlike mineral sources, it is not subject to geopolitical supply risks. Enhanced biological phosphorus removal (EBPR) systems are commonly employed in wastewater treatment plants to accumulate phosphorus biologically. During the aerobic phase, phosphorus-accumulating organisms (PAOs) uptake phosphate, which is later released during sludge dewatering. This process produces a centrate stream enriched in phosphate, with concentrations reaching up to 600 mg PO_4^{3-}/L [6].

To recover phosphorus from these waste streams, coagulants such as ferric and aluminum salts are often used. However, these traditional coagulants require high dosages and may introduce toxicity concerns or generate large volumes of sludge. Recent studies have identified rare earth elements (REEs), particularly lanthanum (La^{3+}) and cerium (Ce^{3+}), as effective and less toxic alternatives for phosphate precipitation [6–10]. These lanthanides form highly stable lanthanide phosphate (Ln-P) compounds under ambient conditions, making them suitable for nutrient recovery.

In this study, we aim to recover phosphate from municipal wastewater using lanthanum and cerium and to evaluate the agricultural potential of the resulting byproducts. Specifically, we investigate two outputs: (1) the lanthanide phosphate precipitate (Ln-P) and (2) lanthanide-reclaimed wastewater (LRWW), which is the treated effluent containing residual lanthanides. We assess their use as phosphorus sources and irrigation water, respectively, for growing corn (Zea mays). Although lanthanides are not classified as essential plant nutrients, prior research suggests that they can enhance plant growth, stimulate physiological processes, and improve nutrient uptake [11–18]. Additionally, they may offer benefits such as improved root structure and enhanced photosynthetic activity [19–23].

By demonstrating the dual value of wastewater-derived lanthanide products for both nutrient recovery and crop production, this research supports a circular economy model. It also contributes to the advancement of sustainable agricultural practices and aligns with the United Nations' Sustainable Development Goals, particularly Goal 2 (Zero Hunger) and Goal 11 (Sustainable Cities and Communities).

2. Materials and Methods

2.1. Lanthanide Phosphate Recovery and Treated Effluent Preparation

The centrate wastewater utilized in this study originated from the dewatering process of activated sludge at the Clark County Water Reclamation Facility, located in Las Vegas, NV, USA. Upon collection, samples were either processed immediately or kept refrigerated at 4 °C until further use.

Phosphorus recovery was achieved using a standard jar test protocol adapted from Kajjumba et al. [6]. The precipitation process involved adding cerium chloride ($CeCl_3$) and lanthanum chloride ($LaCl_3$) directly to the centrate without altering its native pH (~6.7), as lanthanides are known to facilitate phosphate precipitation effectively across a broad pH range (4.0–9.0). A molar ratio of 1:1.2 (PO_4^{3-}:M^{3+}) was maintained for optimal performance. Details on the chemical reagents used, including their purity and source, are presented in Table 1.

Table 1. Summary of chemicals used in the study.

Chemical	Supplier	CAS	Purity (%)	SG
Cerium chloride [$CeCl_3$] $^{\nabla}$	Sigma Aldrich, St. Louis, MO, USA	18618−56−8	99.9	NA
Lanthanum chloride [$LaCl_3$] $^{\nabla}$	Sigma Aldrich, St. Louis, MO, USA	10025−84−0	99.9	NA
Ferric chloride [$FeCl_3$]	Pencco Inc., Vernon, CA, USA	NA	40	1.41
Aluminum sulfate [$Al_2(SO_4)_3.14H_2O$]	Thatcher Company of Nevada, Henderson, NV, USA	NA	47.8	1.333

SG: specific gravity; NA: not applicable; $^{\nabla}$: prepared at 500 mg/L in reverse osmosis water.

After the addition of coagulants, each mixture underwent rapid stirring at 120 rpm for 1 min, followed by gentle mixing at 40 rpm for 20 min. The mixture was then allowed to settle for 30 min. The resulting lanthanide phosphate (Ln-P) solids were separated by filtration and subsequently dried in an oven at 105 °C for three days. These solids were later used as soil amendments. Their composition and bonding structure were verified via energy-dispersive X-ray spectroscopy (EDS) and X-ray photoelectron spectroscopy (XPS).

In parallel, treated secondary effluent from the same facility was repurposed for irrigation trials. This effluent was fortified with one of the selected metal salts—cerium (III) chloride ($CeCl_3$), lanthanum (III) chloride ($LaCl_3$), ferric chloride ($FeCl_3$), and aluminum sulfate ($Al_2(SO_4)_3$)—to achieve a final metal ion concentration of 3.0 mg/L (M^{3+}), thereby simulating metal-amended reclaimed water. The full analytical profile of this irrigation water is presented in Table 2, including key metrics such as pH, nutrient levels, and salinity indicators.

Table 2. Composition of effluent water that was used to irrigate the corn plants [24].

	Units	Average	±
Total coliform	MPN/100 mL	27	32
Conductivity	µS/cm	1518	48
Temperature	°C	28.9	1.1
pH	pH unit	6.88	0.06
Dissolved oxygen	mg/L	6.05	0.49
TDSs	mg/L	996	33
Total BOD	mg/L	4.0	0.9
Orthophosphate (soluble)	µg/L	13.33	4.96
Total phosphate	µg/L	58.80	4.65
Total alkalinity	mg/L as $CaCO_3$	119	2
Chloride	mg/L	214	4
Sulfate	mg/L	285	8
Fluoride	µg/L	713	42
Bromide	µg/L	166	10
NH_3	µg/L	113.33	65.06
Total nitrogen	mg/L	15.6	0.6

BOD: biochemical oxygen demand; TDSs: total dissolved salts; MPN/100 mL: most probable number per 100 milliliters.

2.2. Corn Germination Assay

To assess the impact of lanthanide ions on corn germination, corn seeds were exposed to distilled water containing a range of lanthanide concentrations. Five seeds (Burpee®, Warminster, PA, USA) were placed on moistened paper towels inside 90 mm Petri dishes filled with solutions containing 0, 50, 100, 500, 1000, 2000, or 5000 mg/L of trivalent metal ions (M^{3+}). The dishes were covered and incubated at ambient temperature (~20 °C) in complete darkness to simulate optimal germination conditions. Seed germination was observed daily over a five-day period. A seed was classified as germinated when its radicle extended at least 2 mm. On the fifth day, the germination rate, along with root and shoot lengths, was measured and recorded. To enable comparison, additional test groups were treated with conventional coagulants commonly used in wastewater treatment—ferric (Fe^{3+}) and aluminum (Al^{3+}) salts—alongside the lanthanide treatments (Ce^{3+} and La^{3+}). This allowed evaluation of whether lanthanides present greater, lesser, or similar effects on early plant development relative to traditional coagulants.

2.3. Oxidative Stress Assessment

The concentration of hydrogen peroxide (H_2O_2) was used as a biomarker to evaluate oxidative stress in corn seedlings exposed to metal-based coagulants. Approximately 0.30–0.40 g of germinated seed tissue was weighed and homogenized in 5.0 mL of chilled distilled water maintained at 4 °C. The homogenized mixture was then centrifuged at 9000 rpm to remove coarse debris and large particulates. From the supernatant, 4.0 mL was collected and treated with 100 µL of a titanium chloride solution (99.9%) [25], which reacts with H_2O_2 to form a detectable complex. After a second centrifugation step at 9000 rpm for 5 min, residual solids, including titanium oxide, were removed. The clarified solution was then passed through a 0.45 µm nylon filter (Ks-Tek, China) to eliminate any remaining fine particles. The absorbance of the resulting filtrate was measured at 415 nm using a UV-Vis spectrophotometer [24]. The H_2O_2 concentration in each sample was calculated using a calibration curve generated from known standards processed under identical conditions.

2.4. Soil Preparation and Irrigation

Soil formulation for this study followed the approach outlined by Rader and colleagues [26], which was designed to mimic arid soil environments. A custom blend was created using washed sand (Quikrete®, Atlanta, GA, USA) and tree bark (Miracle-Gro®, Marysville, OH, USA) mixed in a 4:1 volumetric ratio. To minimize microbial interference, the soil was sterilized and allowed to cool in a sterile environment for 48 h before planting. Particle size analysis using dry sieving revealed a composition dominated by coarse-to-medium sand, with low gravel content (approximately 8.1%). The bulk density of the blend was about 1.2 g/cm^3, and among particles smaller than 2 mm, 99.6% were sand, of which 87.8% were coarse to medium-sized.

Based on standard agricultural nutrient guidelines, a typical one-acre plot requires about 82 kg of nitrogen, 41 kg of P_2O_5, and 73 kg of K_2O [27]. Given that an acre-furrow slice contains approximately 0.9 million kg of topsoil, this equates to 46 mg of P_2O_5 (or 20 mg of elemental phosphorus) and 91 mg of nitrogen per kg of soil. In this study, phosphorus was supplemented by blending phosphate-rich precipitates (derived from different metal coagulants) into 2 kg of prepared soil to provide 15 mg P/kg, as outlined in Table 3 [24]. The remaining 5 mg P/kg was supplied through irrigation using lanthanide-reclaimed wastewater (LRWW), which also served as the moisture source. Since LRWW already contained 15.58 $\pm$ 0.64 mg/L of nitrogen and 58.80 $\pm$ 4.65 µg/L of phosphate (see Table 2), no extra nitrogen amendments were necessary.

Table 3. The amount of phosphate precipitate added to 2 kg of soil [24].

Precipitate	g/mol	Mass Added to 2 kg of Soil (mg)
$LaPO_4$	233.9	226.0
$CePO_4$	234.9	227.0
$AlPO_4$	122.0	118.0
$FePO_4$	150.8	146.0

The precipitates from coagulation experiments were dried at 105 °C for at least 24 h before being added to soil.

Corn seeds were soaked overnight in distilled water prior to planting and sown 2–3 cm deep in 17 cm diameter pots. Each pot was initially planted with five seeds and irrigated every 2–4 days using LRWW dosed with 3.0 mg/L of metal ions (Ce^{3+}, La^{3+}, Fe^{3+}, or Al^{3+}). To reduce leaching and mimic drip irrigation conditions, 200 mL or 250 mL of the solution was added per irrigation event. Separate sets of pots were used for each metal treatment and the control group. The cultivation experiment was conducted in a controlled greenhouse setting at the University of Nevada, Las Vegas, from 7 October 2021 to 9 January 2022, under environmental conditions of approximately 23.4 ± 2.2 °C and 32.1 ± 8.4% relative humidity. On day 25, each pot was thinned to retain three corn plants for the remainder of the study.

2.5. Physical and Photosynthetic Parameters

This study evaluated several morphological and physiological characteristics of corn plants, including plant height, stem thickness, leaf count, and dry biomass. Biomass was assessed by drying a known portion of fresh stem tissue at 105 °C for 48 h, after which the dry mass was recorded using a precision analytical balance. Plant height and stem diameter were recorded using a measuring tape and digital caliper, respectively. Leaf chlorophyll levels were measured using a Chlorophyll Content Meter−300 (Opti-Sciences CCM−300, Hudson, NH, USA). For photosynthetic function, an LI−600 Porometer/Fluorometer (LI-COR, Lincoln, NE, USA) was used to assess the following variables: stomatal conductance, gsw ($mol/m^2/s$); transpiration rate, E ($mmol/m^2/s$); quantum efficiency of photosynthetic electron transport through photosystem II, PhiPS2; electron transport rate, ETR ($\mu mol/m^2/s$), vapor pressure deficit (kPa); humidity; and temperature. All physiological measurements were performed during daylight hours to capture active photosynthetic responses.

2.6. Metal Uptake and Elemental Mapping

To assess the absorption and spatial distribution of lanthanides, phosphorus, and related nutrients in plant tissues, electron probe microanalysis (EPMA) was conducted using a JEOL JXA−8900 analyzer (Peabody, MA, USA). In living plant tissues, minerals may redistribute due to internal water movement (capillary action), which can compromise localization accuracy. To prevent this, samples were frozen at −20 °C for a minimum of 24 h prior to sectioning, as described by [24,28]. Following freezing, thin tissue sections were prepared from the roots, stems, and leaves, then thawed and mounted onto microscope slides. Graphite adhesive (Electron Microscopy Sciences, Hatfield, PA, USA) was used to secure the sections to the slides for EPMA scanning. Root tissue was sampled at the junction of seminal and nodal roots. Stem tissue was collected from a point approximately 20% up the plant's height, and leaf sections were taken along the central midrib. Acquired EPMA images were further processed using the ImageJ software, Version 6 (University of Wisconsin, Madison, WI, USA) to visualize and quantify elemental distribution across the different plant tissues.

3. Results and Discussion

3.1. Lanthanide Phosphate Precipitates

High-resolution X-ray photoelectron spectroscopy (XPS) was used to analyze the interactions between lanthanides (Ln) and phosphorus (P), focusing on the shifts in binding energies that indicate chemical bonding. In the La matrix, peaks corresponding to the La $3d_{5/2}$ and La $3d_{3/2}$ orbitals—sublevels within the 3d electron shell—were observed. These orbitals represent core-level electrons, and their binding energies are sensitive indicators of the chemical environment. The La $3d_{5/2}$ and La $3d_{3/2}$ peaks appeared at 836.0 eV and 853.0 eV, respectively, consistent with inner-sphere complex formation [29]. Similarly, in the Ce system, binding energies for the Ce $3d_{3/2}$ (902.4 eV) and Ce $3d_{5/2}$ (883.8 eV) orbitals—also core electron states—were identified, which play key roles in Ce-P interactions. For phosphorus, the most reactive electrons reside in the $2p_{1/2}$ and $2p_{3/2}$ subshells, with binding energies at 136 eV and 135 eV, respectively [29].

The formation of inner-sphere bonds between phosphorus and lanthanides altered these valence electron energies. Figure 1A,B present the XPS spectra of Ln-P, showing clear peaks for Ce, La, P, and O. In the Ce-PO_4 complex, the Ce $3d_{3/2}$ binding energy shifted to 904.0 eV—an increase of 1.6 eV. Likewise, in the La-PO_4 system, the La $3d_{5/2}$ peak shifted by 1.4 eV. These shifts confirm the successful formation of La-O-P and Ce-O-P bonding structures. Figure 1C displays EDS results, showing elemental ratios of La, Ce, O, and P that closely match the theoretical stoichiometry for pure Ce-/La-PO_4. Impurity levels were minimal, with $CePO_4$ containing up to 1.9% impurities and $LaPO_4$ up to 7.9%. Given their purity, these precipitates are suitable for use as phosphorus sources in plant growth applications.

Table 4 summarizes the characteristics of the centrate wastewater used for lanthanide treatment, including the initial concentrations and the percentage removal of phosphorus (PO_4^{3-}-P) and other key parameters following treatment with $CeCl_3$ and $LaCl_3$. The results highlight the high efficiency of both lanthanides in phosphorus removal (>98%) with moderate effects on other water quality indicators.

Table 4. Characteristics of centrate that was collected from wastewater treatment and the performance of lanthanide. Reported as the average value (n $\geq$ 2) with standard deviation [24].

	Initial Concentration			Change	
Parameter	**Average**	**±**	**Unit**	**$CeCl_3$**	**$LaCl_3$**
pH	6.7	0.2		4.6	4.6
PO_4^{3-}-P	165.08	2.77	mg/L	99.2%	98.4%
NH_3-N	57.2	4	mg/L	0.6%	0.0%
TDS	1127	67.9	mg/L	127.4%	124.6%
Turbidity	159.9	24.9	NTU	3.2%	3.3%
Alkalinity	309.6	4.3	mg/L	28%	34%
COD	1189	90.1	mg/L	21.4%	20.9%
TSS	165.6	33.9	mg/L	18.8%	18.2%

Silver, beryllium, cadmium, cobalt, chromium, molybdenum, lead, antimony, tin, titanium, thallium, and vanadium were below the reporting limit; zinc, selenium, nickel, manganese, copper, barium, boron, and arsenic were less than 400 μg/L. Metals were measured using the EPA 200.8 method. % indicate percentage removal.

3.2. Germination Rate and Hydrogen Peroxide

Seed germination begins with water uptake, which activates metabolic processes essential for transforming a dormant seed into a growing plant. These metabolic activities not only determine the likelihood of germination but also influence the future health of the plant. To assess the effect of metal salts on germination, corn kernels (n = 5 per treatment) were grown in Petri dishes with metal solutions at concentrations of 0, 50, 100, 500, 1000, 2000, and 5000 mg M^{3+}/L. After five days of incubation in the dark, the seeds were assessed for germination rate, root and shoot lengths, and hydrogen peroxide (H_2O_2) production. A seed was considered germinated if it developed a visible embryonic axis, regardless of root or shoot length. As shown in Tables A1 and A2, no clear correlation was observed between metal concentration and germination rate. This inconsistency could be attributed to seed dormancy at the time of planting, which may have hindered germination even under otherwise optimal conditions (i.e., proper moisture, light, oxygen, pH, and temperature). However, root and shoot lengths showed a more consistent trend. At concentrations below 1000 mg M^{3+}/L, the root and shoot lengths were comparable to those observed in the control group treated with deionized water. At concentrations above 1000 mg M^{3+}/L, both root and shoot lengths decreased significantly (Tables A1 and A3).

To further investigate these changes, H_2O_2 levels were measured in the germinated kernels, as H_2O_2 is a key reactive oxygen species (ROS) involved in seed metabolism. Water uptake during germination triggers a cascade of biochemical reactions, including the production of ROS such as H_2O_2 [30]. It is estimated that 1−5% of the oxygen consumed during germination is converted into H_2O_2 [31]. Most H_2O_2 in seeds is generated from the dismutation of superoxide anions ($O_2\bullet^-$), which are produced via electron leakage from mitochondrial complexes I, II, and III [32,33].

Another significant source of H_2O_2 is NADPH oxidase, located on the plasma membrane, which is especially active during biotic or abiotic stress. This process—known as the "oxidative burst" or respiratory burst oxidase homologs (RBOHs)—is triggered by melatonin and modulated by S-nitrosylation and phosphorylation, which enhance $O_2\bullet^-$ and, subsequently, H_2O_2 production [31,34,35]. Additional contributors to ROS production during germination include polyamine oxidase [35,36] and peroxisomal metabolism [37,38]. Unlike other ROS, H_2O_2 is relatively stable and can migrate throughout the seed and even into the surrounding environment [39]. While moderate levels of H_2O_2 are beneficial and function as signaling molecules, excessive accumulation can damage DNA, proteins, and lipids, thereby inhibiting germination [40].

Figure 2 illustrates the ratio of H_2O_2 production relative to metal concentration, compared to the control. Despite increasing metal concentrations, H_2O_2 production remained relatively unchanged up to 1000 mg/L. This suggests that low-to-moderate metal levels did not significantly impact oxidative stress. This observation aligns with reports that exogenous H_2O_2 can promote germination by modulating the proteome, transcriptome, and hormone signaling pathways [41]. Specifically, H_2O_2 activates mitogen-activated protein kinases (MAPKs) that suppress abscisic acid while also promoting protein carbonylation and activating the pentose phosphate pathway (PPP). This activation leads to increased NADPH production, which has antioxidant properties that support seed germination and early plant development [30,42]. However, at 2000 mg/L and above, a decline in H_2O_2 levels was observed. This reduction coincided with the suppression of root and shoot development, suggesting that excess metal concentrations may have impaired the physiological processes critical to germination and early growth.

The reduction in root and shoot lengths at higher metal concentrations may be attributed to pH changes, particularly in environments treated with Al^{3+} and Fe^{3+}. As the metal concentration increased, the pH of the Al^{3+} and Fe^{3+} solutions decreased significantly, as shown in Table A4. These coagulants are typically formulated using strong acids such as sulfuric acid and hydrochloric acid [6]. While a slight reduction in pH can help weaken the seed coat—facilitating water absorption into the endosperm—excessive acidification can lead to "water flooding." This condition disrupts oxygen availability within the seed, thereby inhibiting the germination signaling pathways. In contrast, the pH in Ce^{3+} and La^{3+} treatments remained relatively stable, with Ce^{3+} at 5.3 ± 0.1 and La^{3+} at 5.2 ± 0.2 (Table A5). In these cases, the decline in root and shoot development is more likely due to elevated total dissolved solids (TDSs), which increase electrical conductivity. Excessive

TDSs create osmotic stress, limiting water uptake into the seed—a phenomenon often referred to as physiological drought [43]. This water deficit prevents the initiation of germination or restricts early root development. Figure 3 illustrates corn kernel germination in a Ce^{3+} environment. At concentrations between 0 and 2000 mg/L, kernels were frequently covered by a fungal mat. The presence of this fungal growth is believed to aid in nutrient mobilization from more distant parts of the root system [44], thereby improving germination and seedling development. However, at 5000 mg/L, no fungal development was observed. Without fungal assistance, the kernels likely depended solely on localized nutrients near the root surface, which may have limited their growth potential.

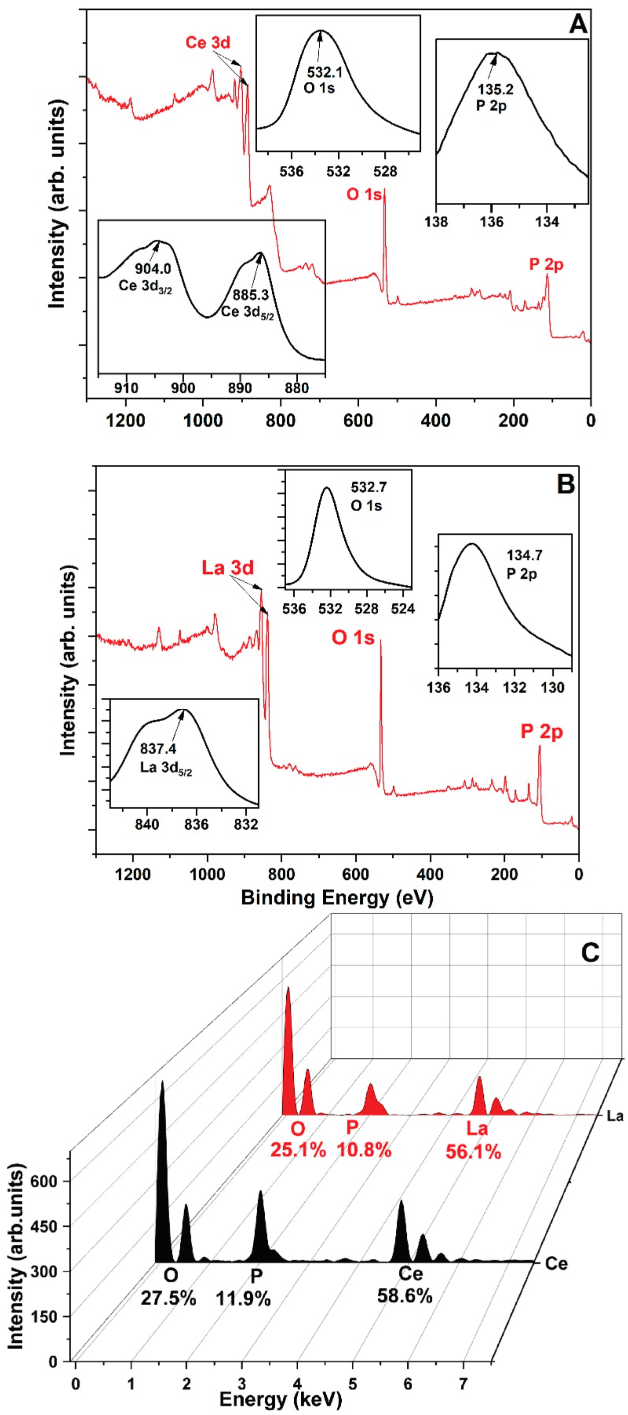

Figure 1. XPS analysis of (**A**) $CePO_4$ and (**B**) $LaPO_4$ and (**C**) EDS pattern of $CePO_4$ and $LaPO_4$ precipitated from wastewater. Impurities detected include carbon, calcium, iron, and sulfur [24].

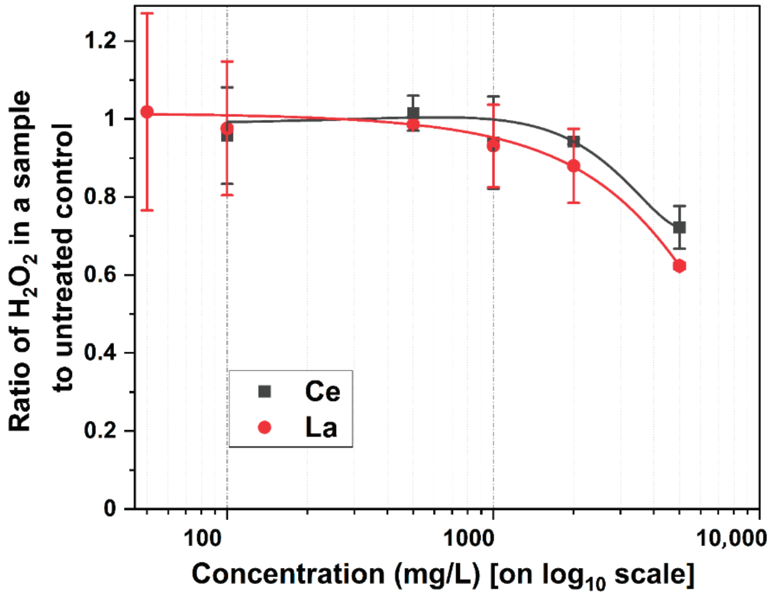

Figure 2. Generation of H_2O_2 at different metal concentrations during kernel germination after five days of incubation in darkness. Measured H_2O_2 in the control (untreated) = 0.0013% ± 0.0003% per 0.39 g of wet weight. Error bars represent one standard deviation, with n = 2 [24].

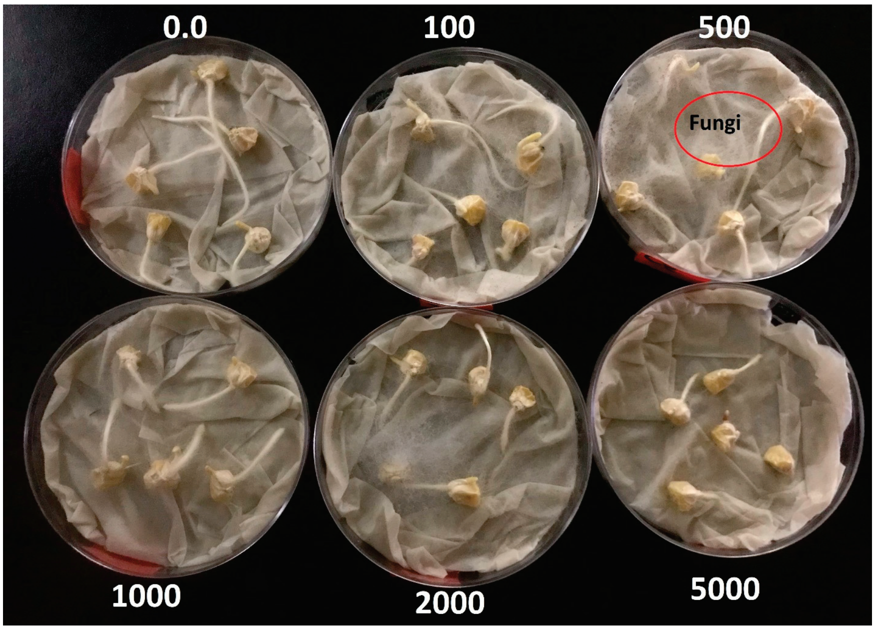

Figure 3. Germination of kernels under a Ce^{3+} environment and the development of fungi at different metal ion concentrations (0–5000 mg/L) [24].

3.3. Corn Physical Characteristics

Throughout the corn growth cycle, key physical characteristics were monitored, including plant height, stem diameter, the number of leaves, leaf area, and dry biomass. These parameters serve as indicators of overall plant health and development. By day 75, each pot had received a total of 4.59 L of LRWW. The average plant height was 42.0 ± 1.7 cm, with corn grown under lanthanum treatment exhibiting the shortest average height at 39.9 ± 11.5 cm (Figure 4A). The average stem diameter across all treatments was 7.44 ± 0.65 mm, with no statistically significant differences observed between treatments (Figure 4B, $\rho > 0.05$). Leaf number increased steadily until day 75, at which point tassels (male flowers) had emerged on all plants. At maturity, plants produced between 11 and 12 leaves (Figure 4C). Leaves play a crucial role in plant physiology, particularly in photosynthesis, where they facilitate CO_2 uptake and water vapor release. Consequently, leaf development influences sugar production and has been correlated with crop yield in several studies [45,46]. At maturity (day 75), the average leaf area per plant was 70.6 cm^2. Plants treated with aluminum showed the largest average leaf area, 72.2 cm^2 (Figure 4D). However, no statistically significant differences ($\rho > 0.05$) were observed among treatments, including lanthanides, the control, and other coagulants. These results suggest that lanthanide treatments do not adversely affect corn leaf development.

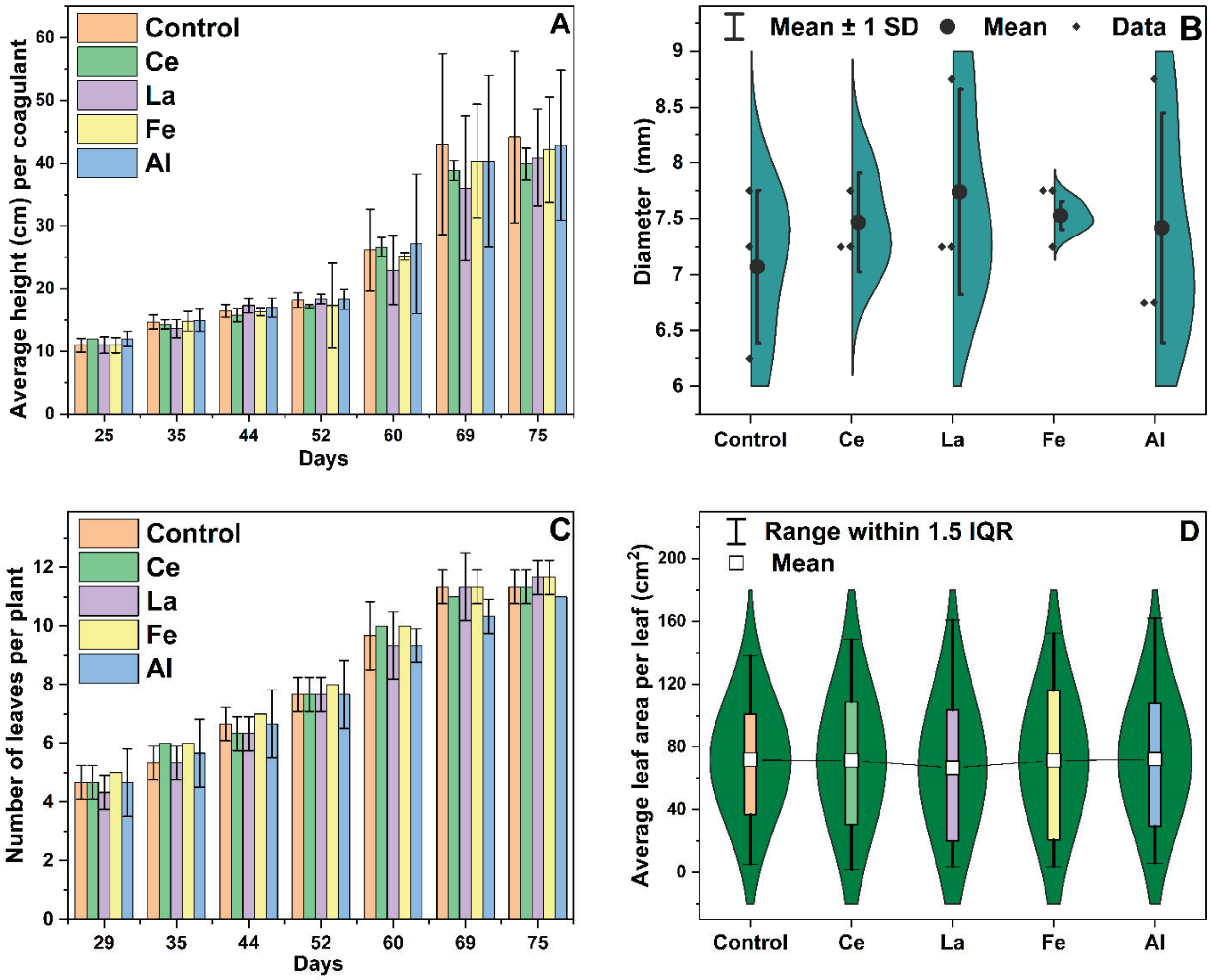

Figure 4. (**A**) Height of corn, (**B**) diameter of corn plant stem on day 75, (**C**) number of leaves per plant, and (**D**) leaf area per plant on day 75. SD: standard deviation; IQR: interquartile range. Error bars represent one standard deviation, with n = 3. There was no statistical difference between the control and plants treated with cerium (Ce), lanthanum (La), iron (Fe), or aluminum (Al) when measured on the same day at a 95% confidence level [24].

3.4. Photosynthetic Parameters

The primary function of stomata is to regulate the exchange of gases—specifically, minimizing water loss while maximizing carbon dioxide (CO_2) uptake. While CO_2 uptake is essential for photosynthesis, excessive water loss poses a threat to plant survival. Plants mitigate this trade-off by optimizing photosynthesis to offset the cost of water loss. Stomatal conductance (gsw) reflects the rate at which CO_2 enters and water vapor exits the leaf. Throughout the corn growth cycle, gsw remained relatively consistent across all treatments involving different coagulants (Figure 5A). As a result, transpiration rates also remained stable, showing no significant variation among treatments (Figure 5B). To assess photosynthetic induction, the electron transport rate (ETR) and quantum efficiency (PhiPS2) were measured. ETR values were not statistically different from the control under any coagulant treatment throughout the experiment (Figure 5C). Similarly, PhiPS2 values remained above 0.5 regardless of metal addition, indicating that the photosynthetic machinery of the plants was not adversely affected (Figure 5D). Quantum efficiency values greater than 0.5 suggest that lanthanides did not negatively impact corn photosynthesis. This consistency is likely due to stable chlorophyll production throughout the experiment (Figure 6A) [47]. A slight decline in chlorophyll levels observed after day 35 can be attributed to reduced daylight hours during the winter season when the study was conducted.

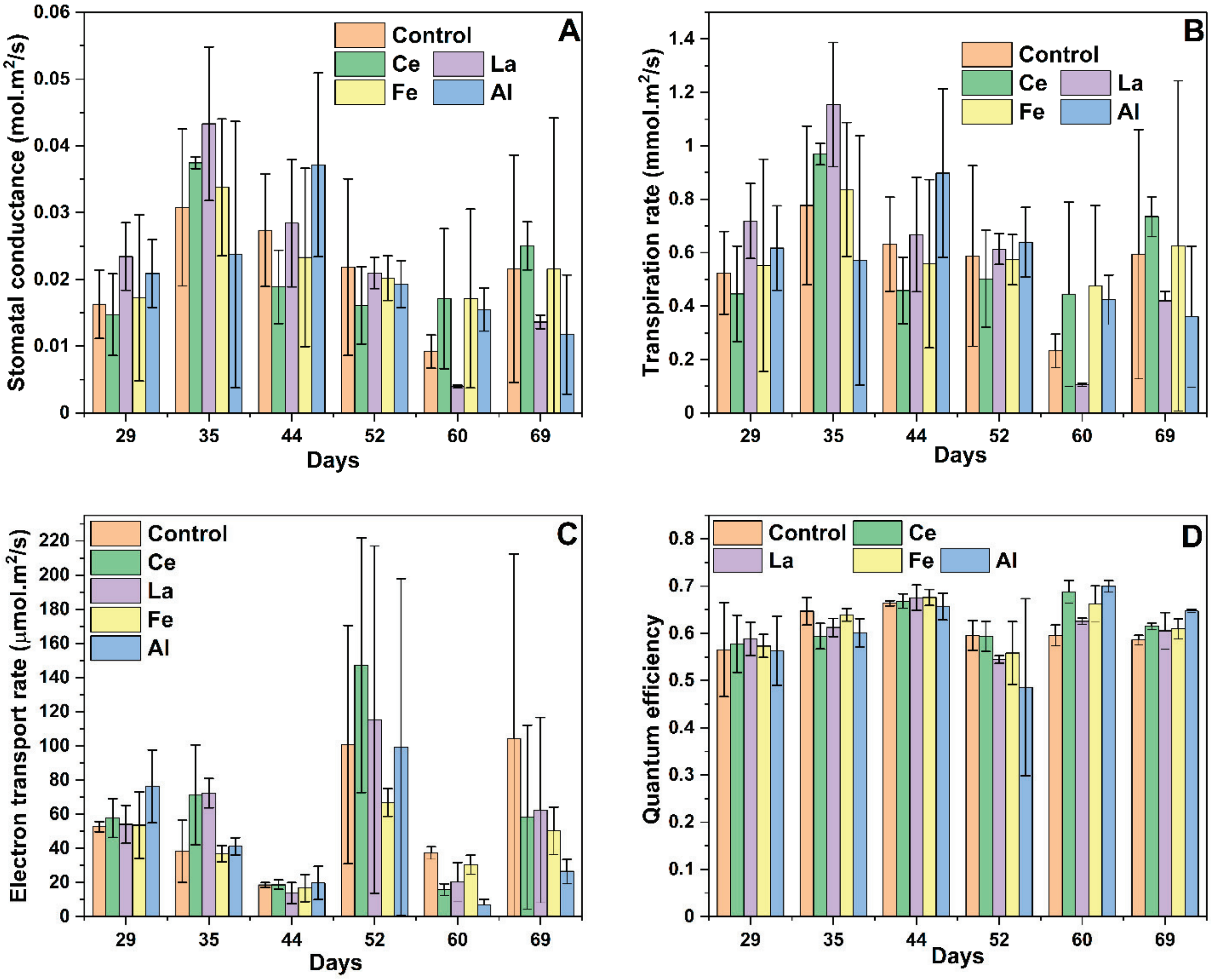

Figure 5. Stomatal conductance (**A**), transpiration rate (**B**), electron transport rate (**C**), and quantum efficiency (**D**) of corn grown with different coagulants. Error bars represent one standard deviation, with n = 3. There was no statistical difference between the control and plants treated with Ce, La, Fe, or Al when measured on the same day at a 95% confidence level.

3.5. Metals Uptake

Due to the strong bond formed between lanthanides and phosphate (Ln–P), it was initially anticipated that Ln^{3+} might reduce phosphorus availability to corn by forming insoluble Ln–P precipitates. Metal uptake analysis was performed on 94-day-old corn plants. Each pot treated with cerium or lanthanum received 165.9 mg of Ce^{3+} and 164.9 mg of La^{3+}, respectively. Figure 7A,B show the uptake of Ce, La, P, Ca, and Mg in the roots of plants grown in Ce and La environments. Compared to the control (Figure 7C), Ln^{3+} treatments did not inhibit or enhance phosphorus uptake. If any interaction between Ln and phosphorus occurred, it is likely that soil fungi and/or mycorrhizae may have played a role in breaking down the Ln-O-P bond to release phosphorus [48], although this mechanism remains unclear and warrants further research. Trace amounts of cerium and lanthanum were detected in the roots, but none were found in the stems or leaves. This absence suggests limited translocation of lanthanides within the plant, likely due to their moderate to high binding affinity with silica-based substrates like sand [49,50], which may immobilize them in the soil matrix.

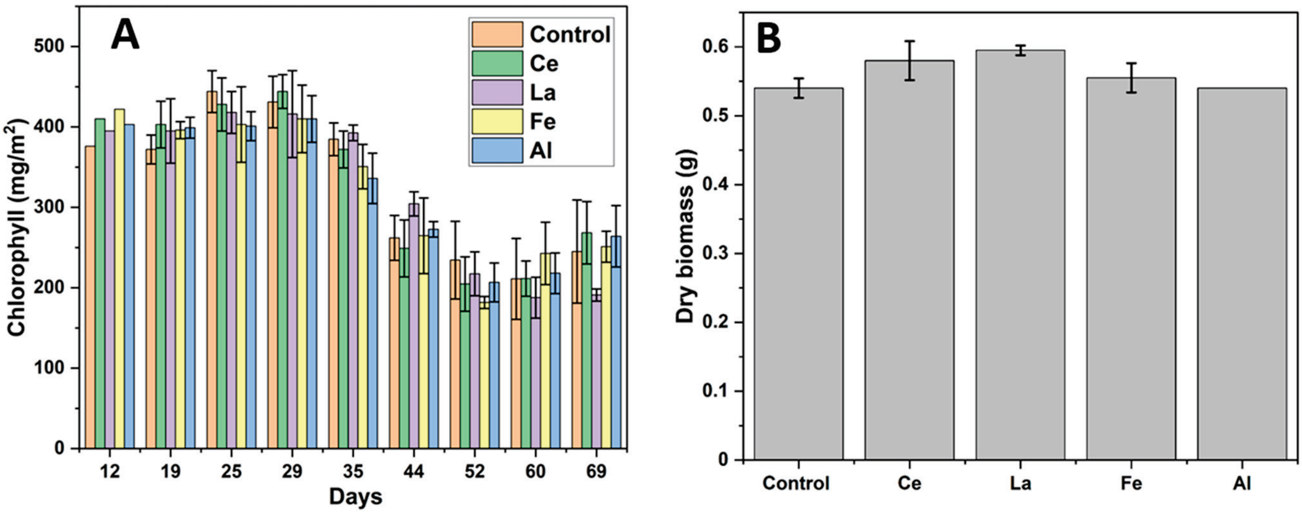

Figure 6. (**A**) The amount of chlorophyll per m^2 under different coagulant environments. (**B**) Dry biomass of corn stems after 94 days. Wet mass of each stem = 1.50 g. Stems were dried for 48 h at 105 °C. Error bars represent standard error, with $n \geq 2$ [24].

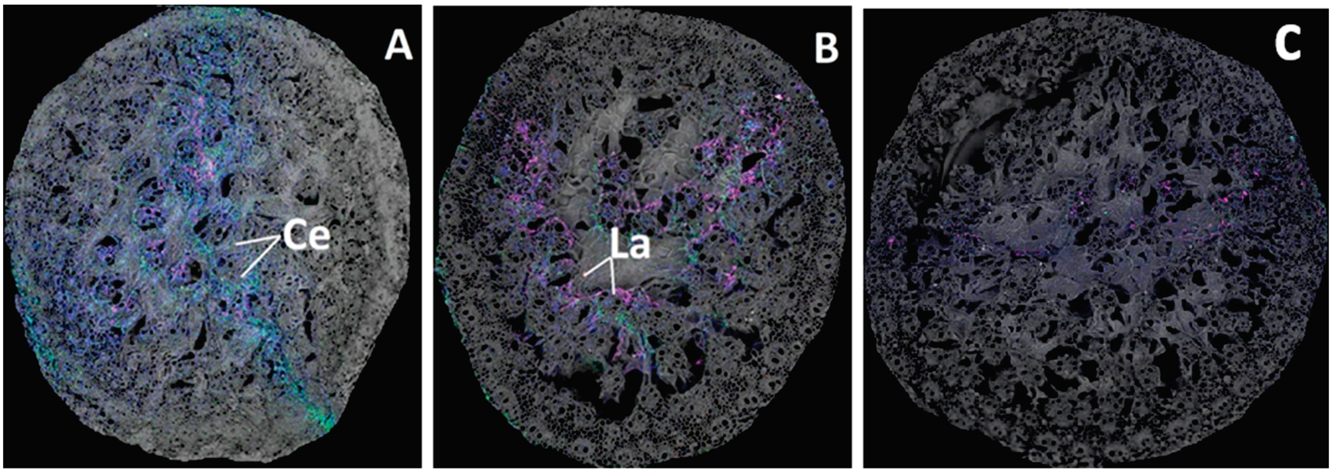

Figure 7. Metal mapping in roots for plants grown with cerium (**A**), lanthanum (**B**), and (**C**) the control. The red spots represent Ce/La, and magenta represents P. Blue is Ca, and green is Mg. Plants were 94 days old, and each respective pot had received 165.9 mg of Ce^{3+} and 164.9 mg of La^{3+} [24].

The presence of other metals (P, Ca, and Mg) in the stems and leaves likely resulted from capillary transport through the plant's vascular system, as the irrigation method used (drip irrigation) avoided direct application of LRWW to aerial parts. Based on fluorescence intensity results (Figure 8), the presence of rare earth elements (REEs) in the root zone appeared to enhance the uptake of P, Ca, and Mg compared to the control. Similar findings have been reported in soybeans, where exposure to lanthanum improved the uptake of metals such as Ca, K, and P [51,52]. Although the precise mechanism by which lanthanides enhance nutrient uptake is not fully understood, one hypothesis is that their interaction with soil silica may liberate micro- and macronutrients, increasing their bioavailability to plant roots and associated fungi. Additionally, as lanthanides enter root tissues, they may create micro-pores or "gates" that facilitate the entry of smaller ions such as Fe and P [53]. This enhanced metal uptake may explain the slightly higher biomass observed in corn plants irrigated with LRWW (Figure 6B). These findings support the potential benefits of using Ln-P and LRWW as phosphorus sources in crop production.

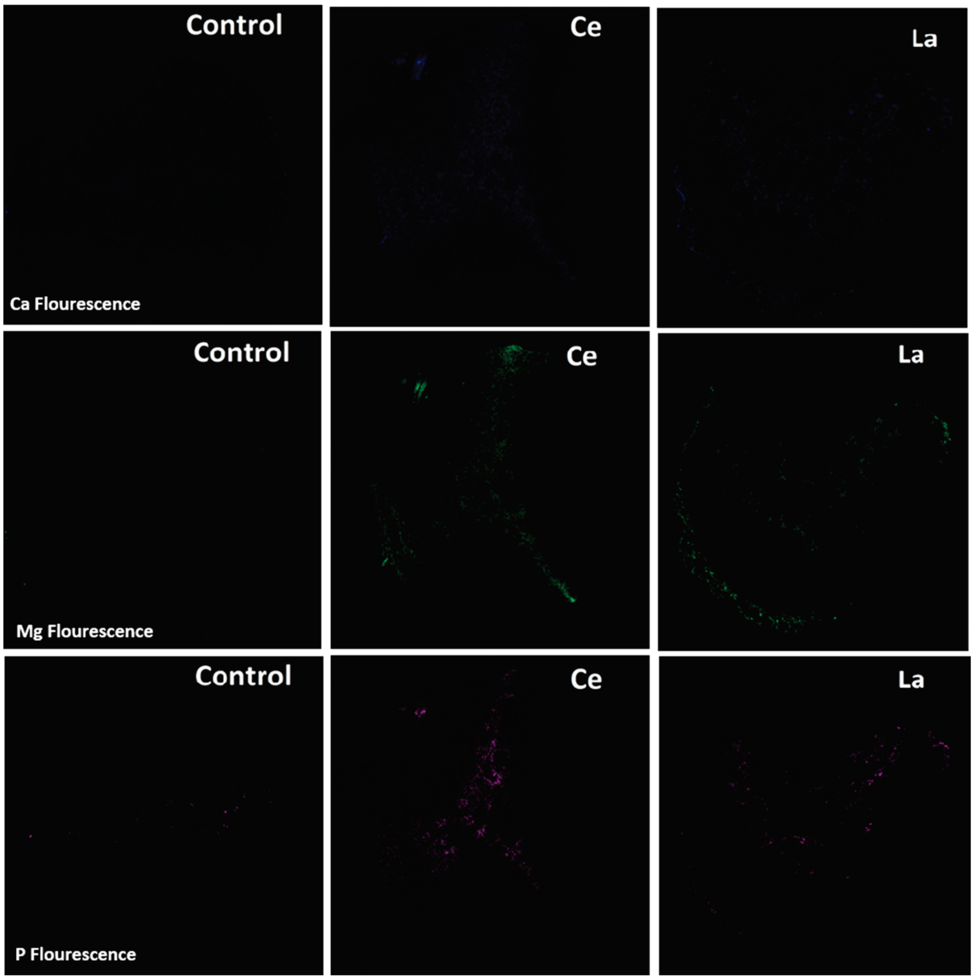

Figure 8. Metal fluorescence in corn roots. Plants were 94 days old, and each respective pot had received 165.9 mg of Ce^{3+} and 164.9 mg of La^{3+} [24].

4. Conclusions

Achieving the United Nations' Sustainable Development Goals—particularly Goal 2 (Zero Hunger) and Goal 11 (Sustainable Cities and Communities)—requires sustainable and integrated strategies that promote nutrient recovery and water reuse. This study demonstrates that lanthanides can effectively recover phosphorus from municipal wastewater, forming high-purity lanthanide phosphate (Ln-P) precipitates ($\geq$98% purity), as confirmed by XPS/EDS analysis.

To assess the potential phytotoxicity of lanthanides, corn seeds were exposed to varying concentrations (0–5000 mg/L) of Ln^{3+}. Compared to traditional wastewater coagulants such as aluminum and ferric salts, lanthanides did not significantly affect germination rates. However, at concentrations above 2000 mg/L, all tested metal treatments—including lanthanides—led to a reduction in root and shoot development. This inhibition was attributed to decreased H_2O_2 production, a critical signaling molecule during germination, and to increased TDS, which imposed osmotic stress and induced physiological drought.

When corn was grown in desert-like soil amended with Ln-P and irrigated using lanthanide-reclaimed wastewater (LRWW), plant development metrics—including height, stem diameter, the number of leaves, and leaf area—showed no statistically significant differences compared to the control group. Likewise, photosynthetic parameters such as stomatal conductance, chlorophyll content, and quantum efficiency remained stable, indicating that lanthanides did not disrupt key physiological processes.

Metal uptake analysis revealed that lanthanide treatments did not inhibit phosphorus absorption. In fact, plants exposed to lanthanides exhibited increased uptake of Ca and Mg, suggesting a potential synergistic effect. Notably, minimal concentrations of lanthanides were detected in plant tissues after 94 days, indicating limited mobility and translocation, with most lanthanides retained in the soil. This immobility not only supports their environmental safety but also raises questions about their role as a long-term phosphorus source.

Overall, the application of Ln-P and LRWW appears to be a promising strategy for sustainable agriculture, especially in arid regions. However, further research is needed to better understand the mechanisms of phosphorus release from Ln-P compounds and their long-term performance as slow-release fertilizers. These insights are essential for advancing circular economy practices in wastewater management and agriculture.

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Appendix A

Table A1. Germination rate of kernels [24].

mg M^{3+}/L	La^{3+}	Ce^{3+}	Fe^{3+}	Al^{3+}
0	70.0%	100.0%	80.0%	40.0%
50	80.0%	100.0%	100.0%	80.0%
100	90.0%	100.0%	40.0%	80.0%
500	90.0%	80.0%	100.0%	80.0%
1000	100.0%	100.0%	80.0%	100.0%
2000	90.0%	100.0%	100.0%	100.0%
5000	100.0%	100.0%	60.0%	100.0%

Table A2. Root length (cm) after 5 days of kernel planting [24].

mg M^{3+}/L	La^{3+}	Ce^{3+}	Fe^{3+}	Al^{3+}
0	4.4	2.8	2.8	1.8
50	4.6	3.2	3.1	3.5
100	4.6	3.6	2.6	4.3
500	1.9	3.3	3.4	3.9
1000	1.6	2.2	4.1	1.8
2000	0.9	0.6	0.8	0.7
5000	0.4	1.0	0.5	0.7

Table A3. Shoot length (cm) after 5 days of kernel planting [24].

mg M^{3+}/L	La^{3+}	Ce^{3+}	Fe^{3+}	Al^{3+}
0	1.2	1.2	1.2	2.3
50	1.5	1.3	1.5	2.2
100	1.4	1.1	1.1	2.8
500	1.0	1.6	1.0	1.6
1000	1.0	1.4	1.2	1.5
2000	0.6	0.6	0.9	0.8
5000	0.5	0.2	0.3	0.4

Table A4. pH after 5 days of kernel planting [24].

mg M^{3+}/L	La^{3+}	Ce^{3+}	Fe^{3+}	Al^{3+}
0	5.5	5.5	5.5	5.5
50	5.1	5.3	3.1	4.0
100	5.1	5.3	2.8	3.9
500	5.2	5.3	2.3	3.7
1000	5.2	5.3	2.1	3.5
2000	5.1	5.3	<0.0	3.4
5000	5.0	5.2	<0.0	3.3

Table A5. Conductivity (μS/cm) after 5 days of kernel planting [24].

mg M^{3+}/L	La^{3+}	Ce^{3+}	Fe^{3+}	Al^{3+}
0	1.5	1.5	1.5	1.5
50	148.3	147.1	528.0	378.0
100	285.0	285.0	1014.0	628.0
500	1204.0	1233.0	3760.0	2108.0
1000	2340.0	2390.0	6680.0	3550.0
2000	4340.0	4500.0	11,780.0	6060.0
5000	9760.0	10,230.0	23,500.0	12,070.0

The number of kernels per Petri dish = 5. Each value represents an average of at least two kernels. M^{3+} = La^{3+}, Ce^{3+}, Fe^{3+}, or Al^{3+}.

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sustainability

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Review

From Crisis to Resilience: A Bibliometric Analysis of Food Security and Sustainability Amid Geopolitical Challenges

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Abstract

Geopolitical instability poses a significant threat to food systems by disrupting production, trade, and market access, thereby undermining both food security and long-term sustainability. Unlike peacetime food insecurity driven by poverty or climate change, conflict-related crises often involve blockades, agricultural destruction, and deliberate famine. This paper conducts a bibliometric review of the academic literature from 2010 to 2024, and partially 2025, to examine how food security and resilience under the influence of conflict have been conceptualized, focusing on their intersections with war, global food systems, and sustainability. We used the Web of Science database and tools such as VOSviewer version 1.6.18, Microsoft Excel and Bibliomagika version 2.10.0, to map thematic clusters, identify influential authors, publishers, and academic partnerships and trace the evolution of scholarly attention on this topic. Our findings reveal a growing recognition of using food as a tool of war, the increasing politicization of food aid, and heightened awareness of the fragility of agricultural systems under conflict. At the same time, significant gaps still persist, particularly in the study of “unconventional” food systems such as black markets and informal supply chains, which often sustain communities during crises but remain underexplored in mainstream scholarship. By identifying these gaps, this review outlines research priorities for developing inclusive and resilient policies, ultimately enhancing the capacity of global food systems to withstand the pressures of conflict and geopolitical instability.

Keywords: zero hunger; food security; sustainable systems; geopolitical instability; resilience; black markets; agricultural disruption; alternative supply chains; famine; bibliometric analysis

1. Introduction

“Food is a weapon.” [1] or “Food is power” [2]. These strikingly simple phrases, famously uttered by U.S. statesmen in the 1970s, capture a grim reality: throughout history, food and hunger have been used as tools of power during times of geopolitical instability. Such weaponization has taken many forms, including military blockades, the withholding of humanitarian aid, the destruction of agricultural infrastructure, or the strategic use of food supplies by powerful nations. Defined as the deliberate use of food to achieve military or political objectives, food weaponization has gained renewed international attention in the 2010s and 2020s amid overlapping global crises. From civil wars and insurgencies (where belligerent forces deny food to populations) to international conflicts (where exports and aid are manipulated as leverage), the intersection of food and conflict poses acute humanitarian and security challenges [3].

Messer and Cohen [4] remind us that food as a weapon is as old as written records. On the one hand, this includes the challenge of feeding armies sufficiently. A well-known quote from the Roman Empire states that “armies are more often destroyed by starvation than battle” [5]. Whenever armies were on the move, the domestic population suffered [6]. For the armies themselves, garrison armies were even more difficult to feed, as local food networks had already been destroyed [7].

The provisioning of armies during warfare is primarily a logistical matter rather than an instance of food weaponization. Over many centuries, sieges were the main instrument of food weaponization. Whether the siege of Jerusalem by the Roman army in the first century [8], the siege of Chippenham by the Vikings in the eighth century [9], or the infamous siege of Leningrad during the 20th century [10], all followed the rationale to cut off the urban population from food supplies to make them unable to defend themselves. In a review of different sieges, McGlynn [11] called hunger “the most decisive weapon of all”.

The more the food trade intensified over the course of history, the more it became a strategic tool for governments as well. Rothschild [12] and Paarlberg [13] were among the first reflecting on this aspect in depth, before the American philosopher William Aiken [14] suggested that food was often used as a weapon. However, it took another 22 years before the term weaponization of food was officially coined by another philosopher in a US university, Eduardo Mendieta [15]. He used it for the notion that, under the shield of the NAFTA agreement, the United States would push genetically modified maize seed into Mexico.

According to Armed Conflict Location & Event Data (ACLED) [16], as of December 2024, 50 countries are actively involved in conflicts, with more than 665 million people being exposed to violence worldwide. Between 1 June 2024 and 30 May 2025, there were 191,448 total events recorded, involving battles, explosions, remote violence, or violence against civilians across 153 countries, marking a near-doubling of incidents since 2020, reflecting a sharp deterioration in global security, mostly located in the Southern hemisphere, as reflected in Figure 1. ACLED’s 2025 Conflict Watchlist [17] warns of long-term crises in these regions, with no near-term resolution expected for Ukraine, Palestine, or Mexico’s cartel wars. According to combined reports from SIPRI (Stockholm International Peace Research Institute, Stockholm, Sweden), FSIN (Food Security Information Network, Rome, Italy), OCHA (Office for the Coordination of Humanitarian Affairs, Geneva, Switzerland), and IRC (International Rescue Committee, New York, USA), conflicts in Sudan, Gaza, and Ukraine, exacerbated through climate shocks and economic collapse, have pushed acute hunger to 295 million people globally, double the 2020 figure [18–20].

Recently, Israel’s restrictions on food delivery into Palestine have drawn significant public attention and sparked worldwide concern over widespread hunger [21]. Yet, similar strategies are routinely deployed in other conflict zones with far less media coverage or international scrutiny. In Syria and Yemen, for instance, warring parties have systematically looted farms, destroyed markets, and obstructed humanitarian aid—weaponizing food as a deliberate tactic of war [22]. In 2018, the United Nations Security Council, recognizing the severity of these tactics, unanimously condemned the starvation of civilians as a warfare method and affirmed the link between armed conflict and food insecurity [23]. Also, the war in Ukraine further underscored the global dimension: Russia’s blockade of grain exports and targeting of Ukraine’s agricultural infrastructure not only sought to weaken an adversary’s economy but also upended global food markets, driving up prices and hunger far beyond the conflict zone [22].

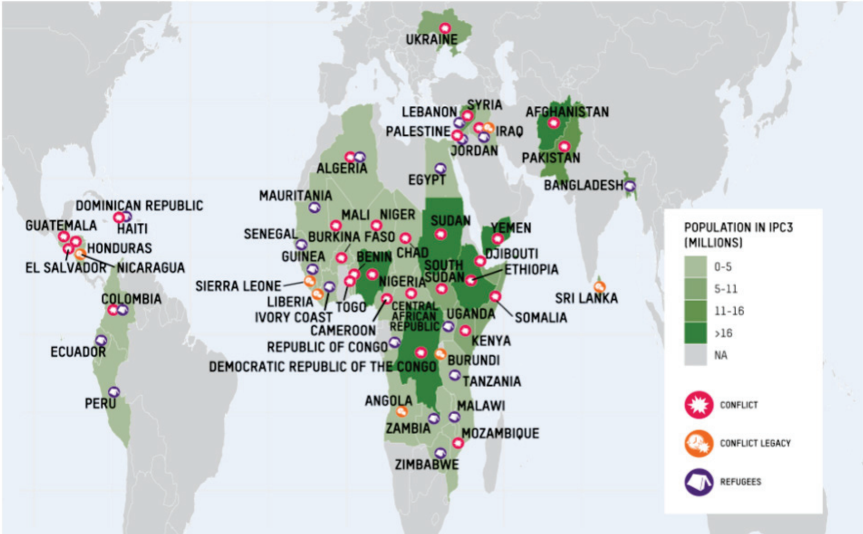


Figure 1. Active conflict sites around the world. Source: "Food Wars: Conflict, Hunger, and Globalization"—FAO Report [24].

The Fragility, Conflict and Violence (FCV) collection, jointly managed by the World Bank, UNHCR, and UK Aid [25] provides one of the most valuable resources highly relevant to food insecurity in conflict settings because it provides empirical data that captures how systemic fragility, violence, and displacement directly affect food systems. The FCV dataset collection offers operational insight into how conflict-induced displacement, agricultural disruption, and institutional collapse interact to produce acute food insecurity, highlighting the empirical foundation beneath conceptual debates around food weaponization. Figure 2 visually reinforces the direct spatial correlation between active conflict zones (as illustrated in Figure 1) and the prevalence of severe food insecurity as a percentage of the total country population (projected value for 2025). Countries in Central and Eastern Africa, the Middle East, parts of South Asia, and Latin America exhibit both high levels of violence and food insecurity, often exceeding a 41% prevalence threshold. This geographic overlap underscores a systemic pattern: conflict not only destabilizes food systems, but does so persistently and predictably in specific regions, compounding vulnerability through repeated cycles of displacement, economic collapse, and institutional fragility.

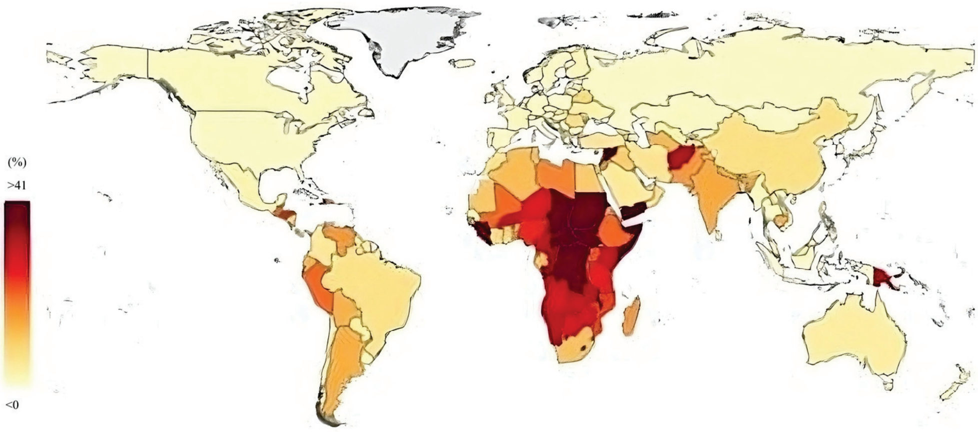


Figure 2. Prevalence of food insecurity in % of the total country population for 2025, Source: World Bank, Development Data Group [26].

The data further supports the argument that food insecurity is not simply a collateral effect of conflict, but often a deliberately engineered outcome, facilitated by the destruction of agricultural infrastructure, market obstruction, and the political manipulation of aid flows. Such overlap aligns with findings from recent FCV datasets and reinforces the urgent need for a research and policy framework that treats food security as a peace and security issue, not just a development concern.

However, the world faces escalating food security threats not only from conflict but also from climate change, pandemics, and economic volatility. All of these other threats often interplay with conflict in a vicious cycle: conflict breeds hunger, and hunger fuels grievances that can spark unrest. By 2021, up to 60% of undernourished people and 75% of stunted children were living in conflict-affected countries, as highlighted in the 2021 Global Hunger Index [27]. Conflict remains the single greatest driver of hunger worldwide, with food systems in conflict-affected countries experiencing severe disruptions across production, trade, and aid delivery channels. The report emphasizes that these disruptions are not incidental but often strategically targeted to weaken adversaries or control populations, further reinforcing the notion of food weaponization as a deliberate mechanism of power. Such sobering statistics jeopardize progress toward the Sustainable Development Goals (SDGs)—notably SDG2: Zero Hunger, as well as goals on poverty, health, and peace [28]. Indeed, food security, conflict, and sustainable development are deeply entwined: without peace, efforts to end hunger struggle; without food security, stable development and conflict prevention are undermined. These interlinkages have given rise to the necessity of a body of research at the confluence of food, conflict, and sustainability, drawing on disciplines of agriculture, political science, economics, public health, and environmental studies.

While doing research for a different project [29], our team observed frequent mentions of conflict in the available academic literature as a facilitator of food insecurity and the disruption of food chain ethics. However, these comments were largely tangential, with conflict and war being treated more like an afterthought than as a focal point. The proximity of a major conflict to the authors' country of origin provided a direct impetus to critically examine the extent to which the academic community has engaged with how natural food supply chains are severely disrupted and strained by the evolving dangers of war. As such, these immediate and observable impacts compelled us to critically examine the extent to which the academic community has engaged with the topic of food supply chain resilience and sustainability in conflict settings across time. How deeply is this issue explored in scholarly research, and are current approaches sufficient to address the growing complexity of food insecurity in times of war?

To guide our bibliometric review, we formulated four interconnected research questions that together provide a comprehensive lens on this topic:

RQ1: *How has scholarly understanding of the role of food in geopolitical contexts evolved since 2010, and how is it connected to broader crisis-related actions?*

RQ2: *Is there a bias in the academic research ecosystem going more towards depoliticizing food-related violence by framing it primarily as a humanitarian or development issue rather than a strategic act of war?*

RQ3: *Are "unconventional" food supply chains, such as black markets, informal networks, and underground distribution systems, adequately examined in the literature, particularly in their role during armed conflict?*

RQ4: *Which other key knowledge gaps and underexplored themes remain in the academic discourse on food security and conflict, and how can researchers strategically address these to enhance the relevance and impact of their work?*

The first question (RQ1) traces how academic scholarship has evolved, establishing the field's trajectory. The second (RQ2) examines biases in framing, particularly whether food-related violence is depoliticized as a humanitarian issue or acknowledged as a deliberate act of war. The third (RQ3) extends this critique by asking whether unconventional food supply chains–often central to survival in conflict–are sufficiently addressed in the literature. Finally, the fourth (RQ4) integrates these insights by identifying underexplored themes and gaps, pointing to where future research should be directed. Taken together, these questions move from mapping developments to interrogating blind spots and, ultimately, to outlining priorities for advancing the field.

This review aims to help fill this gap by using a bibliometric analysis to map and interrogate the state of academic research on the intersection of food, conflict, and systemic disruption, revealing blind spots, disciplinary biases, and thematic silences in the literature.

The four research questions outlined above serve as guiding anchors for our inquiry and help structure the conceptual framework of the study (see Figure 3).

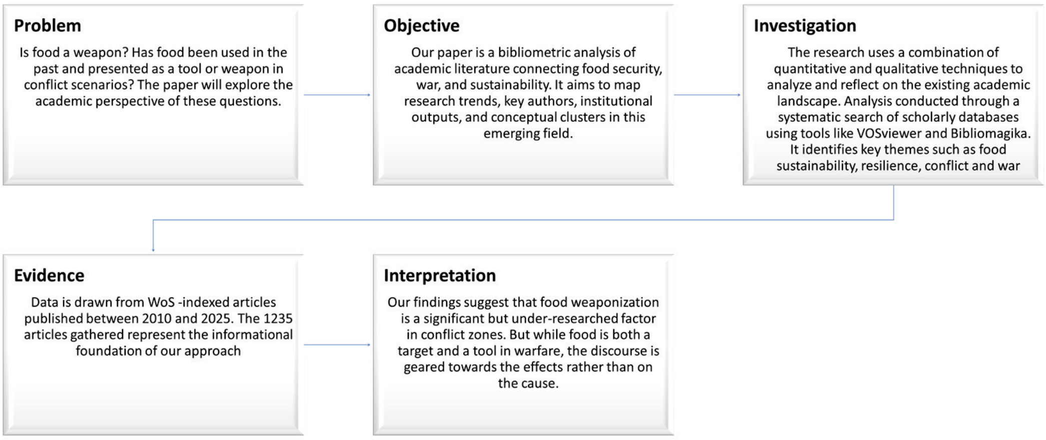


Figure 3. Conceptual framework and workflow for analyzing food as a tool in conflict and security contexts.

Ultimately, the bibliometric evidence generated in this study is intended not only to synthesize past work but also to provoke new intellectual and practical directions. In a time when conflict dynamics are increasingly hybrid and transnational, the capacity to understand and disrupt food-based tactics of coercion must be seen as an essential pillar of peacebuilding, humanitarian intervention, and global food governance.

2. Materials and Methods

2.1. Study Design and Approach

In determining the most appropriate approach for this topic, we evaluated several types of literature reviews, including bibliometric analysis, meta-analysis, and systematic literature reviews. After thorough consideration, appropriating the necessary steps and studying the main points of differentiation [30–34], we chose to employ bibliometric analysis, as our primary objective is to map and synthesize the existing body of literature rather than to develop or extend theoretical frameworks. Also, similar studies have provided both a foundation for our analysis and evidence that this is an increasingly urgent research area, particularly as conflicts intensify in regions with rapidly growing populations. While much of the literature has concentrated on broad issues such as resilience and global food security trends [35–38], several contributions have also examined specific contexts, for example, the war in Ukraine and its disruption of global grain exports, or conflicts in the Middle East and their effects on local food access and humanitarian assistance [39–41], thereby illustrating how food insecurity operates simultaneously as a global systemic challenge and as a localized crisis with devastating human consequences.

2.2. Data Sources

All bibliographic data were retrieved from the Web of Science Core Collection (WoS). This database was selected due to its comprehensive coverage of high-impact, peer-reviewed journals across disciplines and its robust citation indexing system.

2.3. Search Strategy

We carried out two rounds of Topic Search (TS) in the Web of Science database, meaning the search terms were applied to titles, abstracts, and author keywords. The search strategy was structured across three levels of terms to ensure extensive coverage of the subject.

1. The first level addressed food security as a main topic for the research, with connected words like "hunger/malnutrition/nutrition/. . ." etc., because we are thinking about "Food security" as it has been defined in the 2024 Global Report on Food Crises [18]: "(. . .) All people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (. . .)".
2. The second level refers to the context of conflict and systems frailty with search terms like "conflict, fragility, violence, war, "humanitarian crisis", displacement, "fragile settings", "armed conflict", "post-conflict" or "war zones", necessary for understanding the context of food insecurity caused by the conflict setting, not referring to peacetime food insecurity.
3. The third level addresses the solutions proposed across different research articles. Whether these involve policy recommendations, research and development initiatives, strategic approaches, or innovations, we aimed to identify the types of solutions put forward by our peers and assess whether there is a consistent, systemic direction or if the proposed measures are more context-specific and locally adapted.

The initial search query used was designed to identify pertinent literature relevant to the broader theme of enhancing food security in conflict landscapes—an increasingly important area of research that requires more nuanced approaches as live situations evolve on the ground.

Search Query no. 1: *TS = (("food security" OR "hunger" OR "malnutrition" OR "nutrition" OR "food systems" OR "agrifood systems" OR "diets" OR "food access") AND ("conflict" OR "fragility" OR "violence" OR "war" OR "humanitarian crisis" OR "displacement" OR "fragile settings" OR "armed conflict" OR "post-conflict" OR "war zones") AND ("resilience" OR "improving" OR "improvement" OR "policy" OR "policies" OR "intervention" OR "interventions" OR "R&D" OR "research and development" OR "innovation" OR "strategies" OR "solutions")).*

The second search query was designed to assess the scope of academic research on alternative food supply chains in conflict-affected contexts. To build on the initial query, we added an additional set of terms—*"black market" OR "informal food distribution" OR "illicit trade" OR "smuggling" OR "parallel market" OR "war economy"*—in order to capture literature specifically addressing informal and non-conventional food systems.

2.4. Inclusion/Exclusion Criteria

To ensure the relevance and focus of our analysis, we applied specific inclusion criteria during the search process. First, we limited our dataset to articles and review articles published from the year 2010 onward, because presently, conflicts are substantially different from those before 2010, not only in their dynamics but also in the tools and strategies employed, while the accelerating development of technologies and artificial intelligence in the coming decades will likely introduce entirely new forms of warfare, making recent literature more relevant for understanding current and future challenges to food security in a conflict landscape.

Additionally, to capture literature that specifically addresses the food supply dimension of our topic, we filtered results by selecting only those publications linked to Sustainable Development Goal (SDG) 2—Zero Hunger [42]. This criterion was crucial for anchoring our analysis in research that directly engages with issues such as food security, agricultural sustainability, nutrition, and hunger eradication.

An additional exclusion criterion was applied to our query concerning the topical focus of the papers. Specifically, we excluded studies primarily addressing adult—human or animal healthcare, as these tend to frame food-related issues through the lens of nutrition and disease rather than conflict. While such research is valuable, it typically explores food as a vector for health outcomes rather than as a strategic or systemic component of warfare. By contrast, we retained studies addressing child healthcare, as the literature consistently highlights children as the demographic most vulnerable to conflict-induced food insecurity and as directly affected by wartime shortages and disruptions.

2.5. Data Cleaning and Preparation

All bibliographic records, including metadata on authors, affiliations, keywords, and citations, were exported in plain text format and Excel files. Data cleaning steps included removing duplicates from the list of papers, harmonizing affiliations, countries and keywords, applying inclusion/exclusion criteria. The cleaned dataset was then imported into the bibliometric analysis software for further processing.

2.6. Tools

Bibliometric mapping was conducted using Zotero, Microsoft Excel, BiblioMagika version 2.10.0 and VOSviewer version 1.6.18, powerful tools for cleaning, analyzing, and visualizing bibliometric data, tools that enabled the creation of compelling visual outputs revealing key patterns, thematic clusters, and research trajectories, and offering clear insights into the evolution of the field from past developments to future directions.

The four tools we have used in this paper were:

- Zotero—A well-known reference management software used to collect, organize, and manage bibliographic data. Zotero facilitated the systematic collection of publications, ensured consistent citation formatting, and supported the export of metadata required for bibliometric analysis.
- Excel—Used for data cleaning, sorting, and preliminary descriptive analysis. Excel allowed us to manually inspect the metadata, identify inconsistencies, and generate basic statistical summaries
- Bibliomagika—A bibliometric Excel-based software employed to automatically clean, structure, and extract metadata from large publication datasets. Bibliomagika [43] was particularly useful in processing CSV files, standardizing author and keyword fields, and preparing the data for our chosen visualization tool.
- VOSviewer—A specialized bibliometric visualization tool used to map co-authorship networks, keyword co-occurrence, and citation relationships. VOSviewer enabled us to visually explore the intellectual structure and thematic clusters within the literature.

These four software tools were employed in a sequential workflow, from data collection and management (Zotero) to data cleaning and statistical analysis (Excel, Bibliomagika), and finally to network visualization (VOSviewer) to provide the essential metrics and visualization for our research.

2.7. Limitations

While our desire was to produce a highly relevant study, we must also acknowledge several limitations in conducting the current research. First, because our dataset was confined to Web of Science as the sole database, it may have excluded relevant studies indexed in other databases such as Scopus or Google Scholar, as well as publications from non-indexed journals, books, and grey literature that might have been relevant but were not selected. Second, we restricted our analysis to English-language publications due to language barriers. This exclusion may have inadvertently omitted important research published in other languages, particularly in regions directly affected by the geopolitical issues discussed. Third, bibliometric analysis, in general, is more of a quantitative method rather than a qualitative one and it serves to identify publication trends and relationships but does not deeply interpret the content or quality of individual studies. It subsequently cannot assess theoretical nuance or methodological rigor. Lastly, our study is constrained by the rapidly evolving nature of geopolitical events, particularly those related to conflict and food security. As these developments continue to unfold in real time, there is a risk that our findings may quickly become incomplete. This highly dynamic context stresses the importance of viewing our analysis as a snapshot in time, which can—and should—be revisited as new data and reports emerge.

3. Results and Discussion

3.1. How Has Scholarly Understanding of the Role of Food in Geopolitical Contexts Evolved Since 2010, and How Is It Connected to Broader Crisis-Related Actions?

Our initial step involved conducting a comprehensive search within the Web of Science database, and a summary of the preliminary results obtained from this search is depicted in Table 1 below. After cleaning the data and refining the raw results by applying exclusion criteria, we have identified 1073 research articles and 162 review papers, resulting in a final dataset of 1235 documents for analysis and visualization. Only 1099 of these remaining papers (88.9%) have received at least 1 citation indexed in Web of Science.

Table 1. Preliminary dataset extracted from Web of Science.

Description	Values
Time span	2010−2025
Documents before applying exclusion criteria	1687
Documents (articles and review papers)—after applying exclusion criteria	1235
Authors	5300
Affiliations	3365
Countries	130
Cited papers	1099
Times cited—all databases	29,432
Citations per cited paper (average)	26.78
Unique keywords	3681

The volume of publications on food security and geopolitical turbulence has grown exponentially since 2010. In 2010, only 10 relevant papers were published, whereas by 2020 the annual output exceeded 100, and by 2022–2025 it easily exceeded 150 papers per year (Figure 4).

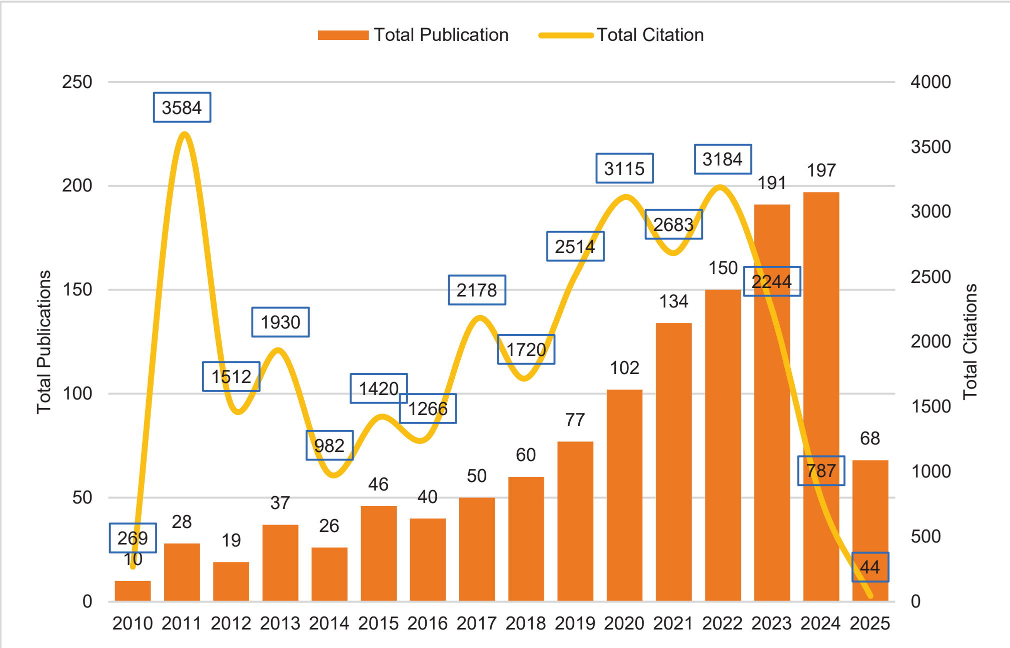


Figure 4. Number of identified articles published between 2010 and 2024 and total citations for the published years. Note: Data for 2025 is partial, extracted on 17 June 2025.

This growth reflects increasing scholarly (and policy) attention to issues of hunger in war and the resilience of food systems amid crises. Several notable inflection points align with real-world events:

- 2011–2013: A slight uptick corresponds with global food price spikes and the Arab Spring, which included countries like Syria, Gaza and Iraq [44–46]. Many papers focus on the nutritional status and challenges faced by specific groups, particularly women and children in regions like India, Kenya, the Democratic Republic of Congo or Uganda. These studies examine undernutrition, maternal autonomy in feeding practices, and fluctuations in child wasting, highlighting health disparities in fragile or resource-limited settings [47–49].
- 2014–2019: A steady rise in papers tracks the long-lasting Syrian civil war, Yemen conflict, and South Sudan famine. Concepts like "weaponization of food" enter the discourse of the UN and WFP. FAO and different NGOs sounded alarms on siege tactics, causing famine. A large number of papers explore the impact of conflict on food security, particularly in countries like Yemen, Nigeria, Somalia, and Gaza. These studies focus on malnutrition, displacement, humanitarian responses, and the structural vulnerabilities exposed during crises. Papers such as "Acute malnutrition among children, mortality, and humanitarian interventions in conflict-affected regions—Nigeria [50] and "The effects of violent conflict on household resilience and food security: Evidence from the 2014 Gaza conflict" [51] underscore the deep entanglement of war, hunger, and systemic fragility. The adoption of UNSC Resolution 2417 in 2018 [23]—explicitly linking conflict and hunger—may have further catalyzed academic inquiry, as indicated by a jump in publications around 2019.
- 2020–2021: The literature expands rapidly, as a natural response to a growing international interest in the topic, and high-impact papers published in this period addressed how climate change exacerbates conflict risks and undermines crop yields. By 2020, the COVID-19 pandemic became another focus: publications emerged on how conflict-affected states coped with pandemic-related supply disruptions. Our data show "COVID-19" rapidly became a top keyword, reflecting concern that pan-

demic lockdowns and economic shocks could intensify food insecurity in fragile settings [52–54].

- 2022–2023: A significant event during this period is Russia's invasion of Ukraine in February 2022. The war's global fallout on food supplies prompted a flurry of research and commentary, from analyses of Black Sea grain exports to broader discussions of food as a geopolitical tool. In 2022 alone, at least 150 publications appeared, including highly cited pieces on the war's impact on global food security [55,56]. 2023 also sustained high academic output, examining ongoing crises (e.g., drought and conflict in the Horn of Africa, instability in Haiti, and the Sahel). Topics widely range from child malnutrition [57,58] to the mental health impact of hunger in fragile settings [59].
- 2024–2025 (partial): While our data for 2025 is incomplete (covering early-year publications up to June), the trajectory suggests continued high engagement. Themes like food systems resilience, climate adaptation, and humanitarian response in conflict zones remain prominent. We also see emergent topics (e.g., the food security implications of the Gaza conflict and sanctions regimes). In these last 2 years, studies span food availability, household coping mechanisms, malnutrition, famine monitoring, and humanitarian assistance evaluation. Papers like "Dying of starvation if not from bombs: assessing measurement properties of the Food Insecurity Experiences Scale (FIES) in Gaza's civilian population experiencing the world's worst hunger crisis" and "Food insecurity and coping strategies in war-affected urban settings of Tigray" [60,61] capture the deadly convergence of violence and hunger while others assess conflict-specific food aid efficiency, nutrition for displaced populations, or post-war agricultural reconstruction (e.g., Ukraine, Colombia, Syria) [61–65] Notably, some 2023–2024 works are already influential—for instance, a Foreign Affairs analysis by Helder et al. (2023) calling food weaponization an "ancient tactic making a deadly comeback" has garnered policy attention [22].

Researchers in this domain tend to have limited publication frequency, with only 189 authors contributing to two or more papers within the dataset, suggesting that while the field is thematically rich, it remains relatively dispersed in terms of sustained scholarly authorship. The most prolific contributor identified is Peter H. Verburg, who stands out with the highest number of publications by a single author (5 in total), indicating a focused and ongoing engagement with topics at the intersection of land use, food systems, and sustainability.

The most cited paper is "Global Land Use Change, Economic Globalization, and the Looming Land Scarcity" by Lambin and Meyfroidt [66] published in Proceedings of the National Academy of Sciences (PNAS), with an extraordinary 2089 citations and a citations number per year (C/Y) of 139.27. This suggests it has become a foundational work in the field, likely due to its early and comprehensive synthesis of land use dynamics, global economic pressures, and ecological constraints. Its inclusion signals how macro-structural, system-level analyses continue to anchor debates in food security and land governance. *PNAS*, as a top-tier journal, amplifies its visibility and reinforces its intellectual authority. While not directly connected to conflict, the main points from the paper can be applied to conflict-affected areas and can help identify how productive land scarcity can negatively impact food security in certain areas.

The second most cited work, "Land Grabbing in Latin America and the Caribbean" by Borras and team [67], also carries significant weight with 373 citations and a solid C/Y of 26.64, published in the *Journal of Peasant Studies*. This reflects the growing relevance of land sovereignty, dispossession, and agrarian justice, particularly in the context of the global south resource politics. The choice of journal is telling: the *Journal of Peasant Studies* is known for its critical, political economy lens, and this work clearly resonates with readers interested in the intersection of land, power, and inequality.

Notably, one of the most recent articles on the list, "Impacts Of The Russia-Ukraine War On Global Food Security: Towards More Sustainable And Resilient Food Systems?", is a very recent analysis of the Russia–Ukraine war's impact on global food security. It has already reached 345 citations and an outstanding C/Y of 86.25. Its publication in *Foods* and its recency underscore both the topical urgency and the rapid diffusion of literature that directly engages with contemporary geopolitical shocks. This demonstrates that timely, conflict-driven analyses, especially when tied to global food system disruptions, are being quickly and widely cited, confirming a paradigm shift toward viewing conflict as central to food system fragility.

While publishing more papers may signal academic productivity, it does not necessarily equate to higher scholarly impact. To better exemplify this dynamic, Figure 5 presents a world map visualizing the ratio between the total number of citations and the number of cited papers-a metric indicative of average citation influence per publication. In this map, darker shades represent countries with higher citations per cited paper (C/CP ratio), suggesting greater visibility or influence of each individual publication:

- Zimbabwe stands out with the highest C/CP ratio (75.0), implying that although the absolute number of publications is very low (1), this paper [68] that addresses various behavioral response patterns of African Farmers tends to receive substantial scholarly attention, possibly due to the high-profile of the case study and its importance for the African Continent.
- Countries like New Zealand (67.4), Argentina (57.2), China (36.81), Australia (37.63) or the United States (34.87) also exhibit high citation-per-paper ratios, reflecting a vast established academic infrastructure, strong global networks, and frequent publication in high-impact journals.
- In contrast, high-output regions like Italy (21.12), Ethiopia (11.21) or Niger (18.14) show lower C/CP values, indicating that while many papers are being produced, their individual citation impact is more modest.
- Notably, conflict-prone states such as Yemen, Syria, and Afghanistan (shown in lighter tones) have medium to upper levels of citation-per-paper ratios, suggesting that while these countries are frequently mentioned, they are often the subjects of external research rather than producers of high-impact academic work themselves, but the work they produce still gathers attention.

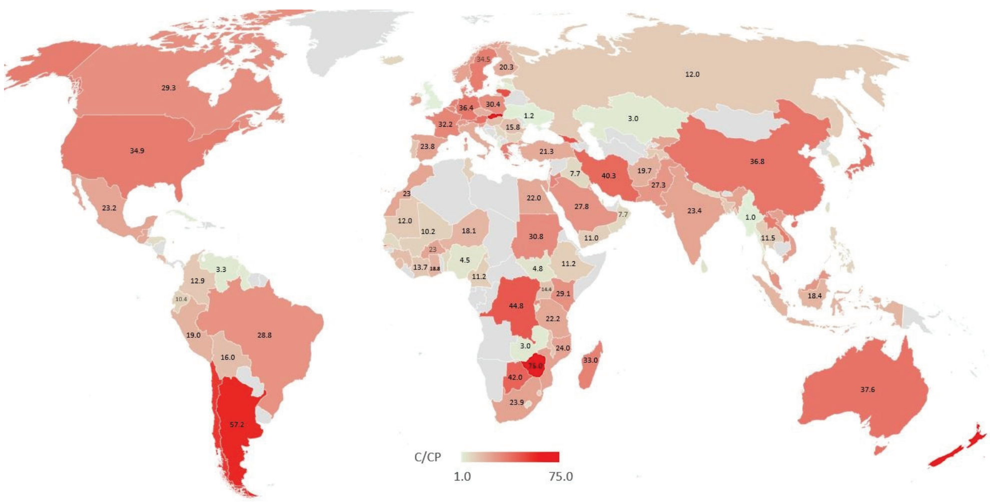


Figure 5. Map dispersion of the total citations per cited paper ratio (C/CP).

In summary, the observed publications trend underscores that this field is dynamic and responsive to contemporary events. The nearly tenfold increase in publication output from 2010 to 2024 mirrors the elevation of food-security-in-conflict as a critical global issue. This growth also reflects broadening scholarly participation: early 2010s research was often led by development economists and agronomists, whereas by the 2020s, we see contributions from security studies, law, public health, climate science, and beyond. Researchers increasingly linked food weaponization to modern warfare strategies, noting that contemporary conflicts exhibit intentional hunger infliction despite international prohibitions. Notably, Russia's invasion of Ukraine brought renewed focus on "geopolitical" food weaponization, especially because by targeting Ukraine's grain infrastructure, Russia endangered multiple African countries dependent on Ukrainian exports.

3.2. Is There a Bias in the Academic Research Ecosystem Going More Towards Depoliticizing Food-Related Violence by Framing It Primarily as a Humanitarian or Development Issue Rather than a Strategic Act of War?

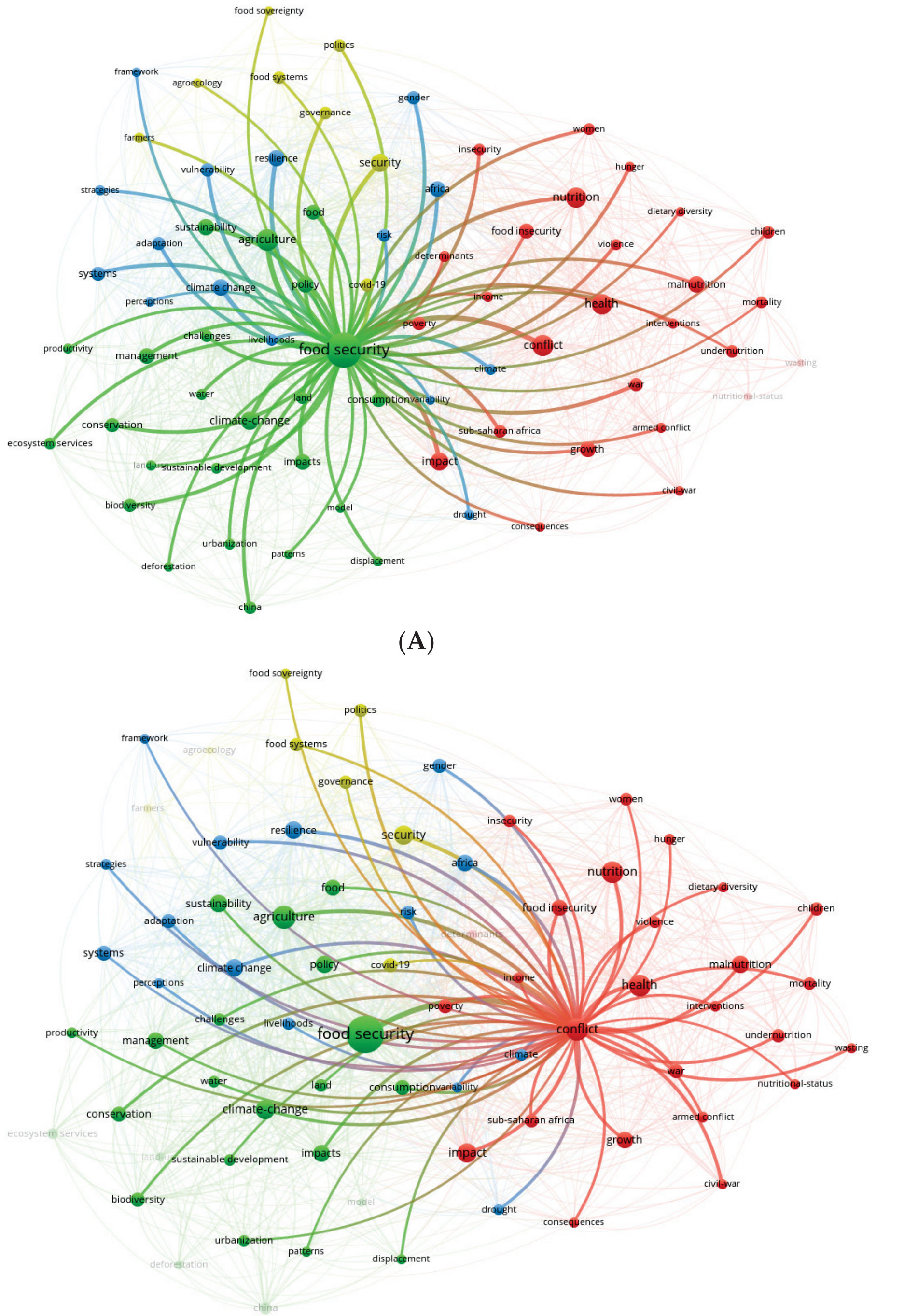
Our analysis reveals a tension in framing within the scholarly literature on food insecurity and conflict. A portion of the research, particularly from development studies and humanitarian journals, presents conflict-induced hunger as a humanitarian problem, emphasizing food insecurity, malnutrition, and nutrition outcomes as tragic but technically addressable consequences of war. These studies often focus on agriculture, food systems, and resilience, assessing how violence affects crop production, market access, or dietary diversity. In doing so, they contribute valuable knowledge, yet they also risk implicitly depoliticizing the issue by framing hunger as a function of disrupted systems or failed development, rather than as a deliberate act of conflict or political violence.

If we compare the dominant keyword clusters visualized in VOSviewer (Figure 6A,B), a clear pattern emerges. The green cluster (Figure 6A) centers around terms such as "food security", "climate change", "agriculture", and "sustainability", and is the largest in both node count and spatial distribution. This indicates a prevailing developmental and environmental framing of food security research, emphasizing systemic challenges, resilience, and long-term adaptation strategies.

In contrast, the red cluster (Figure 6B), centered around the keyword "conflict", composed of terms like "health", "nutrition", "malnutrition", and "children", is smaller and more peripheral in the first visualization.

The keyword "conflict" emerges as a co-dominant node with "health", forming dense linkages with "violence", "armed conflict", "displacement", and "malnutrition". This network structure marks a discursive realignment, wherein conflict is no longer treated as a contextual backdrop but rather as a central driver of food insecurity in this cluster. The proximity of terms like "civil war", "interventions", and "nutrition status" to the conflict node suggests an evolving research agenda after 2015, an agenda that increasingly views hunger not only as an outcome but as a weaponized mechanism within broader geopolitical and military strategies.

Moreover, the strength of interconnections in the second graph, particularly among red-cluster keywords, indicates a maturing and consolidating body of literature at the intersection of conflict, food systems, and health, supporting the idea that academic discourse is gradually shifting towards requiring a greater accountability in the use of hunger as a method of war.



(**A**)

(**B**)

Figure 6. (**A**) VOSviewer network visualizations of keyword co-occurrence (≥20 occurrences; *N* = 73 words) for the dominant "Food Security" cluster (green), focused on systemic and environmental framings. (**B**) VOSviewer network visualizations of keyword co-occurrence (≥20 occurrences; *N* = 73 words) for the "Health" cluster (red), emphasizing humanitarian and nutritional framings in relation to conflict.

By performing a keyword count, widely used terms such as "food security," "nutrition," and "resilience" dominate the literature (with keyword frequencies of 268, 53, and 44, respectively), whereas terms like "starvation crimes" or "weaponization of food" appear far less frequently (Table 2). This emphasis aligns with the humanitarian narrative that centers on the needs and vulnerabilities of populations, particularly in contexts like Sub-Saharan Africa/Gaza/Ukraine and during compounding crises such as COVID–19 or climate change, but often overlooks the agency of perpetrators or the strategic use of hunger in warfare.

Table 2. Comparative frequency of keywords in the analyzed dataset (2010–2025), indicating thematic focus.

Keywords	Mentions
FOOD SECURITY	268
CLIMATE CHANGE	77
AGRICULTURE	59
CONFLICT	57
NUTRITION	53
MALNUTRITION	48
FOOD INSECURITY	48
RESILIENCE	44
COVID-19	40
SUSTAINABILITY	39
FOOD SYSTEMS	36
SUB-SAHARAN AFRICA	28
AFRICA	28
GENDER	27
SUSTAINABLE DEVELOPMENT	24
WAR	19
STARVATION (WAR/CRIMES/DEATH)	3
WEAPONIZING FOOD	1

Many studies detail how conflict disrupts agriculture, markets and nutrition outcomes, but do so in a neutral tone, focusing on quantifying impacts (e.g., reduced dietary diversity or higher child malnutrition) rather than explicitly naming these acts as tactics or crimes [50,69,70], stressing the victims' needs and resilience, while overlooking the agency of perpetrators.

On the other hand, a growing body of scholarship and commentary explicitly politicizes the issue by identifying intentionality and power. These works use terms like "food as a weapon of war", "starvation crimes", or "siege warfare", directly calling out armed actors' strategic logic [48,61,71,72]. For instance, Lin et al. (2022) [73] note that "food insecurity may not only be an externality of conflict but also food deprivation may be utilized as a weapon to discourage residency in contested territories". Alex de Waal, author of the book *Mass Starvation: The History and Future of Famine* [74] and many others argue that famines in places like Yemen are not simply man-made but man-caused—i.e., specific leaders and commanders have purposefully engineered starvation and should be held accountable. However, we see an increase in academic discourse adopting this critical stance, especially after 2017–2018 when the term "starvation as warfare" gained currency following mass atrocities [75–77].

In our dataset, we found 39 papers defined as reviews in "document type", intended to map knowledge production, and a critical reading of these literature reviews reveals a pronounced tendency within academic research to approach hunger as a developmental or public health issue, often stripped of its political and strategic dimensions. Many of these studies emphasize nutrition, food access, and resilience, portraying hunger as a consequence of poor infrastructure, limited agricultural productivity, or climate-induced challenges [78–89], and food insecurity is frequently analyzed through a technical or systems-oriented lens, focusing on improving urban agriculture models, enhancing nutrition delivery platforms, or strengthening food systems in the face of environmental stress. Conversely, a smaller but notable subset of studies engages with hunger as an explicit outcome of conflict, coercion, and geopolitical maneuvering where hunger is not incidental, but rather a deliberately inflicted condition, shaped by blockades, forced migration, destruction of agricultural infrastructure, and the strategic manipulation of food supply in both domestic and international conflicts, positioning hunger within broader structures of power and violence. The distinction between these two framing orientations—technocratic-humanitarian versus political-strategic—is critical, as it shapes the types of solutions researchers prioritize, the actors they hold accountable, and the language through which crises are interpreted and addressed [69,76,90–92].

The keyword analysis for the Reviews reveals a dominant focus on technical, developmental, and humanitarian framings of food-related issues in conflict settings. Terms such as "performance," "safety," "dynamics", "nutrition," "sustainability," and "supply chain" appear prominently, indicating an emphasis on food systems as logistical or public health challenges (Figure 7).

Figure 7. Keyword Emphasis in Bibliometric Reviews on Food Security and Conflict.

In contrast, keywords that reflect strategic or political intent, such as "weaponizing food," "siege," "coercion," or even "starvation as a method of war", are notably absent or marginal. While "conflict" and "risk factors" appear, they are rarely paired with language that suggests intentional manipulation of food systems as a tool of power.

Our findings reinforce that integrating political analysis—naming the use of hunger as a weapon—is crucial for a complete understanding.

3.3. Are "Unconventional" Food Supply Chains, Such as Black Markets, Informal Networks, and Underground Distribution Systems, Adequately Examined in the Literature, Particularly in Their Role During Armed Conflict?

As revealed by the following analysis, there is a low interest in the study of black markets, smuggling networks, and informal food systems in conflict settings, despite their evident and well-documented significance on the ground.

The second targeted query aimed to add a focused layer of analysis connecting food security discourse with illicit trade, parallel food economies, and informal distribution systems—dimensions that are often present in real-world conflict zones but remain marginalized in mainstream academic treatment. While some related records were retrieved, the overall yield reinforces the observation that such intersections between food systems resilience and alternative, extralegal supply chains during armed conflict remain under-theorized and under-represented in scholarly research. This additional query yielded only 54 records, of which 22 were categorized under "History" according to Web of Science subject classifications. Notably, none of these 54 publications intersected with the initial core dataset. A likely explanation is that many of these studies address food and war primarily in a historical context, focusing on famines, blockades, or informal markets in earlier centuries, rather than on present-day conflicts. As such, they often employ different keywords and disciplinary framings—more aligned with history, anthropology, or development studies—than those captured by our core query, which was designed to identify contemporary debates at the intersection of food security, sustainability, and armed conflict. This divergence underscores how scholarship on food and war has long existed in historical research, but only more recently has it become integrated into current discussions on global food security and conflict.

Our results reveal that most research on food, conflict, and related systems is housed in historical analysis, suggesting a strong emphasis on past famines, colonial-era food policies, or historical war economies [93–100], but potentially a lack of contemporary systems-based or policy-forward analysis. From a supply chain standpoint, historical insights are valuable for understanding long-term vulnerabilities and precedents but may not address the complexities of modern supply chain disruption, globalized trade, or technological interventions.

The list of papers generated on this step of our research illustrates the complex interplay between weak governance, conflict, and food insecurity, while highlighting the often-overlooked role of illicit economies and informal supply chains. A 2024 study focused on Torghar, Pakistan, demonstrates how inadequate governance, political instability, and the disruption of formal food supply chains—compounded by smuggling of food commodities—have contributed to heightened vulnerability and hunger at the household level. The study identifies militancy and insurgent activity as factors that not only damage existing logistical infrastructures but also fuel nepotism and underground market practices, directly linking armed conflict to the erosion of food systems [101].

A recent analysis on famine in global war economies co-authored by Alex de Waal situates the reemergence of famine post—2016 within what it terms the "challenge of the BRICS club". The paper argues that politico-economic contestation and normative backsliding at the international level have enabled the resurgence of famine through military and political means, offering a structural understanding of how famine conditions have reappeared and will evolve in post—2000 conflicts [102].

The literature also points to how smuggling and illicit trade in borderland or conflict regions intersect with food insecurity in both direct and indirect ways. A 2020 study on cattle smuggling along the India–Bangladesh border reveals how national export bans and regional demand transform illicit trade into a precarious livelihood strategy. These practices expose marginalized groups—particularly Muslim cattle herders and their families—to extended periods of deprivation and insecurity, oscillating between "windows of opportunity" and "episodes of heightened national security and imminent violence" [103].

Similarly, a study from 2020 on illegal, unreported, and unregulated (IUU) fishing links this activity to broader criminal networks, including human trafficking and labor exploitation. Although not directly tied to narcotics or arms trafficking, IUU fishing is shown to be associated with forced labor, rights violations, and modern slavery, highlighting how illicit markets undermine maritime food security and coastal livelihoods [104].

Other forms of informal cross-border commerce present parallel threats. A 2019 review of transboundary swine disease outbreaks identifies informal livestock trade and personal smuggling of animal products as key vectors for disease spread, jeopardizing both national biosecurity and local farmers' food security [105]. In a related case, a 2014 study on khat smuggling into Saudi Arabia reveals the pesticide contamination of contraband agricultural goods, illustrating how even non-essential commodities circulate through persistent illicit food-linked networks [106].

Amid the current war in Ukraine, a 2024 article underscores the mounting risks of agricultural smuggling under crisis conditions. It emphasizes the critical role of customs enforcement and trade regulation in safeguarding national food security during armed conflict, when opportunistic flows of agricultural goods may bypass oversight mechanisms [107].

However, the low number of resulting papers indicates this is indeed an under-researched area. In many war zones, when formal economies and supply lines break down, unconventional networks arise; these include war profiteers who import or hoard food to sell at high prices, clandestine trade routes that evade blockades, local bartering systems, and diaspora or charity supply pipelines. The existing literature on black markets and informal food economies in conflict-affected regions is predominantly shaped by reports and situational assessments produced by international organizations, rather than by peer-reviewed academic research. Institutions such as the United Nations (UN) [108], the World Food Programme (WFP) [109], World Bank [110] and the Food and Agriculture Organization (FAO) [111] play a central role in documenting real-time developments in conflict zones. These organizations regularly issue field-based analyses, emergency updates, and policy briefs that provide critical insights into how illicit trade networks, informal food distribution systems, and war economies affect food availability and access on the ground.

Unlike academic studies, which often focus on conceptual frameworks or longitudinal datasets, these institutional reports tend to be operational in nature, offering explicit warnings about the rapid deterioration of food security in specific regions, especially in contexts where state capacity is weakened, and formal supply chains are disrupted by violence, blockades, or sanctions.

However, while these reports are indispensable for understanding the lived realities of food insecurity in fragile settings, they are not formally accepted as academic findings. This reinforces a structural divide: grassroots empirical knowledge about black market food systems exists, but it remains largely outside the boundaries of scholarly publication, pointing to a missed opportunity for academic engagement and cross-sectoral synthesis.

By overlooking informal food systems, researchers may miss how civilians actually cope (or fail to cope) with sieges and sanctions, and policymakers may neglect opportunities to support or regulate these networks. Our analysis suggests that, particularly in long-lasting conflicts, informal food networks can play a dual role: they are lifelines for populations (getting food where official channels cannot), but they can also entrench conflict by enriching war profiteers and incentivizing blockades (since traders and commanders can profit). For example, warlords in some African conflicts have deliberately restricted food aid so that black markets under their control thrive—a dynamic known but under-analyzed in academic literature.

In conclusion, the academic ecosystem has yet to fully integrate the study of underground food supply chains during conflict. RQ3′s answer is that such issues are not adequately examined to date, representing a blind spot that, if addressed, could deepen understanding of wartime political economies and inform more effective humanitarian interventions.

3.4. Which Key Knowledge Gaps and Underexplored Themes Remain in the Academic Discourse on Food Security and Conflict, and How Can Researchers Strategically Address These to Enhance the Relevance and Impact of Their Work?

Beyond the under-examination of informal supply chains (as noted above), our scanning of the paper list identified several other blind spots in the scholarly discourse on food security and conflict:

- Neglect of certain regions and conflict types: A large share of the articles focuses on high-profile conflicts in the Middle East and sub-Saharan Africa (Syria, Yemen, South Sudan, Somalia, etc.), as well as on global phenomena like food price spikes. Conflicts in other regions (e.g., Asia or Latin America) where food insecurity plays a significant role have received less attention in the English-language scholarly press. Similarly, slow-onset political crises causing hunger (e.g., Venezuela's collapse) are often analyzed in economic terms rather than conflict terms. Future inquiry could be more geographically inclusive, examining, for example, the interplay of conflict and food security in Central America, South Asia, or the Caucasus. Also, incorporating non-English research (e.g., in Arabic, French, and Spanish) into future analyses would help bring in more diverse local perspectives and offer a more grassroots understanding of the studied topic.
- Discourse and framing analysis: While the keyword analysis highlights the depoliticization vs. strategic framing issue, this has not been explicitly studied in many publications. In other words, few academic papers themselves turn the lens on how narratives are constructed. For example, future research could analyze UN Security Council debates, NGO appeals, and media coverage to see whether the rhetoric around conflict-induced hunger is shifting post—2018 (after UNSC 2417) or whether "hunger as a weapon" remains an uncomfortable topic that is sidestepped in favor of technical jargon. Understanding this will shape how future advocacy can more effectively frame the issue, either galvanizing political action or remaining in the realm of depoliticized development talk.
- Integrated models of conflict-food interactions: The literature tends to silo different aspects of the conflict-food intersection. One stream looks at how food insecurity can lead to conflict (e.g., via riots or recruitment into armed groups when livelihoods fail), an approach that is often treated separately from the stream looking at how conflict causes food insecurity. In reality, on-site reports show that these dynamics form feedback loops. There is a need for holistic frameworks that merge these perspectives, possibly drawing on complex systems theory or conflict trap models. The concept of "food wars" should start including two-way connections between cause and effect. Yet, current quantitative models seldom incorporate both directions simultaneously due to data and methodological challenges. Future research could involve developing models (perhaps AI-based simulations or network analyses) that capture how food insecurity, governance, violence, climate shocks, and external aid interact in conflict-susceptible systems. Such models could identify tipping points where food insecurity might ignite violence or, conversely, where peace interventions could stabilize food systems.

Table 3 offers critical insight into publishing dynamics and scholarly influence of journals active in the intersecting domains of food security, sustainability, agriculture, and nutrition. It evaluates each journal based on several key metrics, including the total number of publications (TP), number of cited articles (NCA), number of citing papers (NCP), total citations (TC), and two citation performance indicators, citations per paper (C/P) and citations per cited paper (C/CP). These indicators allow for a nuanced evaluation of the knowledge ecosystem shaping discourse on food systems under conflict and crisis, particularly in assessing whether visibility, influence, and research quality align with publication output.

Table 3. Comparative bibliometric indicators of leading journals by volume.

Source Title	TP	NCA	NCP	TC	C/P	C/CP
SUSTAINABILITY	56	238	52	1045	18.66	20.10
FRONTIERS IN SUSTAINABLE FOOD SYSTEMS	41	239	33	382	9.32	11.58
LAND USE POLICY	30	117	29	1570	52.33	54.14
FOOD SECURITY	22	84	19	475	21.59	25.00
WORLD DEVELOPMENT	21	86	21	761	36.24	36.24
PLOS ONE	19	136	13	226	11.89	17.38
BMC PUBLIC HEALTH	18	121	15	411	22.83	27.40
LAND	17	102	15	321	18.88	21.40
GLOBAL FOOD SECURITY	16	54	15	503	31.44	33.53
MATERNAL AND CHILD NUTRITION	16	88	13	322	20.13	24.77

Among the most prolific sources, Sustainability stands out with 56 publications in the dataset, making it the top contributor in terms of volume. However, its influence at the level of individual article impact is more modest. The average C/P stands at 18.66, while citations per cited paper (C/CP) are 20.10. These values suggest that although Sustainability publishes a high number of articles relevant to the field, the average impact per article is relatively low, likely a result of the journal's broad interdisciplinary scope and open-access publishing model, which may accommodate a wide range of topics and variable methodological rigor. A similar pattern is visible in Frontiers in Sustainable Food Systems, which also shows a high publication count (TP = 41) but low citation metrics (C/P = 9.32; C/CP = 11.58), supporting the observation that high publication volume does not necessarily equate to greater scholarly influence.

In contrast, several journals exhibit a markedly different profile, publishing fewer papers but achieving significantly higher citation impact per article (Table 4). The standout journal in this list is PNAS, with only 5 publications (TP) but an astonishing 2969 total citations (TC)-yielding both a C/P C/CP value of 593.80. This reflects not only the prestige of the journal itself but also the likely groundbreaking nature or global relevance of the individual articles published there.

Table 4. Comparative bibliometric indicators of leading journals by citations.

Source Title	TP	NCA	NCP	TC	C/P	C/CP
PNAS	5	71	5	2969	593.80	593.80
LAND USE POLICY	30	117	29	1570	52.33	54.14
SUSTAINABILITY	56	238	52	1045	18.66	20.10
WORLD DEVELOPMENT	21	86	21	761	36.24	36.24
JOURNAL OF PEASANT STUDIES	9	20	9	686	76.22	76.22
FOODS	14	49	13	618	44.14	47.54
FOOD POLICY	15	44	15	613	40.87	40.87
REGIONAL ENV. CHANGE	8	25	8	537	67.13	67.13
GLOBAL ENVIRONMENTAL CHANGE	3	11	3	520	173.33	173.33
GLOBAL FOOD SECURITY-AGR. POLICY	16	54	15	503	31.44	33.53

Overall, the data from Tables 3 and 4 reinforce a key structural observation: within food security and sustainability research, there exists a noticeable trade-off between quantity of output and citation impact. High-volume journals like Sustainability and Frontiers play a significant role in shaping the publication landscape, but they often produce research with lower per-article influence. Conversely, journals such as Land Use Policy, Food Policy, Nutrients, and Foods provide leaner but more impactful contributions, suggesting that they may be more strategic venues for authors seeking scholarly recognition and engagement. For researchers, this means that there is a need for strategic dissemination tactics that bridge the gap between highly cited academic work and real-world policy relevance in regions most affected by food crises.

Scholars aiming to publish in the domain of food security, conflict, and informal food systems should prioritize journals that combine scholarly influence with thematic relevance, and targeting these outlets increases the likelihood of meaningful scholarly engagement and ensures contributions are positioned within high-impact debates.

Moreover, researchers have significant opportunities to contribute to understudied and emerging areas. As this report demonstrates, themes such as black markets, informal food supply chains, illicit agricultural trade, and the strategic use of hunger during conflict remain marginal in much of the mainstream literature. Addressing these gaps, especially through empirical case studies or critical discourse frameworks, positions scholars at the forefront of conceptual innovation while responding to urgent real-world dynamics.

Additionally, authors should be intentional about how they frame and keyword their research. Bibliometric analysis shows that a significant portion of the literature remains couched in developmental and technocratic language, emphasizing concepts like resilience and sustainability. However, there is a growing appetite for work that explicitly names the political and strategic dimensions of food insecurity, using terms like "starvation crimes," "siege warfare," or "food as a weapon." Aligning one's framing with these emerging discourses can increase both relevance and citation potential, particularly in the context of international legal, policy, and humanitarian debates.

Finally, while academic journals remain the primary venue for peer recognition, scholars should also consider dual-track publication strategies that engage both academic and practitioner audiences. Publishing condensed versions of findings, such as policy briefs, working papers, and commentaries for organizations like the FAO, WFP, IFPRI, or regional NGOs, can amplify real-world impact and bridge the gap between scholarship and applied food system interventions. This blended approach ensures that research not only contributes to academic debates but also informs practice and policy in conflict-affected and food-insecure regions.

4. Conclusions

Between 2010 and 2025, scholarly understanding of the links between food security and conflict significantly expanded, both in depth and scope. Tactics such as starvation sieges, crop destruction, and food supply blockades are now increasingly recognized as central features of contemporary warfare and as urgent humanitarian and political concerns [112]. Our bibliometric and discourse analyses confirm a growing interdisciplinary interest in these issues and reveal a slow but discernible shift in framing: where hunger in conflict zones was once described in technocratic or apolitical terms, today we see an increasing willingness to label it as weaponization and demand accountability from involved parties. Bridging this divide between technocratic and political-strategic framing remains a critical challenge for the research community.

Our findings highlight several key areas of convergence within the scholarly communities and international organizations' reports:

- There is a growing consensus that deliberate starvation tactics violate international norms, yet they continue to be deployed with near-to-no consequences in conflicts ranging from Syria to Ethiopia [113].

- Impacts of conflict on food systems are not only immediate, causing hunger and displacement, but also long-term, undermining human development, governance, and regional stability.
- Durable solutions require a cross-sectoral approach that integrates humanitarian aid, development planning, security policy, and local knowledge. Communities affected by conflict have developed adaptive strategies, from smuggling networks to informal farming systems, that deserve closer scholarly attention and institutional support, not marginalization [114].

Environmental and development perspectives dominate, while critical engagement with informal economies, actor intentionality, and the strategic logic of hunger remains underdeveloped. Informal food supply chains—such as black markets, smuggling routes, and war economies—even though essential to survival in many conflict-affected areas, remain largely ignored in peer-reviewed literature, tending to remain in the grey literature and institutional reports rather than in mainstream academic outlets. Addressing this gap is not only a matter of academic completeness but a necessity for shaping more responsive and just policy interventions and prompting competent authorities to take action.

The research community must also acknowledge the profound disruptions that acute conflict inflicts on formal food systems [80]. As conflicts grow in both frequency and complexity, there is an urgent need to design adaptive, decentralized, and scalable interventions that can operate in unstable environments. Solutions cannot be one-size-fits-all, nor can they be imposed from above. Instead, they must emerge from inclusive, context-sensitive research and collaboration with affected populations [115].

Another structural issue concerns epistemic inequality in global knowledge production. While Northern and Anglophone scholars and institutions dominate citations and authorship, many of the regions most affected by food weaponization remain underrepresented in high-impact publishing. This imbalance raises questions about research gatekeeping and the marginalization of Southern voices, which are critical to understanding local dynamics, resistance practices, and culturally appropriate interventions. Future research must prioritize inclusive co-authorship, equitable knowledge sharing, and capacity-building for local scholars and institutions.

To advance the field, greater interdisciplinary integration is needed. Scholars of war and peace must engage more directly with experts in food systems, and vice versa. Theoretical contributions from political ecology, conflict–resource theory, and food regime analysis can enrich this dialogue by situating food weaponization within broader structures of global inequality, trade dependency, and resource control.

Looking forward, the direction of academic inquiry will directly influence the global community's capacity to confront and preempt the weaponization of hunger. However, to maximize impact, scholars must also be strategic in where and how they publish—choosing journals with both high visibility and thematic relevance will help ensure that findings reach both policymakers and communities of practice.

In conclusion, while the past 15 years have seen important progress, famines continue to be used as tools of war, and food is still exploited as leverage. To shape a different future, the paradigm must shift from analyzing "food as a weapon" to building frameworks for "food as peace". This means not only documenting abuse but also advancing solutions for accountability, resilience, and justice. The scholarly community has a central role to play in this transformation by naming power, amplifying the voices of marginalized individuals, and building bridges between disciplines, sectors, and regions.

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Development of a Strategy to Reduce Food Waste in a Preschool Food Service

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Abstract

Food loss and waste in school food services generate economic cost, environmental impacts, and social effects. Waste occurs in the final stages of the supply chain. It is particularly critical in educational institutions, leading to low nutrient intake during early stages of development and negatively impacting food security. Aiming to design a waste reduction strategy for the meal service of a preschool serving children aged 0–5 years, a descriptive observational study was conducted over a 6-month period. This study combined the measurement of the primary outcome (proportion of the served portion not consumed by food group) with the assessment of menu acceptability, the children's food preferences, and the exploration of perceptions of both at-home caregivers and preschool professionals. Overall, the most frequent reasons for rejection were texture, preparation methods, and unfamiliarity with the food. The highest levels of waste were found in fruits and vegetables, with 17% left uneaten; protein-rich foods had a 15% waste rate, and cereals and tubers showed a 10% waste rate. Based on these findings, a family–school strategy is proposed that would increase household exposure to a wider variety of foods and establish periodic menu reviews to identify critical foods and ensure proper use in school food services. These results demonstrate that by enhancing food acceptance, we can decrease food waste, and in early stages, strengthen food security and nutritional use.

Keywords: food waste; early childhood; food education; sustainability

1. Introduction

The Food and Agriculture Organization of the United Nations [1] states that FLW—Food Loss and Waste—occurs when food intended for human consumption is discarded, which can happen at any stage of the food supply chain. However, there is a distinction between food loss and food waste: food loss occurs in the early stages of production, post-harvest, and food processing, whereas food waste takes place during the distribution and consumption stages [2]. FLW also includes imported products that are disposed [3]. The global impact of this problem is valued at 1 trillion dollars, which also affects the environment, generating between 8 and 10% of GHGs—Greenhouse Gases—and using 30% of agricultural land to grow food that will ultimately be discarded. This issue is particularly serious when compared to the 783 million people suffering from hunger and the 150 million children experiencing impaired cognitive and physical development due to chronic malnutrition [4], factors that contribute to inequality.

In 2022, it is estimated that food waste reached 1.050 billion tons globally, originating from the retail sector, food services, and households. This figure translates to 132 kg per capita per year, of which 36 kg per capita per year is attributed to food services, amounting to 290 million tons [3]. In Colombia [4] it was reported that in the same year, the country wasted 70 kg per capita annually, based on measurements taken in food services and retail sectors. Although this figure is lower than in other Latin American countries such as Mexico (105 kg), Ecuador (96 kg), Argentina (91 kg), and Peru (88 kg) per capita annually, it remains a significant problem due to the inefficient use of resources such as water, land, and labor, as well as the environmental impact caused by the decomposition of this wasted food [4].

The specialized literature on food loss and waste can be organized into three main streams: (1) studies that analyze the causes, effects and determinants along the chain and in food services; (2) works that develop, compare, and validate measurement tools and instrumentations; and (3) more recent contributions oriented toward reduction, which design, implement, and evaluate strategies, programs, and policy instruments. In accordance with this classification, this review is structured into three streams.

Authors such as [5] highlight the nutritional approach, pointing out how FLW (Food Loss and Waste) prevents food from fulfilling its nutritional function, increases problems such as hunger and malnutrition, and especially affects people in vulnerable conditions. Thus, they argue that reducing food waste would improve food security. The second approach is environmental, as negative impacts are generated, such as greenhouse gas emissions and inefficiency in the use of finite natural resources.

Ref. [6] describe that the causes of food waste can be found in all areas that are part of the food service system, studying the case of a university. They highlight the need for a system-based analysis to develop strategies that effectively reduce the problem. There are also various studies aimed at identifying the causes of food waste in school food services, monitoring the most discarded food components, training programs, catering company management, among others [7,8]. These studies emphasize the importance of good planning and execution of food service activities, quality of raw materials to improve food acceptance, improvements in the presentation of prepared meals, nutritional education, and adjustments to portion sizes [9].

The second stream synthesizes the multiple tools and methodologies available to measure FLW, which vary depending on the context and the availability of resources. According to the Commission for Environmental Cooperation, notable methods include field diaries, used to record the types of food and the causes of waste [10]; direct measurement, which is highly accurate but requires more time and therefore more financial resources to carry out; analysis of containers where plate waste is collected; smart bins that quantify waste by food group and collect detailed information; as well as surveys and interviews with stakeholders involved in the supply chain.

Other authors, such as [11], used mathematical models to optimize food preparation, resulting in a 37% reduction in food costs and a 20% decrease in waste in a hospital setting, considered a large-scale food service operation. Therefore, it is necessary to develop strategies and plans to reduce FLW, focusing on early education, raising awareness, and the proper management of resources.

The final stream reviews interventions and policy instruments aimed at reducing FLW. Authors like [12] compiled 84 initiatives being developed worldwide, which include prevention, recycling, and education through consumer-focused campaigns, as well as collaborative activities between public and private organizations. Likewise, several strategies or initiatives have been promoted across various regional, national, and global geographic contexts, led by multiple organizations such as the European Union, Inter-American Development Bank (IDB), Community of Latin American and Caribbean States (CELAC), national government agencies and private entities and companies to reduce FLW.

There are also initiatives aimed at raising consumer awareness. For example, a plate waste tracker led to a 17% reduction in food waste among students, as it allowed each student to see the volume of food they personally discarded [8]. Additionally, Malaysia has launched campaigns to raise awareness and to show how discarded food can be turned into compost and generate income [13]. Moreover, [14] demonstrated that changing the serving order of dishes—starting with side dishes—resulted in a 33% reduction in vegetable waste.

Unlike aggregate approaches, food services require process-level diagnostics that identify critical waste points in each activity: receiving, storage, preparation, portioning, distribution, consumption, and leftovers management, to guide targeted intervention [15]. However, in early childhood education, gaps persist in systematic operational analyses that connect measurement, causes, and improvement actions, and simultaneously integrate objective indicators and key stakeholders' perceptions.

To address this gap, we conducted a diagnostic study at a Bogotá City Hall preschool, serving breakfast and lunch to 165 enrolled children, where high waste was observed. The study designed and applied a process-based measurement and analysis methodology, focusing on consumption-related waste with the primary outcome defined as the proportion of the served portion left uneaten by food group and its operational determinants. This was complemented by children's acceptance and the perceptions of parents, student caregivers, and food service and classroom professionals who supervise mealtimes.

Hard or otherwise unsuitable textures (notably in fruits), unfamiliarity with the food, and unappealing presentations were identified as factors leading to rejection. In general, fruits and vegetables are the food group with the highest level of waste (24%), while 16% of meats, eggs, and legumes—belonging to the protein group—were not consumed. Meanwhile, cereals, roots, tubers, and plantains showed an 11% waste rate.

Drawing on these findings, we developed a comprehensive waste-reduction strategy targeting service management (menu adjustments, portioning and preparation practices, and family–school coordination to increase exposure to diverse foods at home). The objective of this paper is to propose and substantiate this strategy for reducing waste in preschool food services and to outline its implications for program management, staff training, and policy design aimed at improving acceptance, reducing waste, and supporting child nutrition.

2. Materials and Methods

This research employed a mixed-methods design consisting of three phases, integrating quantitative measurement of food waste with qualitative observation of eating behaviors in early childhood education settings. The unit of analysis was defined at the individual plate level, with aggregation later performed by child, meal, food group, and day, allowing comparison across age groups and menu items.

Phase 1: Literature Review and Comparative Framework. The first phase involved a systematic review of existing methodologies for quantifying and reducing food waste, with emphasis on tools applied in educational institutions. Comparative frameworks were drawn from prior studies [16,17], which guided the development of a tailored measurement protocol for preschool food services.

Phase 2: Diagnostic and Measurement Protocol. The diagnostic phase was conducted over one month, covering a complete preschool menu cycle at the institutional food service. The meal services included breakfast and lunch, both provided daily by the preschool, following the national dietary guidelines of the Colombian Family Healthy Plate, developed by the Colombian Institute of Family Welfare (ICBF) distributed in proportions that ensure adequate energy intake, a balanced macronutrient profile, and sufficient micronutrients. A typical menu consisted of a starch-based dish (e.g., rice, pasta, potatoes, or cereals), a protein source (meat, poultry, fish, or legumes), vegetables, fruit, and a dairy product. Accordingly, foods were categorized into four groups: cereals and legumes, fruits and vegetables, proteins, and dairy, excluding fats and sugars, which were hardly present in the standardized menu [18].

Children were divided into four age groups: 6–8 months, 9–11 months, 1–2 years and 11 months, and 3–5 years, plate waste was assessed using the direct weighing method. A calibrated digital kitchen scale (precision: 1 g; Electronic Scale Capacity 5000 g was employed. Calibration was performed daily with standardized weights, and scales were zeroed (tare) before each measurement.

The measurement protocol was as follows. Pre-service weighing—each meal component was weighed individually according to the portion size specified in the preschool's standardized recipe before being served. For mixed dishes (e.g., stews), a standardized portion was homogenized and sampled for measurement. Post-consumption weighing—after meals, each plate was collected, and edible leftovers were separated from inedible fractions (bones, peels, seeds).

Waste calculation—percentage plate waste was calculated per component as:

$$\%\ \text{Waste} = \frac{(\text{Weight served} - \text{Weight consumed})}{\text{Weight served}} \times 100$$

Data were aggregated at multiple levels: by food item (e.g., rice, chicken, banana); by food group (cereals and legumes, proteins, fruits and vegetables, dairy); by meal (breakfast or lunch); by age group and by day of observation. The primary analysis unit was the individual plate per child per meal. Mean values were calculated at the child level, and then aggregated to group comparisons.

For statistical analysis, descriptive statistics (means, medians, standard deviations, and confidence intervals) were calculated. To account for the nested structure of the data (plates nested within children and across days), a mixed-effects model was specified, with child and day as random effects and age group, meal, and food group as fixed effects.

Qualitative data were collected through structured daily observation logs, documenting children's eating behaviors (acceptance, rejection, partial consumption, and food-handling behaviors such as spitting out or mixing foods). Additionally, surveys were conducted with 12 participating children, 2 professionals (the kindergarten psychologist and nutritionist), and 196 caregivers or parents of the students.

Moreover, photographic records of post-consumption plates were taken under standardized lighting and angle conditions. These images were later used to validate weighing data and to identify recurrently rejected items. Images with incomplete visibility or poor resolution were excluded based on predefined quality criteria.

Phase 3: Strategy Development. Based on the diagnostic results, a waste-reduction strategy was designed by applying Management by Objectives (Drucker) in combination with a results-oriented, continuous innovation framework [19]. The resulting action plan emphasized portion-size adjustments, menu optimization, and educational interventions to improve children's food acceptance.

Ethical Considerations. The study was approved by the Fundación Universitaria Los Libertadores Ethics Committee, Approval No. 01092025. Written informed consent was obtained from the preschool authorities. All data were anonymized and treated according to ethical standards for research with minors.

3. Results

3.1. Comparison of Food Waste Quantification Methods and Strategies for Its Reduction

There is general agreement that developing training and awareness strategies, along with the quantification and monitoring of food waste, is essential for its reduction in food service operations within educational institutions. For example, at the University of Costa Rica, direct weighing activities were implemented, and awareness and training campaigns were conducted with staff and students, resulting in a 55% reduction in food waste [20]. Similarly [21], conducted talks targeting the educational community and the public, leading to significant behavioral changes regarding food waste. In addition [22], quantified food waste in Swedish food services and later extended the study to hospitals [23] to determine the amount of waste in grams per portion served [24].

3.2. Diagnostic Activity in the Food Service

The menus followed the dietary progression defined by the ICBF: exclusive breastfeeding until 6 months, thick purees between 6 and 8 months, pre-chopped foods from 9 to 11 months, and, starting at 12 months, incorporation into the family diet with varied textures and promotion of dairy products as the main source of calcium and high-quality proteins. The menus consisted of a starch-based dish (e.g., rice, pasta, potatoes, or cereals), a protein source (meat, poultry, fish, or legumes), vegetables, fruit, and a dairy product with an emphasis on a higher proportion of fresh fruits and vegetables for their contribution of fiber, vitamins, and minerals. Complex carbohydrates from cereals and tubers were maintained as the primary energy base, while protein intake was diversified through animal and plant sources.

A menu is composed of several preparations, and for each one, a serving quantity is established according to the standard meal plan. For example, breakfast includes a portion of cheese, bread, and apple, while lunch consists of stewed beans, ground beef stew, white rice, salad (lettuce, tomato, avocado, and cilantro), and baked plantain. Each group of students has a different serving weight; for example, for rice: 6–8 months 22 g, 9–11 months 28 g, 1–2 yrs 11 months 35 g, and 3–5 yrs 50 g, respectively. The data corresponding to the serving weight of each menu item are provided in the Supplementary File.

The diagnostic and measurement phase of this study was developed over a one-month period, corresponding to a complete cycle of the institutional menu, in which all meals served (breakfast and lunch) were recorded following the ICBF nutritional guidelines. For this study, twenty menus corresponding to the meal plan cycle for four groups of students at two mealtimes—breakfast and lunch—were analyzed. The observations were recorded by food group, for a total of 457 entries. Each is composed of the established food groups (cereals and legumes, fruits and vegetables, proteins and dairy products), while fats and sugars were excluded due to their minimal presence in the standardized menu. Food waste was quantified through the direct weighing method and photographic records. Likewise, those post-consumer images that did not meet the visibility and resolution criteria defined in the quality protocol were discarded from the analysis base.

It was observed that the highest levels of food waste occurred in the group of children aged 6 to 8 months. This may be due to their difficulty chewing, as they are beginning their teething process, and to instances where fruits are not at their optimal ripeness, highlighting the importance of selecting products that meet maturity standards. Another contributing factor is that students are trying certain foods, especially solids, for the first time, such as granadilla, which leads to increased waste. Additionally, consistent food waste was observed in this group during breakfast, particularly with certain egg preparations.

In Figure 1, it can be observed that children aged 9 to 11 months show the highest levels of food waste in the protein group, while children aged 1 to 2 years and 11 months exhibit greater waste in the fruits and vegetables group, which is consistent with the findings of [25]. Notably, food in the cereals group is most frequently wasted during lunch by two student groups: those aged 6 to 8 months and 9 to 11 months. Overall, the average food waste during both breakfast and lunch is approximately 14%. The data detailing food waste for the entire cycle and for each student group are included in two Supplementary Files.

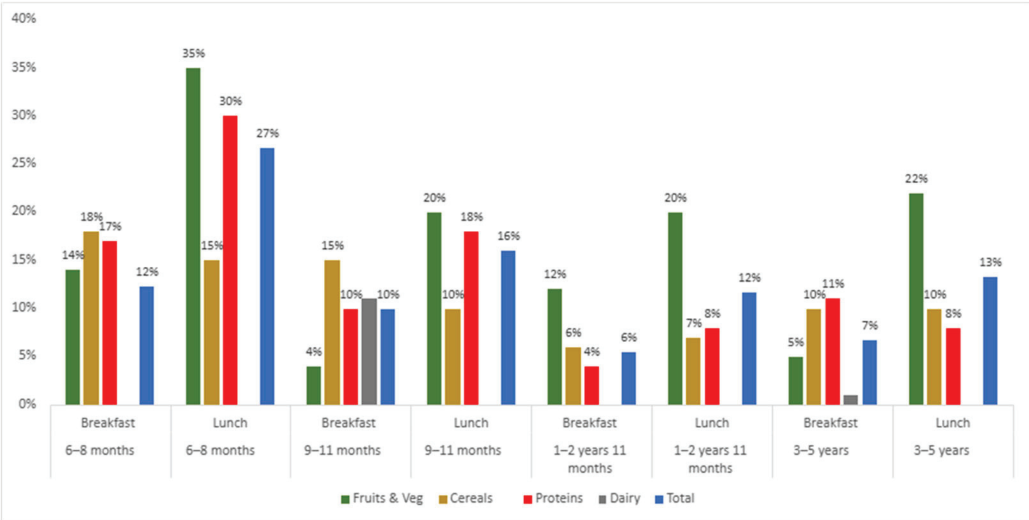

Figure 1. Food waste by mealtime and student group. Note: Prepared by the authors.

When analyzing food waste by mealtime, the highest percentage is observed at breakfast among the group of students aged 6 to 8 months. This same group also shows a high level of waste during lunch, generating three times more waste than the average. Similarly, students aged 9 to 11 months exhibit a high percentage of waste, particularly at lunch; however, a significant amount of food also goes uneaten during breakfast. The remaining two student groups show similar waste percentages, with a slightly higher proportion occurring during lunch.

Overall, the most wasted foods belong to the fruit and vegetable group, accounting for 17%, followed by proteins, and cereals. In contrast, dairy products show the highest consumption rates, as illustrated in Figure 2.

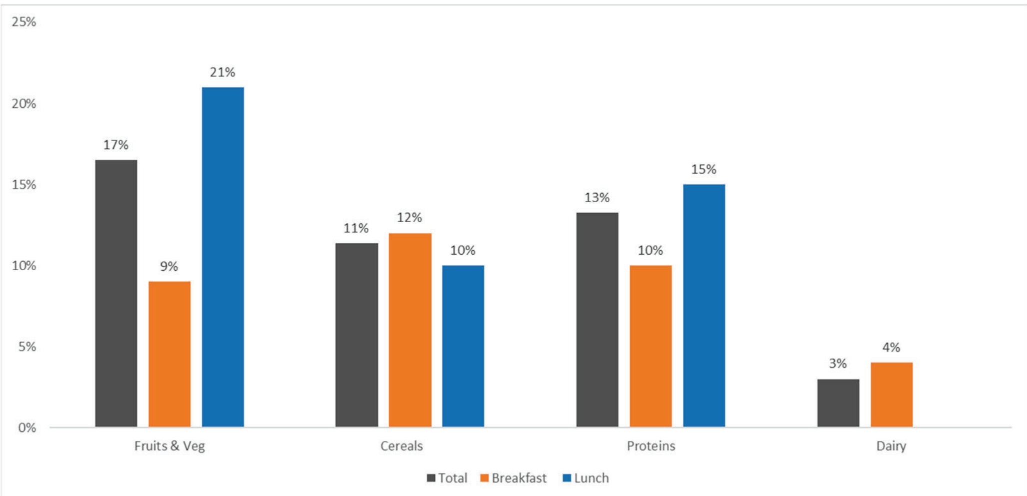

Figure 2. Food waste by food group. Note: Prepared by the authors.

Table 1 presents the foods with the highest percentage of waste. Waste was classified as critical when they exceeded the average level for its respective food group (>15% for proteins, >10% for cereals, >17% for fruits and vegetables and >1% for dairy products). Waste was considered *high* when it was above the group average but within 6% points of critical threshold. The consolidation of food waste percentages and their organization by food group are included in the Supplementary File.

Table 1. Food with the highest percentage of waste by age group.

Food Group	Age Group	Meal Time	% Critical Waste	Preparation	Food Group	Age Group	Meal Time	% High Waste	Preparation
FRUITS & VEGGIES	6–8 months	Breakfast	0%	Apple	FRUITS & VEGGIES	1–2 yrs 11 months	Lunch	17%	Salad (spinach, papaya, mango, and cream)
	9–11 months	Breakfast	0%	Apple		1–2 yrs 11 months	Breakfast	18%	Apple
	9–11 months	Breakfast	0%	Mango		9–11 months	Lunch	18%	Vegetables with mayonnaise
	6–8 months	Breakfast	0%	Papaya		3–5 yrs	Lunch	19%	Stew cucumber
	6–8 months	Breakfast	0%	Pear		1–2 yrs 11 months	Lunch	20%	Chard with egg
	9–11 months	Lunch	0%	Pumpkin with green peas		1–2 yrs 11 months	Breakfast	20%	Pear
	3–5 yrs	Lunch	0%	Salad (lettuce, tomato, avocado, cilantro)		1–2 yrs 11 months	Lunch	21%	Beetroot salad
	3–5 yrs	Lunch	0%	Salad (spinach, papaya, mango, and cream)		3–5 yrs	Lunch	21%	Vegetable (carrot, pumpkin)
	9–11 months	Lunch	0%	Vegetable (carrot, pumpkin)		1–2 yrs 11 months	Lunch	22%	Pumpkin with green peas
	3–5 yrs	Breakfast	1%	Watermelon		1–2 yrs 11 months	Lunch	23%	Salad (cucumber, tomato, and cilantro)
	3–5 yrs	Breakfast	1%	Papaya		1–2 yrs 11 months	Lunch	23%	Pumpkin with green peas
	1–2 yrs 11 months	Lunch	1%	Salad (spinach and mango)		1–2 yrs 11 months	Lunch	23%	Vegetable (carrot, pumpkin)
	9–11 months	Lunch	2%	Avocado		3–5 yrs	Lunch	27%	Pumpkin with green peas
	3–5 yrs	Lunch	2%	Salad (lettuce, tomato and carrot)		3–5 yrs	Lunch	28%	Chard with egg
	1–2 yrs 11 months	Breakfast	2%	Watermelon		9–11 months	Lunch	29%	Beetroot salad
	9–11 months	Breakfast	3%	Watermelon		3–5 yrs	Lunch	33%	Pumpkin with green peas
	3–5 yrs	Breakfast	4%	Mango		1–2 yrs 11 months	Lunch	36%	Salad (grated carrot and tomato)
	9–11 months	Lunch	4%	Salad (spinach and mango)		9–11 months	Lunch	39%	Salad (spinach, papaya, mango, and cream)
	9–11 months	Lunch	4%	Salad (spinach, papaya, mango, and cream)		9–11 months	Lunch	41%	Salad (lettuce and tomato)

Table 1. *Cont.*

Food Group	Age Group	Meal Time	% Critical Waste	Preparation	Food Group	Age Group	Meal Time	% High Waste	Preparation
FRUITS & VEGGIES	1–2 yrs 11 months	Lunch	5%	Avocado		9–11 months	Lunch	43%	Salad (cucumber, tomato, and cilantro)
	9–11 months	Breakfast	5%	Pear		1–2 yrs 11 months	Lunch	50%	Salad (spinach, apple, and cream)
	9–11 months	Lunch	5%	Salad (lettuce, tomato, avocado, cilantro)		3–5 yrs	Lunch	53%	Salad (spinach and mango)
	3–5 yrs	Lunch	5%	Vegetables with mayonnaise		9–11 months	Lunch	69%	Salad (grated carrot and tomato)
	3–5 yrs	Breakfast	6%	Apple		3–5 yrs	Lunch	88%	Salad (spinach, apple, and cream)
	1–2 yrs 11 months	Breakfast	6%	Papaya		6–8 months	Breakfast	100%	Granadilla
	9–11 months	Breakfast	6%	Papaya					
	1–2 yrs 11 months	Breakfast	9%	Mango					
	3–5 yrs	Lunch	9%	Salad (cucumber, tomato, and cilantro)					
	3–5 yrs	Lunch	10%	Avocado					
	3–5 yrs	Breakfast	10%	Pear					
	1–2 yrs 11 months	Lunch	10%	Stew cucumber					
	1–2 yrs 11 months	Lunch	12%	Salad (lettuce, tomato, avocado, cilantro)					
	6–8 months	Lunch	13%	Chard with egg					
	9–11 months	Lunch	13%	Chard with egg					
	3–5 yrs	Breakfast	13%	Mango					
	6–8 months	Breakfast	13%	Mango					
	9–11 months	Lunch	13%	Stew cucumber					
	6–8 months	Breakfast	14%	Watermelon					
	3–5 yrs	Lunch	14%	Beetroot salad					
	9–11 months	Breakfast	14%	Granadilla					
	6–8 months	Breakfast	15%	papaya					
	1–2 yrs 11 months	Lunch	15%	Salad (lettuce, tomato and carrot)					
	3–5 yrs	Lunch	15%	Salad (grated carrot and tomato)					
	1–2 yrs 11 months	Lunch	15%	Vegetables with mayonnaise					

Table 1. *Cont.*

Food Group	Age Group	Meal Time	% Critical Waste	Preparation	Food Group	Age Group	Meal Time	% High Waste	Preparation
CEREAL	3–5 yrs	Breakfast	0%	Corn arepa	CEREAL	1–2 yrs 11 months	Lunch	11%	Steamed potato
	1–2 yrs 11 months	Breakfast	0%	Flavored cookie		9–11 months	Lunch	12%	Conchiglie
	3–5 yrs	Breakfast	0%	Flavored cookie		3–5 yrs	Breakfast	13%	Corn bread
	6–8 months	Breakfast	0%	Flavored cookie		3–5 yrs	Lunch	13%	Plantain with guava paste
	1–2 yrs 11 months	Breakfast	0%	Soda crackers		9–11 months	Lunch	13%	Cassava (yuca)
	3–5 yrs	Breakfast	0%	Soda crackers		9–11 months	Lunch	14%	Rice with carrot
	6–8 months	Breakfast	0%	Wholemeal bread roll		9–11 months	Lunch	14%	Arracacha sticks
	1–2 yrs 11 months	Breakfast	0%	Sliced bread		3–5 yrs	Lunch	14%	Steamed creole potato
	3–5 yrs	Breakfast	0%	Sliced bread		1–2 yrs 11 months	Lunch	15%	Arracacha sticks
	9–11 months	Breakfast	0%	Sliced bread		9–11 months	Breakfast	15%	Puff pastry bread
	9–11 months	Lunch	0%	Steamed potato		3–5 yrs	Lunch	15%	Steamed potato
	3–5 yrs	Lunch	0%	Potato chips		6–8 months	Lunch	15%	Steamed creole potato
	1–2 yrs 11 months	Lunch	0%	Roasted ripe plantain		9–11 months	Breakfast	16%	Flavored cookie
	3–5 yrs	Lunch	0%	Roasted ripe plantain		3–5 yrs	Lunch	16%	Ripe plantain boiled with cinnamon
	9–11 months	Lunch	0%	Roasted ripe plantain		9–11 months	Breakfast	17%	Soft bread
	9–11 months	Lunch	0%	Fried ripe plantain slices		9–11 months	Lunch	17%	Potato chips
	1–2 yrs 11 months	Breakfast	0%	Toast		1–2 yrs 11 months	Breakfast	18%	Wholemeal bread roll
	3–5 yrs	Breakfast	0%	Toast		9–11 months	Lunch	19%	Plantain with guava paste
	1–2 yrs 11 months	Breakfast	1%	Soft bread		3–5 yrs	Breakfast	20%	Wholemeal bread roll
	1–2 yrs 11 months	Lunch	1%	Rice with cilantro		1–2 yrs 11 months	Lunch	21%	Pasta shells
	3–5 yrs	Lunch	1%	Rice with cilantro		6–8 months	Lunch	24%	Pasta shells
	1–2 yrs 11 months	Lunch	2%	Fried ripe plantain slices		9–11 months	Breakfast	25%	Wholemeal bread roll
	3–5 yrs	Lunch	2%	White rice		3–5 yrs	Lunch	25%	Pasta shells
	1–2 yrs 11 months	Lunch	2%	Rice with noodles		6–8 months	Breakfast	26%	Soft bread

Table 1. *Cont.*

Food Group	Age Group	Meal Time	% Critical Waste	Preparation	Food Group	Age Group	Meal Time	% High Waste	Preparation
CEREAL	3–5 yrs	Lunch	2%	Rice with noodles	CEREAL	3–5 yrs	Lunch	28%	Arracacha sticks
	1–2 yrs 11 months	Lunch	2%	Rice with carrot		9–11 months	Breakfast	28%	Corn bread
	1–2 yrs 11 months	Breakfast	3%	Corn arepa		6–8 months	Lunch	33%	Rice with carrot
	1–2 yrs 11 months	Lunch	3%	Ripe plantain boiled with cinnamon		9–11 months	Lunch	33%	Ripe plantain boiled with cinnamon
	1–2 yrs 11 months	Lunch	4%	White rice		6–8 months	Lunch	34%	Spaghetti
	1–2 yrs 11 months	Lunch	4%	Potato chips		1–2 yrs 11 months	Lunch	40%	Cassava (yuca)
	3–5 yrs	Lunch	4%	Crispy potato		9–11 months	Lunch	43%	Crispy potato
	9–11 months	Lunch	5%	White rice		6–8 months	Breakfast	48%	Puff pastry bread
	6–8 months	Lunch	5%	Rice with noodles		3–5 yrs	Lunch	49%	Cassava (yuca)
	3–5 yrs	Lunch	5%	Rice with carrot					
	6–8 months	Breakfast	5%	Soda crackers					
	9–11 months	Breakfast	5%	Soda crackers					
	1–2 yrs 11 months	Breakfast	5%	Corn bread					
	1–2 yrs 11 months	Lunch	5%	Steamed creole potato					
	1–2 yrs 11 months	Lunch	5%	Crispy potato					
	1–2 yrs 11 months	Lunch	5%	Plantain with guava paste					
	1–2 yrs 11 months	Lunch	5%	Spaghetti					
	6–8 months	Lunch	6%	White rice					
	9–11 months	Lunch	6%	Rice with cilantro					
	1–2 yrs 11 months	Breakfast	6%	Puff pastry bread					
	3–5 yrs	Breakfast	7%	Puff pastry bread					
	9–11 months	Lunch	7%	Steamed creole potato					
	3–5 yrs	Lunch	7%	Spaghetti					
	3–5 yrs	Lunch	8%	Fried ripe plantain slices					
	3–5 yrs	Breakfast	8%	Soft bread					

Table 1. *Cont.*

Food Group	Age Group	Meal Time	% Critical Waste	Preparation	Food Group	Age Group	Meal Time	% High Waste	Preparation
CEREAL	9–11 months	Breakfast	9%	Corn arepa					
	9–11 months	Lunch	9%	Rice with noodles					
	9–11 months	Lunch	10%	Spaghetti					
PROTEINS	6–8 months	Lunch	0%	Grilled pork	PROTEINS	6–8 months	Lunch	16%	Ground pork
	3–5 yrs	Lunch	0%	Beef goulash		9–11 months	Lunch	16%	Tuna with vegetables
	3–5 yrs	Lunch	0%	Stewed ground beef		9–11 months	Lunch	18%	Meatball in sauce
	6–8 months	Lunch	0%	Stewed ground beef		9–11 months	Lunch	18%	Beans
	3–5 yrs	Lunch	0%	Chicken hearts		1–2 yrs 11 months	Lunch	18%	Tuna with vegetables
	9–11 months	Lunch	0%	Chicken hearts		3–5 yrs	Lunch	19%	Grilled pork
	3–5 yrs	Lunch	0%	Beans		3–5 yrs	Lunch	19%	Tuna with vegetables
	3–5 yrs	Lunch	0%	Chickpeas		9–11 months	Lunch	22%	Grilled chicken breast
	3–5 yrs	Breakfast	0%	Egg with corn		6–8 months	Lunch	23%	Grilled chicken breast
	6–8 months	Breakfast	0%	Blended egg		3–5 yrs	Lunch	24%	Grilled beef
	1–2 yrs 11 months	Breakfast	0%	Scrambled eggs with tomatoes and onions		9–11 months	Breakfast	25%	Boiled egg
	3–5 yrs	Breakfast	0%	Scrambled eggs with tomatoes and onions		1–2 yrs 11 months	Lunch	25%	Beef liver
	1–2 yrs 11 months	Breakfast	0%	Scrambled egg		9–11 months	Lunch	26%	Chickpeas
	1–2 yrs 11 months	Breakfast	0%	Cheese omelet		9–11 months	Lunch	27%	Roasted pork
	3–5 yrs	Breakfast	0%	Cheese omelet		9–11 months	Lunch	27%	Lentils
	3–5 yrs	Lunch	0%	Grilled chicken breast		6–8 months	Lunch	28%	Beef
	6–8 months	Lunch	0%	Stewed chicken breast		9–11 months	Lunch	29%	Stewed pork
	1–2 yrs 11 months	Lunch	1%	Grilled beef		9–11 months	Lunch	29%	Chicken breast
	3–5 yrs	Breakfast	1%	Scrambled egg		9–11 months	Lunch	34%	Grilled beef
	1–2 yrs 11 months	Lunch	1%	Chicken breast		9–11 months	Lunch	36%	Beef liver

Table 1. *Cont.*

Food Group	Age Group	Meal Time	% Critical Waste	Preparation	Food Group	Age Group	Meal Time	% High Waste	Preparation
PROTEINS	1–2 yrs 11 months	Lunch	2%	Beef goulash	PROTEINS	6–8 months	Lunch	37%	Chicken hearts
	9–11 months	Lunch	3%	Beef goulash		3–5 yrs	Lunch	37%	Beef liver
	3–5 yrs	Lunch	3%	Ground beef		3–5 yrs	Breakfast	39%	Boiled egg
	3–5 yrs	Lunch	3%	Roasted pork		6–8 months	Lunch	54%	Ground beef
	3–5 yrs	Lunch	3%	Lentils		6–8 months	Breakfast	55%	Boiled egg
	1–2 yrs 11 months	Lunch	3%	Grilled chicken breast		6–8 months	Lunch	88%	Bolognese ground beef
	3–5 yrs	Lunch	3%	Stewed chicken breast		6–8 months	Lunch	100%	Roasted pork
	3–5 yrs	Lunch	4%	Stewed pork					
	1–2 yrs 11 months	Lunch	4%	Stewed ground beef					
	1–2 yrs 11 months	Lunch	5%	Meatball in sauce					
	3–5 yrs	Lunch	5%	Meatball in sauce					
	3–5 yrs	Lunch	5%	Hamburger patty					
	6–8 months	Breakfast	5%	Scrambled egg					
	9–11 months	Breakfast	5%	Scrambled egg					
	1–2 yrs 11 months	Lunch	6%	Ground beef					
	9–11 months	Lunch	6%	Ground beef					
	1–2 yrs 11 months	Lunch	7%	Hamburger patty					
	1–2 yrs 11 months	Lunch	7%	Pork in pineapple sauce					
	6–8 months	Lunch	7%	Pork in pineapple sauce					
	9–11 months	Lunch	7%	Pork in pineapple sauce					
	1–2 yrs 11 months	Lunch	7%	Chicken hearts					
	9–11 months	Breakfast	7%	Scrambled eggs with tomatoes and onions					
	1–2 yrs 11 months	Lunch	8%	Grilled pork					
	1–2 yrs 11 months	Lunch	8%	Roasted pork					

Table 1. *Cont.*

Food Group	Age Group	Meal Time	% Critical Waste	Preparation	Food Group	Age Group	Meal Time	% High Waste	Preparation
PROTEINS	1–2 yrs 11 months	Lunch	8%	Beans					
	9–11 months	Lunch	10%	Grilled pork					
	9–11 months	Lunch	10%	Stewed ground beef					
	9–11 months	Lunch	10%	Hamburger patty					
	6–8 months	Breakfast	10%	Scrambled eggs with tomatoes and onions					
	9–11 months	Breakfast	10%	Cheese omelet					
	1–2 yrs 11 months	Lunch	10%	Lentils					
	1–2 yrs 11 months	Breakfast	11%	Egg with corn					
	1–2 yrs 11 months	Lunch	12%	Beef					
	1–2 yrs 11 months	Lunch	13%	Chickpeas					
	1–2 yrs 11 months	Lunch	14%	Stewed pork					
	3–5 yrs	Lunch	14%	Beef					
	1–2 yrs 11 months	Breakfast	15%	Boiled egg					
	3–5 yrs	Lunch	15%	Pork in pineapple sauce					
	6–8 months	Breakfast	15%	Egg with corn					
	9–11 months	Breakfast	15%	Egg with corn					
DAIRY PRODUCTS	1–2 yrs 11 months	Breakfast	0%	Cheese	DAIRY PRODUCTS	9–11 months	Breakfast	11%	Cheese
	3–5 yrs	Breakfast	1%	Cheese					

Note: Prepared by the authors.

Differences can be observed between age groups. Children aged 6 to 8 months exhibited the highest percentage of waste. Within this group, roasted pork was not consumed, while Bolognese ground beef, boiled eggs, and ground beef showed rates of 88%, 55%, and 54%, respectively, all exceeding the average waste for the protein group. These low acceptance rates may be due to the texture or inadequate presentation of these foods. In the 9 to 11-month-old group, although food consumption improves, there are still high waste rates for beef liver (36%) and grilled beef (34%). Students aged 1 to 2 years and 11 months, as well as those aged 3 to 5 years, exhibit lower food waste percentages and show a greater overall acceptance of various foods. However, beef liver and boiled eggs remain significant sources of waste, with a waste rate of 25% for children aged 1 to 2 years and 11 months, and

37% and 39% for children aged 3 to 5 years (see Table 1). This suggests that the methods used to prepare these foods are crucial for improving acceptance. Changing the preparation, such as serving them scrambled instead, could increase consumption.

Food waste decreases as children grow older, which correlates with the development of their motor skills, digestive processes, and eating habits. In general, small-sized meats, legumes, and scrambled eggs are better accepted. Conversely, foods that are mixed, such as tuna with vegetables, and solid preparations tend to be rejected by younger children. Therefore, adapting the texture and presentation of high-protein foods, particularly meats, is essential during the introduction of solid foods. This perspective is supported by [26], who emphasize the importance of sensory processing in children's acceptance of food. It is also essential to prioritize the most accepted preparations and to identify rejection patterns, such as boiled eggs, which persist among preschool-aged children.

In contrast to the previously reported trends, foods such as blended egg, beef goulash and scrambled egg demonstrated higher acceptance and, consequently, very low waste levels. Chicken breast was well accepted by older children, whereas ground beef was frequently rejected by younger ones, especially those in the 6 to 8-month age group. Regarding dairy products, both milk and cheese showed consistently high acceptance by children, with virtually no waste observed in most cases.

As suggested by [27], there is low acceptance among children regarding the fruit and vegetable group. In the present study, this was particularly evident among the youngest children with regard to the sweet granadilla. Salads also showed a high level of rejection, especially among the 9 to 11-month and a 1 to 2 years and 11 months groups, indicating a generally low acceptance of raw vegetables. In contrast, fruits such as papaya were well accepted across all groups, showing minimal waste. Pears showed variable acceptance, depending on factors such as ripeness and presentation. Meanwhile, mango and cucumber registered moderate levels of waste, while avocado, despite being included in several preparations, displayed relatively stable acceptance levels. There are multiple possible explanations for these findings. One, described by [25], identifies a link between unfamiliar odors, specifically negative olfactory awareness, and the rejection of vegetables.

In the cereal food group, waste levels above 11% were observed (see Table 1). Specifically, cassava, puff pastry bread and crispy potato were more frequently rejected by children, which may be attributed to their dry or dense textures. For items such as white rice, creole potato, and rice with pasta, the level of waste varied depending on the age group and time of consumption, although these foods tended to generate less waste compared to baked cereal products. Cereals incorporated into mixed preparations, such as flavored cookies or cassava, also showed moderate levels of rejection. Notably, there were zero-waste records for foods like rice and potatoes in certain groups, indicating higher acceptance depending on age or preparation method.

The photographs used in this research were intended to visually document the stages of the food waste measurement process through the direct weighing method. These images complemented the direct observation recorded in the field log, providing visual evidence of consumption behaviors by age group, and serving as visual support for the analysis and interpretation of the results. Also the photographs serve as an educational and awareness-raising resource, facilitating the understanding of the findings by the educational community and promoting a culture of food waste reduction in early childhood.

Figure 3 makes it possible to identify patterns of rejection associated with the texture and consistency of the food, especially in the case of the ground beef, which appears partially uneaten. This coincides with the observation recorded in the logbook, where it is mentioned that the participant had difficulty chewing due to the absence of teeth. Therefore, the photograph illustrates the weighing results and supports the interpretation of the causes of food waste, linking the sensory aspects of the food with children's eating behavior.

Breakfast Lunch

Figure 3. Food waste—age group 6–8 months. Note: Photographic record taken by the authors.

3.3. Perception of Food Consumption and Waste

The teachers who accompany the children and are part of the preschool staff reported that the most frequently wasted foods include tough meats, unripe fruits such as pears, cold pasta dishes like shell pasta with mayonnaise, and foods with dry or gritty textures. They also noted that vegetables or salads cut into large pieces and oversized portions, such as wholemeal bread rolls, are commonly rejected. These observations were supported by the nutritionist, who emphasized that unfamiliar or visually unappealing foods tend to be refused. The institution's psychologist explained that the lack of exposure at home to foods such as beef liver or vegetables directly affects their acceptance in the school setting. She also highlighted the importance of food texture and the need for consistency between eating habits at home and preschool. Additionally, it was noted that poor presentation and disproportionate portion sizes contribute to food rejection, an issue also discussed by [9]. In contrast, [28] emphasizes the importance of involving children with food preparers and engaging them in kitchen activities to build a more positive relationship with food and cooking.

3.3.1. Children's Perception

In the evaluation of four menus, children's food perceptions were assessed through logbook recordings and the interpretation of facial expressions. It was found that children preferred familiar foods such as rice, plantain, and soft-textured proteins like ground beef, these items consistently elicited positive reactions across all evaluations. In contrast, vegetables, salads, and certain tubers like cassava were frequently rejected. It was common for children to separate out specific ingredients, such as spinach or apple slices in salads, during meals. However, in a complementary evaluation conducted with twelve participants, five of them expressed dislike for salad through nonverbal cues. Interestingly, this dish was consumed when strategies were used, such as adult accompaniment, the sequencing of food presentation, and seating arrangements that grouped children with peers who had similar food preferences.

Beef cubes, offered on one of the menus, were also rejected, this was attributed to their texture. These findings are consistent with perceptions reported by families, staff, and nutritionists, who all emphasized that children are more likely to accept familiar foods with soft textures. Such results suggest that specific textures can lead to food rejection among children, creating a significant barrier to the development of healthy eating habits [29], as well as contributing to increased food waste.

3.3.2. Caregivers' Interviews

The responses from families of students in the two youngest groups, 6 to 8 months and 9 to 11 months, revealed differing opinions regarding the children's food selectivity, which may be linked to unfamiliarity with certain foods and their textures. In contrast, caregivers of the older groups identified a moderately selective attitude, as reported by the families. This is likely related to the children's longer time spent at the preschool and the gradual development of their eating habits.

According to family members' perceptions, children most commonly reject foods such as squash, vegetables, and salads, which account for nearly half of the mentions (49.7%). In contrast, fruits showed the highest level of acceptance, with only 9.2% rejection reported. Legumes and tubers had moderate rejection rates (25.6%), while meats, eggs, and dairy products were generally accepted at intermediate levels. Childcare workers noted that children tend to prefer mild, familiar flavors and consistently reject vegetables, an observation that aligns closely with previous findings.

In general, children's attitudes toward food were predominantly moderately selective (55.90%), especially among the 1–2 years and 11 months and 3–5 years age groups. Younger children (6–8 and 9–11 months) display behaviors at both ends of the spectrum. This contrast may be attributed to individual factors such as the stage of solid food introduction and eating habits at home. Overall, these findings highlight the need for age-specific strategies that promote the gradual acceptance of foods and reduce food selectivity from the early years of life, which is consistent with the observations of [30]. The verbatim responses from the parents and guardians of the students participating in this study are provided in the Supplementary File.

3.3.3. Staff Interviews

Responses from preschool staff, complemented by interviews with the nutritionist and psychologist, revealed that the foods most frequently wasted included tough cuts of meat, unripe fruits such as pears, and certain pasta dishes (e.g., shell pasta with mayonnaise). Additional factors contributing to rejection were identified as dry or gritty textures, excessively large pieces of vegetables or salad, and portion sizes poorly aligned with children's appetites, particularly in the case of wholemeal bread rolls. Staff members consistently noted that unfamiliar foods, or those seldom consumed at home, such as beef liver or specific vegetables, were among the items most frequently rejected by children. This behavior has been described by [25] as food neophobia, or unfamiliarity with foods. Furthermore, children tend to separate and discard foods they dislike. Texture emerged as one of the main factors contributing to waste: hard or difficult-to-chew foods are consistently refused by children. Lastly, unappealing presentations and inappropriate portion sizes were noted as harming food acceptance.

The preschool's psychologists and nutritionists also noted that food waste was closely linked to emotional, family [31], and cultural factors that directly influence children's eating behavior. Children transitioning to solid foods, particularly those from families with unstructured eating routines or from migrant households with dietary habits different from those of the local community, tend to reject foods more frequently. Negative emotions such as anxiety or stress during mealtimes were also identified as triggers for food refusal. These factors have also been described by [32] as indicators of children's rejection responses toward food. Additionally, the professionals highlighted that unappealing presentation or unfamiliar tastes and textures lead to high levels of food waste. Both experts agreed on the importance of creating a participatory, playful, and emotionally safe environment around food. However, they emphasized that reducing food rejection and waste requires collaboration between families and institutions, which are key to supporting positive eating behaviors.

In a previous study conducted by the preschool's administration on the nutritional classification of children, based on weight and height measurements, it was found that 69% have an appropriate weight for their age, suggesting that their food intake meets basic nutritional needs. However, 27% of participants are at risk of being overweight, indicating the presence of inadequate dietary practices that could compromise their health in the medium and long term [33]. Additionally, 4% are at risk of malnutrition requiring urgent attention due to its impact on physical, cognitive, and emotional development.

The distribution described above aligns with the nutritionist's observation, who emphasizes that food rejection is linked to a lack of familiarity with certain foods, unappealing presentation, and inadequate alignment between institutional menus and eating habits at home. The psychologist, in turn, associated food waste with family dynamics and the developmental challenges children experience during the transition to solid foods. This perspective is also supported by [30], who highlight the essential role of parents in helping their children develop healthy dietary patterns and become familiar with new foods and textures.

4. Discussion

The analysis of food waste in the preschool food service revealed that rejection patterns are strongly associated with the sensory characteristics of foods and the developmental stage of the children. Quantitative data indicated that the youngest groups (6–8 and 9–11 months) generated the highest levels of waste, particularly in foods with fibrous or dry textures, such as roasted pork and boiled eggs. These results suggest that limited chewing ability and early exposure to solids are major determinants of food acceptance. This finding aligns with the qualitative observations of caregivers and teachers, who reported that hard, dry, or grainy foods are often refused due to difficulties in chewing or swallowing. Similar relationships between oral-motor development and food rejection have been reported by [34], who emphasized the importance of texture adaptation in early feeding.

The direct weighing results also showed that visual presentation and portion size significantly influenced consumption. Oversized portions and visually unappealing dishes tended to generate greater waste, while foods with attractive color and proportionate serving sizes were better accepted. For instance, breakfast waste peaked among the 6–8-month group, coinciding with larger portions relative to their appetite. This finding is consistent with observations by [9], who noted that presentation and portion control are decisive factors in improving food acceptance and minimizing waste in institutional contexts.

Fruits and vegetables accounted for the highest percentage of waste (17%), largely due to unfamiliarity and sensory rejection. Foods like sweet granadilla were consistently refused, while papaya, softer and sweeter, was well accepted. Salads, however, presented the highest rejection rates, which qualitative data linked to the large size of vegetable pieces and their uncommon consumption at home. This pattern underscores the influence of food familiarity on children's preferences and supports the need for gradual sensory exposure from early childhood. Comparable trends have been observed by [27], who found that children show low acceptance of vegetables due to limited exposure and negative sensory associations.

Cereal-based foods exhibited variable levels of waste depending on texture and preparation. Children often rejected cassava, puff pastry bread, and wholemeal bread rolls due to their dry or dense textures, while they widely accepted rice and creole potato, which were softer and more familiar. These results indicate that texture and familiarity are key factors shaping children's eating behavior. In contrast with findings among older students, where rice and pasta are often the most wasted foods [7], this study shows that familiarity and softness reduce waste during early feeding stages.

Protein sources displayed significant differences in acceptance according to preparation. Fibrous meats, such as pork and beef cubes, and boiled eggs showed the highest waste rates, while ground beef, shredded chicken, and scrambled eggs had the lowest. These findings confirm that the cooking method and texture adaptation directly affect children's willingness to eat protein-rich foods. [26] similarly emphasize that improving texture and cooking techniques enhances children's acceptance of meats and reduces plate waste. In contrast, cheese and milk showed nearly full consumption across all groups, reflecting their mild flavor, soft texture, and consistent presence in household diets. This aspect was previously highlighted by [35] as beneficial for both nutrition and cognitive development.

The integration of qualitative evidence allowed the interpretation of specific waste peaks. For example, both teachers and the preschool nutritionist identified emotional factors, such as anxiety or discomfort during mealtime, as triggers for food rejection. The psychologist added that differences in home feeding practices and cultural backgrounds influence food acceptance at the preschool, particularly during the transition to solid foods. These findings align with [32], who associate food refusal with emotional and contextual variables. Additionally, children from families with irregular eating routines or limited exposure to diverse foods tended to reject institutional meals more frequently, a behavior comparable to food neophobia, as described by [25].

A progressive improvement in food acceptance was observed among children who had been enrolled at the preschool for longer periods. The combination of structured eating routines, peer influence, and adult accompaniment appeared to encourage the tasting and eventual acceptance of previously rejected foods. Staff reported that strategies such as sequencing food presentation, adjusting textures, and grouping children with similar preferences facilitated positive eating experiences. This evidence reinforces the preschool as a formative environment for developing healthy and sustainable eating habits, consistent with the pedagogical approaches advocated by [28].

Overall, the findings indicate that food waste in early childhood results primarily from four interrelated factors: inadequate texture, unfamiliarity, poor visual presentation, and inappropriate portion size. These causes are age-dependent and influenced by both sensory and cultural elements. The combination of quantitative and qualitative data revealed that modifying cooking techniques (e.g., replacing boiled with scrambled eggs), ensuring optimal fruit ripeness, and serving visually appealing portions can significantly reduce waste. Furthermore, aligning institutional menus with children's developmental stages and home eating habits could enhance acceptance and sustainability.

The study also highlights the critical role of family participation in reinforcing positive eating behavior. Caregivers' testimonies showed that at-home exposure to a variety of foods increases acceptance in the preschool setting. This observation supports the perspective of [30], who emphasize the need for parental involvement in the formation of healthy food preferences. Hence, collaboration between families and educational institutions emerges as a necessary condition for sustaining long-term reductions in food waste and promoting balanced nutrition.

The main strength of this study lies in the direct weighing method combined with photographic records, which provided objective and precise quantification of food waste by age group and food type. Additionally, the integration of qualitative insights from children, caregivers, and staff enriched the interpretation of sensory and behavioral causes behind waste peaks. This mixed-methods approach enabled the identification of both physical and emotional drivers of food rejection. However, the research was conducted in a single preschool and covered one complete menu cycle, which limits the generalizability of results. Future studies should extend the observation period and include multiple institutions to evaluate the long-term effects of menu adjustments, sensory education, and participatory feeding strategies on food waste reduction in early childhood settings.

Strategy and Action Plan

Based on the findings of this study, a comprehensive strategy (Figure 4) and action plan (Table 2) are proposed to reduce food waste in the preschool setting. The design of this plan is grounded in the quantitative evidence obtained through direct weighing and in the qualitative insights gathered from teachers, caregivers, and children. The results revealed that food waste in this context is primarily explained by four interrelated factors: inadequate texture, unfamiliarity with certain foods, unappealing presentation, and inappropriate portion sizes, in addition to emotional and environmental aspects influencing children's acceptance during meals. Therefore, each stage of the strategy directly addresses these determinants through context-specific actions.

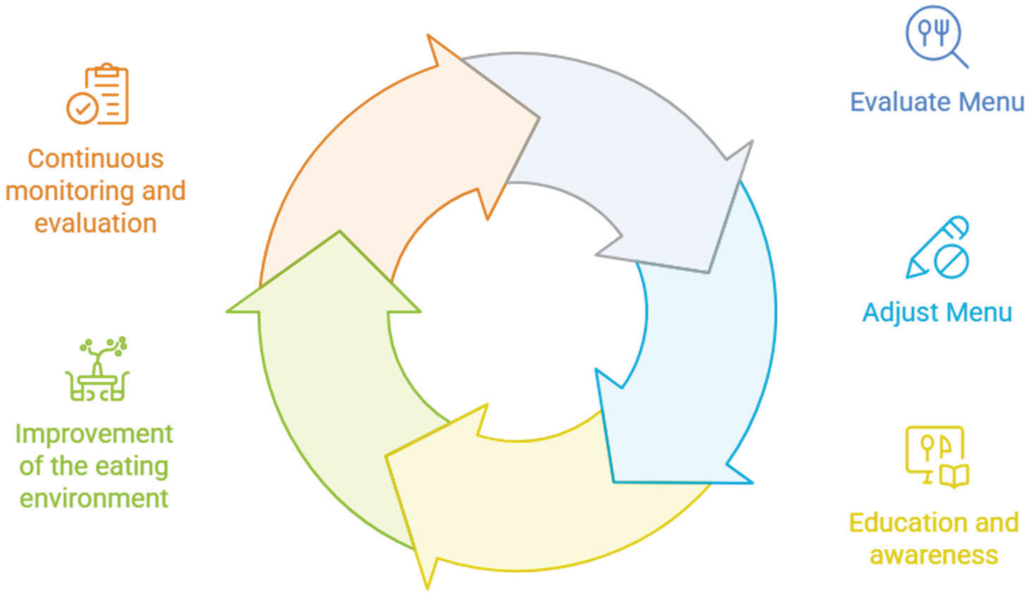

Figure 4. Strategy for reducing food waste. Note: Prepared by the authors.

Table 2. Action plan for reducing food waste.

Stage	Activity	Objective	Resources
1. Data collection (evaluate menu)	1.1 Review and adjust menus based on waste data. Modify food preparations and portion sizes according to waste patterns (e.g., replace boiled eggs with scrambled, serve ripe fruits, reduce dry foods).	Improve acceptance of critical items (proteins, salads, cereals) by adapting texture, portion size, and presentation to each age group.	Direct weighing matrix, portion size charts, observation logs, staff meetings.
2. Adjust menu	1.2 Implement pilot menu trials. Introduce small-scale menu tests to assess the impact of changes in preparation and presentation	Evaluate improvements in acceptance and texture adaptation	Kitchen staff collaboration, child-friendly utensils, feedback forms.

Table 2. *Cont.*

Stage	Activity	Objective	Resources
3. Education and awareness program	Conduct food education workshops for families and staff. Quarterly sessions focusing on food diversity, persistence in introducing new foods, and techniques to make meals more appealing.	Align home and institutional practices to reduce food neophobia and reinforce consistent exposure.	Educational materials, facilitators, workshop spaces.
	Involve children in food preparation. Monthly pedagogical activities to encourage tasting and sensory exploration.	Promote familiarity with foods and positive emotional engagement during meals.	Safe kitchen tools, ingredients, supervision.
4. Improvement of the eating environment	Implement structured and supportive mealtime routines. Include pre-meal rituals (handwashing, table setting, food introduction).	Reduce anxiety and distraction; promote autonomy and positive mealtime behavior.	Visual routine materials, staff training.
	Enhance presentation and dining area aesthetics. Use colorful plating and child-appropriate serving materials.	Increase sensory appeal and stimulate appetite.	Institutional kitchen equipment, tableware for children.
5. Continuous monitoring and evaluation	Weekly weighing and record keeping. Continue direct weighing and visual documentation of leftovers.	Quantify progress and identify emerging waste trends.	Scales, logbooks, trained staff.
	Quarterly review of implementation impact. Evaluate behavioral changes and menu acceptance.	Ensure continuous improvement and evidence-based adjustments.	Evaluation tools (surveys, checklists), team meetings.

Note: Prepared by the authors.

Unlike generic food waste reduction frameworks, this model was tailored to the specific findings of the preschool under study. For example, the diagnostic phase showed that fibrous meats (e.g., pork and beef cubes) and hard-boiled eggs were frequently rejected due to texture and chewing difficulty, while raw vegetables and salads were largely wasted due to unfamiliarity and presentation issues. Thus, the first stage focuses on menu reformulation to adjust the texture, presentation, and portion size of these foods. Similarly, qualitative data indicated that limited exposure to certain foods at home and emotional discomfort during mealtimes contributed to rejection, highlighting the need for educational and environmental interventions addressed in the second and third stages.

This strategy aims to strengthen food acceptance, promote healthy habits from early childhood, and foster a culture of responsible consumption through coordination among families, staff, and institutional management. These components have also been emphasized by authors such as [9,24,32,35]. As suggested by [36], such integrative approaches enhance both the sustainability of food services and children's nutritional well-being.

5. Conclusions

This study identified that the main drivers of food waste in the preschool food service are related to the sensory properties of the meals, particularly texture, presentation, and familiarity, as well as the alignment between institutional menus and family eating habits. Quantitative results showed an average food waste of approximately 14%, with the highest levels occurring among children aged 6–8 months, who generated up to three times more waste than the overall mean. This was mainly attributed to difficulties in chewing fibrous meats and the rejection of unripe or unfamiliar fruits and vegetables. Food waste decreased progressively with age, reflecting improvements in developmental and motor skills, as well as greater exposure to a variety of foods within the food service environment.

Based on these findings, four targeted recommendations are proposed to reduce food waste and improve food acceptance in early childhood. First, cooking methods and food textures should be adapted for protein-rich foods. Replacing fibrous or hard preparations, such as roasted pork or boiled eggs, with softer alternatives like shredded meats or scrambled eggs is expected to reduce protein waste by 20–30% in the 6–11-month age groups. Second, improvements should be made to the presentation and portion size of fruits, vegetables, and cereals. Serving ripe fruits, cutting vegetables into smaller pieces, and providing age-appropriate portions could lower fruit and vegetable waste by approximately 10 percentage points, particularly among children aged 1–3 years.

It is recommended to promote food familiarity through educational and sensory activities. Implementing monthly cooking and tasting sessions with children's participation could increase the acceptance of previously rejected foods and reduce overall waste by 5–8 percentage points across a complete menu cycle. Likewise, continuous monitoring and active family involvement are essential to sustain progress. The regular application of the direct weighing method, combined with participatory workshops for caregivers, can consolidate the reductions achieved and strengthen alignment between eating practices at home and in the preschool environment, keeping total food waste below 10% of the portions served.

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