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New Trends in Agri-Food Sector

Environmental, Economic and Social Perspectives

Edited by
Riccardo Testa, Giuseppina Migliore, Giorgio Schifani and József Tóth

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Contents

Preface

The reprint of Topic "New Trends in Agri-Food Sector: Environmental, Economic and Social Perspectives" represents a selection of 30 out of 82 published papers on the following issues: a) agroecology and organic farming; b) green economy; c) consumer behavior; d) innovation adoption; and e) the sustainable development of rural areas.

Specifically, this issue aims to collect scientific contributions on the sustainable agri-food sector, providing useful insights for scholars, marketers and policymakers.

Riccardo Testa, Giuseppina Migliore, Giorgio Schifani, and József Tóth
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Article

Does the COVID-19 Pandemic Change Consumers' Food Consumption and Willingness-to-Pay? The Case of China

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Abstract: Since COVID-19 was first detected in China in 2019, governments around the world have imposed strict measures to curb the spread of the coronavirus, which substantially impacted people's life. Consumers' food consumption behavior has also changed accordingly with reduced grocery shopping frequency, replaced in-person grocery shopping with online shopping, and increased valuation on food. In this paper, we aim to investigate the change in Chinese consumers' food consumption and their willingness to pay (WTP) for vegetables and meat, using a dataset with 1206 online samples collected between February and March 2020. Consumers' WTP for vegetables and meat is estimated using a double-bounded dichotomous contingent valuation design, and factors affecting their WTPs are also investigated. Results show that consumers have a higher WTP for these food products during the pandemic, and their WTP is positively affected by their anticipated duration of the COVID-19, their online shopping shares, their direct exposure to infected patients, their gender, and their income. These results imply that the food industry shall try to develop online market channels as consumers are willing to share the costs, while lower-income consumers may not be able to meet their food needs with prices increased beyond their WTP and thus may call for the government's support.

Keywords: food consumption; pandemic; willingness-to-pay; double-bounded

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1. Introduction

Unexpected public crises may cause drastic changes in consumer behaviors. The most recent worldwide public crisis is the COVID-19 pandemic which first broke out in Wuhan, China, in December 2019. To control the epidemic, the Chinese government immediately issued a lockdown order in most cities, which affected the food supply chain, and consumers responded quickly with adjustments to their purchasing behaviors. Many families chose to hoard more food products based on the psychology of panic to reduce the risk of being infected [1–3]. Some consumers changed their shopping channels from offline supermarkets and wet markets to online stores [4,5]. As COVID-19 quickly became a world pandemic, most countries imposed similar measures to restrict direct human contact and resulted in the same consumer behavior changes [6,7].

Consumers' willingness to pay (WTP) is often used to analyze their purchasing intentions [8–11]. WTP usually refers to the maximum amount of money that a consumer is willing to pay in exchange for a unit of goods or service. It is a consumer's personal valuation of a specific item, with a strong subjective evaluation component. However, instead of estimating WTP for a whole product or service, studies have been focused on WTP for specific attributes of a market product or non-market service. For example, compared to the ordinary food available in markets, people have estimated WTP premiums for the attributes of non-Genetic Modified, organic, geographically-identified, high-quality, and animal welfare foods [12–16]. Meta-analyses summarizing and comparing these WTP studies are conducted [17,18]. Results from WTP studies can also be used as a market segmentation factor for food consumers to promote sustainability as most of these studied attributes are eco-friendly attributes [19–25].

Studies investigating WTP for the whole product are rather few, except for new products that are not available in the market, such as biobatteries [26]. This is because when a product is sold on the market, revealed preferences can be observed by the market price and purchasing quantity so that there is no need to solicit consumers' WTP using stated preference. However, during unexpected public crises, market equilibrium is disrupted abruptly, and the WTP for whole products, especially the necessity for food products in daily life, needs to be solicited to understand consumer behavior to avoid food shortage.

The impact of public crisis events on consumer behavior and WTP has attracted wide attention. Scholars have studied WTP for specific products under public crisis events and have achieved meaningful results. Lee et al. [27] studied consumers' WTP in terms of taxes and fees for specific mad cow disease tests when there was an outbreak of mad cow disease in Korea. Facing the outbreak of H1N1, consumers also had high WTP for a specific vaccine [28]. Zheng et al. [29] studied the WTP for face masks during COVID-19 and found consumers expect a higher price and are willing to pay more for face masks. While these studies are for specific products or services that directly mitigate the adverse effects of public crises, it is especially worth investigating WTP for the essential food products because their market price may increase beyond the normal range of fluctuation due to excessive demand and supply disruption.

Understanding consumers' WTP for essential food products such as vegetables and meat can provide important consumer side information and help the government make policies to alleviate food shortages and supply chain ruptures. At the same time, the industry can adjust market strategies to satisfy consumer needs. This article will investigate consumers' WTP for essential food products, vegetables, and meat, during the first outbreak of COVID-19. We fill the gap in the literature that WTP is for the whole product instead of product attributes after disasters while the product is not directly disaster mitigating but rather life essential—food.

In this article, we conducted a contingent valuation study using a double-bounded dichotomous choice approach to estimate consumers' WTP for vegetables and meat under the influence of the COVID-19 pandemic. We also analyzed the factors affecting WTP. The objectives of this article are (1) to study whether and to what extent Chinese urban consumers are willing to pay for vegetables and meat beyond regular market prices during the COVID-19 pandemic; (2) to study the role people's expectations of the epidemic's duration that affect their WTP for vegetables and meat, and; (3) to explore the impact of the COVID-19 pandemic on consumption perspectives for consumers with different socio-demographic characteristics. As the coronavirus variants are emerging, the world keeps fighting. The battle is not over yet, and the pandemic's impact on food consumption continues. Thus, our study on this issue is valuable in terms of helping understand consumer's behavior in the COVID-19 environment.

2. Research Methods

The contingent valuation method is widely used in non-market valuation. This method is to establish a hypothetical market similar to the research object. Under the premise of this hypothetical market, the consumer WTP is estimated through data obtained from surveys. The method was firstly used by Davis [30] who conducted an empirical study on the recreational value of forest areas in Maine, USA. In 1979, the U.S. Department of Water Resources successively wrote the contingent valuation as one of the basic methods of resource assessment into regulations [31]. Since the 1970s, it has gradually been used in the benefit evaluation of various public goods and related policies, mainly involving outdoor entertainment, air quality, health risks, water quality, nuclear pollution risks, culture and art, and many other fields. Bennett and larson [32] reviewed these early studies and provided a summary.

With the double-bounded dichotomous choice method, survey participants are asked whether they are willing to pay or accept the bid value of a certain amount for the product. Then, depending on their response, they will be asked if they would be willing to pay a higher or lower amount. Thus, the double-bounded dichotomous choice method can collect more information about WTP [33]. This method is considered more efficient than the previous single-bounded method [34,35]. To a certain extent, it reduces hypothetical bias and strategic bias, and more accurately reflects the respondents' WTP, and improves the accuracy of the research. Thus, we used the double-bounded dichotomous choice contingent valuation design to estimate consumer's WTP for vegetables and meat.

In this study, the participants were asked whether he or she was willing to buy vegetables or meat if the market price of the products is raised by B_O. The percentages were randomly selected from five situations, namely 15%, 30%, 60%, 100%, and 150%. When the respondents answered "yes" for the first question, they would be asked another higher bid quote of B_H as the second question, otherwise, they would be provided with another lower bid quote of B_L, where $B_L < B_O < B_H$. In these five price rise scenarios (see Table 1), $B_O = 2B_L = B_H/2$, except in the first scenario where B_L = 5% instead, indicating that the price increase was very low.

Table 1. Double Bounded Choice Price Scenarios.

Scenario	B_L	B_O	B_H
1	5%	15%	30%
2	15%	30%	60%
3	30%	60%	120%
4	50%	100%	200%
5	75%	150%	300%

Note: B_O is the price rise level offered in the first question, and B_L and B_H are low and high price rise levels offered in the follow up question.

For *WTP*, the respondent's answer would have the following four possibilities.

$$T = \begin{cases} 1 & WTP < B_L, & \text{The answers are (no, no)} \\ 2 & B_L \le WTP < B_O, & \text{The answers are (no, yes)} \\ 3 & B_O \le WTP < B_H, & \text{The answers are (yes, no)} \\ 4 & B_H \le WTP, & \text{The answers are (yes, yes)} \end{cases} \quad (1)$$

where T is the observed choice indicator variable that falls into one of the four categories. Assume that the *WTP* of the respondent is linear in parameters.

$$\text{WTP} = x\beta + \theta \quad (2)$$

where x is a vector of exogenous variables that affect the WTP, β is the corresponding coefficient vector, θ is the residual term and follows normal distribution $\theta \sim N(0, \sigma^2)$. The parameters can be estimated by the ordered Probit model (3) using maximum likelihood estimation.

$$\text{Prob}(T = t) = \begin{cases} G\left(\frac{B_L - x\beta}{\sigma}\right) \\ G\left(\frac{B_O - x\beta}{\sigma}\right) - G\left(\frac{B_L - x\beta}{\sigma}\right) \\ G\left(\frac{B_H - x\beta}{\sigma}\right) - G\left(\frac{B_O - x\beta}{\sigma}\right) \\ 1 - G\left(\frac{B_H - x\beta}{\sigma}\right) \end{cases} \quad for\ t = \begin{cases} 1 \\ 2 \\ 3 \\ 4 \end{cases} \quad (3)$$

3. Survey and Data

From February to March 2020, due to the impact of Covid-19, China was in a state of national lockdown. During this period, we conducted an online survey on the consumers' WTP for vegetables and meat using a reputable survey company to recruit survey participants from its large national panel. In the end, 1206 surveys were collected in three sample cities of Beijing, Wuhan, and Chongqing. Beijing is the capital city, Wuhan is the city where the coronavirus was first detected and experienced the most turmoil, and Chongqing is a city close to Wuhan which was also hit hard by the coronavirus. The respondents were adults of 18 years and older, and were grocery shoppers.

Fresh vegetables and meat refer to two categories of necessary daily foods in the typical Chinese diet. In 2019, per capita consumption of major foods by Chinese residents was 507.7 kg, of which vegetable consumption accounts for 19.4% and meat accounts for 8.1% [29]. They are the two largest food categories by value. Recent data show that the largest food spending by Chinese consumers was on meat and poultry (27.9%), followed by vegetables (18.8%), fruits (13.6%), dairy (9.9%), and fish (8.4%) in 2005 and are expected to change to 21.9%, 18.5%, 13.6%, 12.5%, and 11.6% by 2025, respectively [36,37]. Table 2 is a report of sample descriptive statistics.

Table 2. Descriptive Statistics of Demographics and Perception Variables.

Variable	Description	Mean	Std. Dev.	Min	Max
Female	=1 if female; =0 otherwise	0.56 *	0.49	0	1
Age	Age, in years	34.09	8.19	19	74
Eduhs	=1 if high school or lower education; =0 otherwise	0.06	0.23	0	1
Eduass	=1 if with an associate degree/some college; =0 otherwise	0.19	0.39	0	1
Eduba	=1 if having a bachelor's degree; =0 otherwise	0.68	0.46	0	1
Hhnum	Number of people in the household	3.53	0.98	1	11
Children	number of children	0.89	0.62	0	3
foodfreq_b	Number of purchases of fresh food before Covid-19 over a two-month period	24.34	14.78	1	60
foodfreq_d	Number of purchases of fresh food during Covid-19 over a two-month period	11.77	8.36	1	60
foodexp_a	Per capita weekly expenditure of fresh food during Covid-19 (yuan)	137.48	101.32	8.33	1250
Foodpriceup	=1 perceive the price of food increases; =0 otherwise	0.87	0.33	0	1
foodprice down	=1 perceive the price of food decreases; =0 otherwise	0.01	0.11	0	1
foodsupplyc	=1 perceive sufficient food supply; =0 otherwise	0.26	0.43	0	1
foodsupplyb	=1 perceive significantly short of food supply; =0 otherwise	0.10	0.30	0	1
Relocate	=1 relocate to the city within a year; =0 otherwise	0.09	0.29	0	1
Pred	Anticipating Covid-19 duration (days)	60.13	36.71	7	150
Ffinfect	=1 if family or close friends infected with Covid-19; =0 otherwise	0.08	0.28	0	1
Ffmed	=1 if family or friends have health care workers or other frontline positions at risk; =0 otherwise	0.29	0.45	0	1
Hhinc	annual household income(10,000 ten thousand)	22.78	12.87	2.5	60
Beijing	=1 if from Beijing; =0 otherwise	0.33	0.47	0	1
Wuhan	=1 if from Wuhan; =0 otherwise	0.33	0.47	0	1
Vegonline_b	online vegetable purchase as a percentage of all vegetable purchases before Covid-19	30.65	23.86	0	100
Vegonline_d	online vegetable purchase as a percentage of all vegetable purchases during Covid-19	48.96	30.49	0	100

Table 2. *Cont.*

Variable	Description	Mean	Std. Dev.	Min	Max
Meatonline_b	online meat purchases as a percentage of all meat purchases before Covid-19	29.74	24.38	0	100
Meatonline_d	online meat purchases as a percentage of all meat purchases during Covid-19	44.60	30.82	0	100

* The mean of a dummy variable taking values of 0 and 1 only represents the share of the observations with value 1, and a share of those taking value 0 is then 1 minus the mean value.

Among the 1206 respondents, the proportion of women was slightly over half, and the average age was 34 years old. The largest education level group was the group with a bachelor's degree, as high as 68%. The proportions of the other two groups, the group with graduate degrees and the group with high school or lower education, were similar, about 7% and 6%, respectively. The remaining 19% of the respondents had associate degrees. The family size was 3.5 people on average, and there was an average of one child under the age of 18 in each household. The average annual family income was 227,800 yuan (about $35,303). These demographic variable values are in line with similar recent studies for the same Chinese urban consumer food consumptions [1,2,38].

The average number of fresh food shopping trips in every two-month period was 24.3 before the Covid-19, or about every other day, but it dropped to 11.8 during the Covid-19 pandemic, which was quite a significant change. During the Covid-19 pandemic, respondents spent an average of 137.5 yuan per week on fresh food, with a variation of 101.3 yuan and a range from 8.3 to 1250 yuan, showing a significant variation. About 87.4% of the survey participants perceived that the price of fresh food had increased during the Covid-19 pandemic compared to the same period last year, however, 1.4% of the interviewees perceived that the price had dropped and 11.2% perceived the price did not change. About 26% of the respondents perceived that the food supply was as adequate as that of the same period last year, but 10% perceived that the supply was significantly lower. Before the Covid-19 pandemic, the proportion of vegetables that respondents purchased online accounted for about 30% of their households' vegetable purchases and the proportion of meat purchased online was about the same. However, during the COVID-19 pandemic, the proportion of vegetables and meat purchased online increased to 49.0% and 44.6%, respectively. This was because people tried to avoid shopping in stores or markets to mitigate the risk of being infected.

One-third of the participants were recruited from each of the three cities, i.e., Beijing, Wuhan, and Chongqing (The three cities are located in different regions in China and heterogeneity will be taken into consideration in the model). About 29% of the respondents had relatives or friends working as medical staff or faced risks in other front-line positions. There were 8% of respondents that had family members, relatives, or friends who were infected with Covid-19. Only 9% of respondents moved into the current cities from other places within a year. On average, respondents were quite optimistic and expected the epidemic to end in two months. This was not surprising because the most recent epidemic the Chinese experienced was SARS, which occurred in 2003 and ran for only a few months. Their perceptions of the market and consumption were likely based on this underestimated duration of the pandemic.

4. Empirical Results and Discussion

As mentioned earlier, we used two common types of food products to demonstrate the impact of the COVID-19 pandemic on consumers' WTP—vegetables and meat. Ordered Probit regressions of Equation (3) for vegetables and meat on the many possible influential factors are reported in Table 3, each with two alternative specifications. Regression results in equation format are available in the Appendix A. The estimation was completed in STATA (StataCorp LLC, College Station, TX, USA). Various model specifications were examined with alternative forms of independent variables, and the logarithm of the predicted length of the pandemic was used instead of just the predicted length itself. Note that these are coefficients in Equation (2) of consumers' WTP measured in percentage of price change. In the following, we report the estimated coefficients that were statistically significant, interpret the results, and discuss the findings.

Table 3. Regression Results.

Variable	Vegetable		Meat	
	Model 1	**Model 2**	**Model 1**	**Model 2**
Ln(Pred)	30.06 ***	30.56 ***	11.35 ***	10.77 **
	(5.06)	(5.08)	(4.21)	(4.24)
Ffinfect	44.56 ***	49.77 ***	43.22 ***	52.57 ***
	(14.15)	(14.05)	(11.84)	(11.81)
foodfreq_b	0.83 ***	0.81 ***	0.43 **	0.55 ***
	(0.25)	(0.25)	(0.21)	(0.21)
foodfreq_d	−0.33	−0.28	−0.11	−0.18
	(1.05)	(1.04)	(0.90)	(0.89)
Female	−13.86 **	−13.35 *	−10.92 *	−10.32 *
	(6.96)	(7.02)	(5.79)	(5.86)
Hhinc	0.56 *	0.53	0.61 **	0.61 **
	(0.33)	(0.34)	(0.28)	(0.28)
Relocate	44.37 ***	48.20 ***	27.32 ***	33.46 ***
	(12.67)	(12.52)	(10.45)	(10.28)
Children	9.99	9.74	12.87 **	13.58 **
	(6.46)	(6.50)	(5.43)	(5.48)
Eduhs	−9.80	−14.45	−8.19	−14.50
	(20.65)	(20.68)	(17.13)	(17.29)
Eduass	−9.16	−13.38	−12.89	−16.10
	(16.68)	(16.61)	(13.92)	(13.99)
Eduba	−9.95	−11.60	−15.89	−17.24
	(14.50)	(14.52)	(12.10)	(12.22)
Ffmed	−4.97	−2.93	7.10	10.14
	(8.09)	(8.00)	(6.72)	(6.70)
foodexp_a	0.20 ***	0.210 ***	0.17 ***	0.19 ***
	(0.04)	(0.04)	(0.03)	(0.03)
online_b	0.47 ***		0.30 **	
	(0.16)		(0.13)	
online_d	0.12		0.42 ***	
	(0.12)		(0.10)	
foodprice_up	−16.73	−12.94	8.54	14.84
	(11.37)	(11.31)	(9.24)	(9.21)
foodprice_down	−20.97	−6.56	1.41	9.21
	(31.46)	(31.41)	(26.08)	(26.09)
foodsupplyc	−7.95		−5.42	
	(8.31)		(6.95)	
foodsupplyb	18.49		17.86 *	
	(12.08)		(10.05)	
Age	0.14	0.02	−0.59	−0.70 *
	(0.46)	(0.46)	(0.38)	(0.38)
Hhnum	0.90	0.49	2.89	2.65
	(4.24)	(4.26)	(3.53)	(3.56)
Beijing	20.62 **	23.79 ***	12.71 *	17.69 **
	(9.08)	(9.07)	(7.56)	(7.58)
Wuhan	8.23	9.16	−5.65	−3.38
	(9.06)	(8.92)	(7.55)	(7.48)
Constant	−79.95 **	−60.64 *	−29.39	−8.518
	(37.07)	(35.67)	(30.29)	(29.66)
Σ	103.1 ***	104.1 ***	87.68 ***	88.97 ***
	(3.30)	(3.33)	(2.69)	(2.74)
Log likelihood	−1699.31	−1706.64	−1776.57	−1791.34

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Several variables were statistically significant in the regression. The variable we were most interested in was consumers' expectations about the ending time of the COVID-19 pandemic. The coefficient was significantly positive at about 30 and 11 respectively for vegetables and meat. That means consumers were willing to pay a 30% higher price for vegetable products and 11% higher for meat products if the expected duration of the pandemic increased by 100%, or doubled. Vegetables were more essential than meats for Chinese consumers, their WTP was higher for the former. This confirmed our expectation that the more pessimistic views consumers had for the COVID-19 and thinking it would last for a longer time, the more likely they would be willing to pay higher prices on hoarding food. Using the logarithm of the variable, we assumed the marginal effect of *Pred* on WTP was not constant. Since it was generally believed at the beginning that the pandemic would last for two months, which would cause great inconvenience in the food distribution system, consumers raised their willingness to pay for the necessities as a rational decision. This was consistent with other studies documenting consumers' behavior patterns during the COVID-19 pandemic [2,39–41]. Consumers' behavior patterns during the COVID-19 pandemic can be divided into three stages: reacting, coping, and longer-term adapting [39]. In the first stage, consumers perceive the pandemic as a threat and react by hoarding to restore the loss of control, gain security and comfort, and win the competition over the product scarcity due to supply chain disruptions [42–44]. The pandemic has lasted a year and a half by now, which means they would have been willing to pay 66 ($(\ln 500 - \ln 60) \times 30$) and 25 percent higher prices for vegetables and meat, respectively. Had people known this pandemic would last an unprecedentedly long period like this, they might have had a different WTP at that time.

At the same time, several variables were also significantly positive. If they had family members, relatives, or close friends infected by COVID-19, a consumer's WTP would increase from 43% to 53% for the two types of foods in the alternative models. This was consistent with our intuition. When family and friends in their close circle get infected, people can truly feel the threat of the virus and are willing to accept higher prices for goods to save more foods at home in case they are also exposed to the virus. This was similar to other studies which found that consumer behavior is directly linked to the anticipated time spent in self-isolation and the severity of the situation during the COVID-19 pandemic [45].

For the variable of shopping frequency before the outbreak, people who went to the supermarket to buy food more frequently had a higher WTP. Consumers were willing to pay an 0.8% higher price for vegetable products and 0.4% higher price for meat products for each additional shopping trip made during the two months before the epidemic outbreak. This was also reasonable because those who made more shopping trips would habitually have a higher risk of getting infected if they did not alter their shopping behavior, so they had a higher value for food under the new situation of restricted shopping trips.

For demographic variables, compared to the base group of men, women's WTP ranged from 11% to 14% lower, holding everything else constant. The literature has mixed results about gender heterogeneity on WTP. Many show females tend to have a higher WTP for organic and sustainable food attributes, which is different from our results because women cared more about food safety and quality and food security for their families [2,46–48]. On the other hand, there are studies showing women tend to pay less on similar food attributes, consistent with our results [49,50]. This could be a result that they have more experience with the food market and grocery shopping, and thus they are less panicked to offer very high price premiums.

Income was positively significant, which is consistent with both the economic consumption theory as well as most empirical studies such as [51–53]. People with higher incomes can afford a higher price. This will leave low-income people at a big disadvantage if food price rises during the pandemic.

Relocate referred to whether the consumer was new to the city and was significant at a 1% level across all models, suggesting that if people just moved to the large city, they would have a higher WTP for vegetables and meat. This was also in line with conventional wisdom. When a person moves to a new city, s/he does not have a deep understanding of the grocery logistics of that city, and s/he has no confidence in whether the logistic chain can cope with a larger impact brought by the COVID-19 pandemic, and s/he is willing to pay more to mitigate risks.

For meat products, the coefficient for the number of children at home was about 13, which was significant at the 5% level. This means that for every additional child in the family, consumers were willing to pay 13% more for meat products. For families with children, parents pay more attention to the COVID-19 situation and are concerned that the food supply may be interrupted resulting in higher prices. The protein in meat products is a necessary ingredient for the growth of children, so parents were willing to pay more for meat. There exist studies showing that consumers with children in families are more willing to pay for high-quality foods [54,55].

It is interesting that education is insignificant. Education usually contributes to WTP on food attributes that are new or scientifically advanced such as environmental-friendly or animal-friendly claims in the U.S. [56] and organic foods in the United Arab Emirates [52], because people with higher education tend to acquire and comprehend new information for these attributes. However, the value of basic food during the crisis did not require consumers to have a higher education background to be aware, and thus consumers' WTPs did not differ by the educational background in this case.

With the estimated coefficient, the fitted WTP value for each participant could be calculated as in Equation (2) and are reported in Table 4. Note, because our model in (1) through (3) was fitted with the percentage increase of prices, the WTP result is also expressed in terms of price percentage increase.

Table 4. WTP for Vegetables and Meat.

Variable	Mean	Std.Dev	Min	Max
Vegetable	200.42	44.89	0	404.97
Meat	141.48	39.63	39.71	326.04

Table 4 shows that the average WTP for vegetables and meat was 200 and 141 percent higher than prices in normal times, respectively. This was higher than reported by Wang et al. [3] who estimated that Chinese consumers on average were willing to pay about 60.5% premium for fresh products reserves during the Covid-19 pandemic. Meixner found that consumers were inclined to be willing to pay a higher premium for ensured beef during the COVID-19 pandemic [57]. This means in general, during the COVID-19 pandemic, consumers are willing to pay a much higher price than in regular times. For both meat and vegetable, about 45% of the sample respondents have a WTP above the average value, while all are willing to buy meat and vegetables at a price exceeding the normal price to ensure the supply of themselves and their families.

When analyzing the WTP for meat and vegetables together, we found a positive correlation between the two types of foods. That is, consumers who had a greater (or smaller) WTP for vegetables also had higher (lower) WTP for meat. This was consistent with our intuition. For a rational consumer, the decision he makes comes from his perception of changes in the external environment and available options. In many cases, consumers are more likely to choose an easy and quickly attainable option than an option that was more distant but more valuable [58]. Under the Covid-19 health crisis, consumers face a high degree of uncertainty and are subject to travel restriction measures. To avoid the situation that the household may run out of foods and cannot take shopping trips to purchase them, consumers chose to pay premiums to stock up their refrigerator and freezer. In addition, consumers may experience value conflicts while making food choices and will adopt logical and feasible strategies to achieve a balanced state [59]. Goals are critical for determining value and affecting consumers' choices [60]. When they feel that the COVID-19 pandemic is serious and may take a long time to recover, they increase their WTP for both products at the same time.

5. Conclusions

Covid-19 is a global issue that deserves continuous attention in the coming years. The pandemic disrupted the normal order of markets, trade, and supply chains in various countries, and affected all aspects of people's life. One of the greatest impacts on consumers is to increase the uncertainty of their food accessibility due to possible food supply interruptions.

Through the study, we find that the epidemic has a significant impact on consumers' expenditure on fresh foods as most of them reported perceiving food prices increase. During the Covid-19 pandemic, the city lockdown has led to an asymmetry of information about food prices and supplies. The government should ensure the transparency of food market information for citizens, which can help citizens stock up food rationally and ease their panic.

On average, consumers are willing to pay higher prices for food, because they feel the pressure of a possible food supply interruption and are willing to pay more to guarantee sufficient foods for the family.

Consumers' concerns about the increased cost of the food supply chain as well as their panic about the future have significantly increased their willingness to pay for typical food products. The higher-income consumers are willing to pay more than the lower-income ones. This is consistent with the consumption theory. This means the low-income people may not be able to obtain adequate foods if prices rise beyond their willingness to pay levels. This should warrant the public and the government's attention. During a crisis like the COVID-19 pandemic, the lower-income population may have a tighter budget and a higher financial need, which calls for the consideration of government relief plans.

The positive effect of the pandemic duration expectation on the willingness to pay together with Chinese consumers' over-optimistic estimation of 60 days suggests that consumers were not prepared for a prolonged pandemic like this one. The results show that the longer consumers believed the Covid-19 pandemic would last, the more likely they are willing to pay higher prices on hoarding vegetables and meat. We draw implications with a caveat since at this point the pandemic has lasted for about one and half years, much longer than the average duration Chinese consumers expected, i.e., about 60 days, at the time they completed the survey. The sudden outbreak of the pandemic changed consumers' behaviors in terms of reducing shopping trips, hoarding foods, and paying higher prices for essential food products. However, with the prolonged pandemic situation, consumers have experienced fatigue which also impacts their consumption behaviors. Our results may not have sufficient prediction power for this long duration of the pandemic. This is the major limitation of our research and further research examining consumer behaviors and choices over a longer duration of the COVID-19 pandemic may fill this gap. This becomes possible and necessary as the COVID-19 pandemic has run near two years, longer than most people's expectations.

Consumers take measures themselves to cope with the crisis by reducing their shopping trips and switching to online shopping. Online shopping itself also induces consumers to pay more to cover the cost of delivery services for the food products. This suggests that the food retail industry should consider selling products on online platforms and be prepared for the cannibalization of traditional offline sales. As consumers' preferences for online shopping are different than in traditional offline markets [61–63], the industry needs to adjust its marketing emphasis. It also gives an opportunity for the logistic industry.

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Data Availability Statement: Data used in the analysis are collected from a survey conducted by the authors.

Conflicts of Interest: There is no conflict of interests.

Appendix A

The regression results are reported in equation format below.

WTP for vegetable Model 1 estimated equation:

$$\begin{aligned} \hat{WTP}(Vegetable) &= -79.95 + 30.06Ln(Pred) + 44.56Ffinfect + 0.834foodfreq\_b - 0.330foodfreq\_d \\ &-13.86Female + 0.562Hhinc + 44.37Relocate + 9.990Children - 9.799Eduhs - 9.155Eduass \\ &-9.949Eduba - 4.973Ffmed + 0.201foodexp\_a + 0.466online\_b + 0.121online\_d \\ &-16.73foodprice\_up - 20.97foodprice\_down - 7.946foodsupplyc + 18.49foodsupplyb \\ &+0.135Age + 0.901Hhnum + 20.62Beijing + 8.231Wuhan \end{aligned}$$

WTP for vegetable Model 2 estimated equation:

$$\begin{aligned} \hat{WTP}(Vegetable) &= -60.64 + 30.56Ln(Pred) + 49.77Ffinfect + 0.813foodfreq\_b - 0.275foodfreq\_d \\ &-13.35Female + 0.529Hhinc + 48.20Relocate + 9.737Children - 14.45Eduhs - 13.38Eduass \\ &-11.60Eduba - 2.933Ffmed + 0.210foodexp\_a - 12.94foodprice\_up - 6.557foodprice\_down \\ &+0.0199Age + 0.491Hhnum + 23.79Beijing + 9.158Wuhan \end{aligned}$$

WTP for meat Model 1 estimated equation:

$$\begin{aligned} \hat{WTP}(Meat) &= -29.39 + 11.35Ln(Pred) + 43.22Ffinfect + 0.434foodfreq\_b - 0.109foodfreq\_d - 10.92Female \\ &+0.609Hhinc + 27.32Relocate + 12.87Children - 8.192Eduhs - 12.89Eduass - 15.89Eduba \\ &+7.097Ffmed + 0.174foodexp\_a + 0.298online\_b + 0.424online\_d + 8.537foodprice\_up \\ &+1.413foodprice\_down - 5.415foodsupplyc + 17.86foodsupplyb - 0.585Age + 2.890Hhnum \\ &+12.71Beijing - 5.652Wuhan \end{aligned}$$

WTP for meat Model 2 estimated equation:

$$\begin{aligned} WT\hat{P}(Meat) &= -8.518 + 10.77Ln(Pred) + 52.57Ffinfect + 0.546foodfreq\_b - 0.175foodfreq\_d - 10.32Female \\ &+0.614Hhinc + 33.46Relocate + 13.58Children - 14.50Eduhs - 16.10Eduass - 17.24Eduba \\ &+10.14Ffmed + 0.191foodexp\_a + 14.84foodprice\_up + 9.209foodprice\_down - 0.695Age \\ &+2.649Hhnum + 17.69Beijing - 3.384Wuhan \end{aligned}$$

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Article

Adoption and Diffusion of Agroecological Practices in the Horticulture of Catalonia

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Abstract: The environmental impact of conventional food production systems imposes a rapid transition towards sustainable production systems through the adoption of agroecological practices. The barriers and accelerators of the adoption of agroecological practices were identified for horticultural crops in Catalonia. Eight interviews and thirty surveys were conducted with local producers. Results show that the loss of producer income and the lack of social awareness regarding organic products are among the important barriers to the adoption of agroecological practices, while information about the experience of other farmers is considered a motivational factor. Finally, the study concludes that the adoption of agroecological practices has economic, political, social, academic and agronomic components.

Keywords: agroecological practices; barriers; accelerators; farmers' adoption

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1. Introduction

Agroecology is a type of agriculture which appeared at the end of the last century with the objective of providing an alternative to conventional agriculture (that is, agriculture which favors destruction of the circular economy and the loss of biodiversity [1]). Hallmarks of organic farming include: the use of biological control to treat pests and diseases, and of organic amendments, livestock and/or plant remains to fertilize the fields; direct seeding or minimum tillage to reduce the loss of soil through erosion and increase biodiversity, soil fertility and the content of organic matter in the soil; increased crop application of coverage and use of microorganisms to help the plant absorb nutrients in the soil with greater ease, in order to strengthen the plant against pests and diseases and thus increase yields; and application of genetics to extract more climate-resistant cultivable species with high yields under changing climatic conditions involving drought, saline soils, pests and diseases, etc. In addition, the application of genetics allows for diversification and crop rotation, which are the two fundamental pillars of agroecology.

According to Róger [2], agroecology is a scientific discipline which gathers, synthesizes and applies knowledge from agronomy, ecology, sociology and ethnobotany, and with a holistic and systemic ethics; therefore, it is an agricultural system which provides a rational ecological base for the management of the agroecosystem through innovative production technologies, stable and highly adaptable to the environment and society. Wezel et al. [3] classified agroecological practices according to the level of integration that the crops have and depending on the degree of implementation they have. According to them, the integration of organic fertilization, cover crops, irrigation by drip and biological pest control, among others, have already reached an average level of integration into current agriculture and have high potential for wider application in the next decade, already benefiting from a good scientific knowledge; however, the integration of allelopathic plants, biofertilizers, agroforestry systems and the management of landscape elements at scale have a low level of integration, and will not be easily implemented in the field in the near future, as these rely on a larger scale of management and largely on the regional and national general conditions which are subject to project framework and territorial development planning.

This article shows how agroecology affects the social, economic, environmental, political, ethical and cultural aspects. At the social level, agroecology aims to configure a system which values the food sovereignty of producers and reinforces the health and well-being of present and future generations of farmers and independence and autonomy in their development, participation and decision-making. In the field of economics, agroecology assumes that the associated benefits make it possible to cover the needs of the producer and reduce the risks associated with dependence on markets, inputs or low product diversification; it makes efficient use of goods, services, production and equitable distribution, without damaging the renewal, reproduction and distribution of the agroecosystem. In the same way, politics analyzes and act on social conditions, networks and conflicts resulting from the support for sociocultural agroecological change, with a view to achieve a sustainable social or socio-vital metabolism, which affects the construction of styles of food (patterns and networks of production, distribution and consumption) and equitable and sustainable democratization of food. Finally, agroecology understands that at an ethical and cultural level, humans should reduce their excessive food consumption and environmental degradation and incorporate ancestral and character values and knowledge in order to eliminate hunger, poverty and negative consequences for the environment, and that farmers should decide to modify natural ecosystems to transform them into agroecosystems through the choice and distribution of spontaneous crops, animals and plants considering their values, beliefs and objectives.

Over the last few years and coinciding with what Gil et al. [4] reported, consumers, companies and administrations have been becoming aware of issues related to food safety and environmental problems. Consumers' concern for food safety has increased sensitivity to environmental degradation. That is why their conscience and behaviors (which are closely related to ecology) have been taking a center stage in such a manner that they try to make their actions less damaging to the environment. The tendency to purchase organic products is influenced by demographic, socioeconomic, psychographic and behavioral variables. All of them explain in different studies why consumers, companies and institutions are committed to buying and selling organic products [5,6]. Díaz et al. [7] found that consumer lack of information and knowledge as well as high prices are the most relevant barriers to the consumption of organic food. Grymshi et al. [8] analyzed consumer' purchasing behavior towards ecolabeled food products and based on the degree of familiarity and consumption patterns, they identified three typologies of consumers including indifferent, committed, and skeptical. At the European level, age is a very important factor when buying organic products. The people who are more interested in purchasing organic products are between 15–55 years of age [9]. In particular, 26% of this segment are people under 35 years old, while 76% are above 35 [10].

Agriculture in general is undergoing a change at the social, economic, political and environmental levels which requires farmers and ranchers to adopt more sustainable agricultural practices and methods. This will force the transition from a polluting conventional agriculture characterized by excessive use of chemical inputs (fertilizers, pesticides, etc.) to a green agriculture, efficient, profitable and socially, economically and environmentally sustainable. This reality is reflected in the great interest shown by the scientific community (Brzozowski and Mazourek, 2018; Keulmans, 2019; Clark and Tilman, 2017) in assessing the economic, social and environmental conditions of agriculture in recent years. However, despite social pressure, environmental awareness, warnings from national and international environmental organizations and public support, with favorable policies and programs, the rate of adoption of agroecological practices among farmers and ranchers continues to be very low, as reflected by the low presence of organic products in the market. The objectives of the present work are: (i) to make a diagnosis on the diffusion of agroecological practices in the horticulture of Catalonia; (ii) to assess farmers' intentions to adopt agroecological practices; (iii) to describe the profile of potential adopters of agroecological practices; and (iv) to understand the most relevant barriers and drivers. To reach these objectives, interviews and surveys were conducted among a group of farmers in Catalonia.

Literature showed that the adoption of agroecological practices is determined by a series of barriers and motivations [11]. Horrillo et al. [12] showed how organic farms are not economically profitable for farmers. Horrillo et al. [13] also reported that organic livestock farms could be economically remunerated for the ecosystem services they provide to society, especially when their net CO_2 balance is negative. Dessart et al. [14] classified the behavioral factors that affect the decision to adopt or not adopt agroecological practices as dispositional (personality, motivations, values, beliefs, preferences, goals), social (interactions, social norms, signaling motives) and cognitive (learning, reasoning, perceptions of benefits, costs and risks). Pearce et al. [15] and Damalas et al. [11] indicated that the variation in pesticide use among farmers is associated with a set of factors including low level of internal inputs, market demand, the presence of pests and diseases, the need to produce food in abundance, the pursuit of the greatest financial benefit, the adoption of methods of organic farming, the efficacy of pesticides, and concerns about pesticide exposure and environmental pollution. Horrillo et al. [16] identified the stagnation of sales, the lack of self-sufficiency in organic feed and the difficulty of access to organic certified slaughterhouses as relevant barriers to the transition from a conventional farm to an organic system.

Runhaar et al. [17] identified age, sex, social and educational level, knowledge and experience of the farmer, as well as the size of the farm as variables which affect the willingness of farmers to adopt innovative practices. Hashemi and Damalas [18] highlighted the importance of such factors as the perception of pesticide safety and knowledgeable experience of pest integration methods in the decision of farmers to adopt or not adopt alternatives to conventional agricultural practices.

Other authors [17] highlighted the role of factors such as motivations, information, social context, government agreements, demand, particular skills and abilities of implementation, legitimization, the holistic framework which integrates personal and contextual factors, and the multidisciplinary framework (nature conservation and factors that stimulate behavior change) in the decision to adopt sustainable alternatives by farmers. For example, some authors [19,20] investigated farmers' intention to adopt new soil conservation practices focusing on variables such as biophysical, economic, social, regulatory and institutional conditions (Table 1).

To adopt a new practice, a farmer should be sure of the steps he or she is going to take, so he or she should know if he or she can receive financial aid, if the crop is going to be profitable [21] and should also know the new practices and products. He or she also needs to have knowledge, awareness, attitude and perception of the risks associated with these practices [22]. Another very important factor is the prior adoption of ecological practices by other farmers who can positively influence those who have not yet taken the decision to switch to agroecological practices.

Table 1. Barriers and Solutions.

Authors	Subject	Barriers	Solutions
Valerio et al., (2016)	Conservation agriculture (Mexico)	Business orientation; The short term expected objectives; The economic limitations.	
Brzozowski and Mazourek (2018)	Organic plague management	Biological complexity due to having difficulty in accessing data and concepts.	Invest in: cultivar development adapted to the environment and/or resistant to pests and diseases; plant breeding; understanding and promotion of plant-relations rhizosphere.

Table 1. *Cont.*

Authors	Subject	Barriers	Solutions
Schoonhoven and Runhaar (2018)	Adoption of agroecological practices: holistic frame	Absence of commercial models; Structural difficulty/barrier→difficulties to find funds.	
Hashemi and Damalas (2011)	Farmer perceptions towards the plaguicide efficiency	Beliefs, perceptions and preferences; Scarcity of technical and advisory support.	
Bijttebier et al., (2014)	Adoption of conservation practices in Europe	Changes in economic conditions after adoption; Lack of adequate machinery; Presence of the plow; Soil texture (compaction); Slope; legislation; nature of crops; Yields (decrease); Lack of stimulation.	Understand the differences between countries when adopting practices for soil conservation; Informing people or institutions.
Pearce et al., (2019)	Promotion of alternatives to plaguicides	Lack of training (and knowledge); Difficulties accessing the network.	Alternatives to the use of pesticides: Train the farmers; Educate the young students through practical classes with the help of technology.
Malina et al., (2019)	Disposition and perception to pay for bioplaguicides	Literature shortage; The perceived risk; the price of the biopesticide; High perception of pesticide efficacy.	Introduce definitions of pesticides and biopesticides in the interviews; Perform communication efforts (campaigns of information and education). For sustainable agriculture: Development of techniques to reduce negative impact of chemical inputs; Implementation of a legal framework; The contribution of consumers; More research to understand needs, motivations or factors that hinder the consumption of sustainable products; Conduct studies taking into account the intensity of the willingness to pay.
Dessart et al., (2019)	Factors affecting the adoption of agrological sustainable: politics.	Group behavior; Resistance to change; Difficulty in policy agricultural segmentation; Treat all farmers the same; Lack of knowledge of sustainable agriculture practices by the citizen; Lack of Knowledge→Lack of participation; Greater fluctuation in demand and the offer of organic production; Prohibition of the use of chemical fertilizers or synthetic pesticides→increases the risk of failure of crops; The variability of the soil reaction to sustainable practices and uncertain efficacy of sustainable practices; Uncertainty; financial risks.	Segment farmers indirectly according to: age, sex and country or region; Design a combination of policies based on voluntary adoption and mandatory sustainable practices; design subsidized environmental schemes. Policy tools to decrease Perceived risks: offering Insurance; Promotion of mutual funds; Promotion of free practice sustainable tests.

Table 1. *Cont.*

Authors	Subject	Barriers	Solutions
Keulemans (2019)	Can we grow without the use of herbicides, fungicides and insecticides?	For increased performance: acidification; The loss of biodiversity; Soil erosion; the eutrophication of superficial water. Reduction of active substances→higher resistances→decrease in the effectiveness of the products→higher losses. Longer time required to get a new product; Sub-optimal factors: fertilizers, adapted varieties, irrigation, other techniques of crops; Difficulty relating the use of phytosanitary products with performance through experimental and quantitative data; Unclear and imprecise media communication; Lack of knowledge of diseases or pests and of the impact of these by agronomists, advisers or farmers; The MIP incorporates a wide range of practices, but does not establish explicitly the degree of reduction of APP at farm level; Little/Low accuracy on whether the greater biodiversity in organic agriculture is due to the management of biopesticides or the low performance.	To bridge the gap: Promote sustainable intensification of agriculture; reduce losses and food waste; Change diet; Prohibit crop production for bioenergy; Give an optimized use of phytosanitary products.
Damalas and Koutroubas (2017)	The training in the use of pesticides associated to safety behavior	Low acceptance of training on pesticides and job aging; Limited studies on the relevance and effectiveness of the training; Lack of educational guides for treating the destruction of beneficial insects; Problems: Spray more often and at a higher dose; Factors (1 and 2) to evaluate the training by any means available: The decision making (1) and To design most effective training components (2).	Increase awareness of alternative pest control practices with less pesticide use.
Clark and Tilman (2017)	Comparative Analysis of environmental impacts of the system of agricultural production, efficiency of the agricultural inputs and choice of food.	The limitation focused on food of animal origin or a single environmental indicator; the comparative environmental impacts of control practices with a lower use of pesticides.	Apply management technologies and techniques to increase the efficiency of agricultural inputs through: agriculture of precision, conservation tillage and cover crop, feed intake in livestock systems: use of agricultural waste and by-products; Interventions to reduce future environmental impact aspects of agriculture: adoption of low-meat diets in countries with excessive meat consumption, increase sustainable yields of crops and reduce waste of food; Implementation of initiatives and policies in education designed to increase the adoption of low-fat food impacts, of less impact on production systems and systems with high efficiency of agricultural inputs.

Table 1. *Cont.*

Authors	Subject	Barriers	Solutions
Damalas et al., (2018)	Criteria for the selection and use of pesticides	Little evidence on use of pesticides patterns; Limited information; Technique limitations; Little research on nature of farmers' criteria for selection and use pesticides; Reduction of subsidies; Limited knowledge of allowed amounts of pesticides; Low levels of education and training in management of pesticides; Ineffectiveness of training courses.	
Kragt et al., 2017	Motivations and barriers so that large extension land Occidential Australian agricultures adopt carbon agriculture	For participation: The complexity of the scheme (amount of paperwork involved for becoming a registered provider); the strict program rules (requirements for permanence); Information limitations.	

2. Materials and Methods

In this work, two research techniques were combined including a qualitative method (interviews) and a quantitative technique (questionnaire). The purpose of the interviews with the farmers was to extract ideas which would feed the preparation of the questionnaire. In total, eight farmers were interviewed in the province of Barcelona. The farmers interviewed mostly practiced traditional horticulture. Three of the eight farmers were engaged in fruit growing; two were from conventional agriculture and one from ecological agriculture. The interviews were planned to be conducted physically in the field; however, we were forced to carry out these interviews via telephone due to the restrictions imposed by the authorities to reduce the propagation of COVID-19.

Based on the interviews and the literature review, a first survey was carried out as a pilot test. The pilot test was carried out with ten farmers from different sectors in order to correct errors, refine the questions, and identify important aspects not included in order to take them into consideration, as well as to estimate the average time required to complete the survey. Subsequently, we proceeded to the realization and shipment (via email) of the final survey. For data collection, we proceeded to contact farmers, companies and public and private institutions in the agri-food sector such as cooperatives, ADVs (Groups of Plant Defense of Catalonia), associations and universities. It took two months to collect the 30 surveys. This delay was due to the fact that the months of collecting data coincided with the full harvest period.

The interview script consisted of open or semi-open questions. For example, the first question consisted of finding out the characteristics of the farm and the farmer (cultivable hectares, farmer's age, number of family members who are engaged in agricultural exploitation, number of workers, etc.) and what type of agriculture they practice and the type of crops they cultivate. The following questions were dedicated to extracting information about whether they adopted (or not) agroecological practices and why. To do this, they were asked directly if they had ever adopted any agroecological practice and what type, and if they had done it with or without aid, what type of barriers and/or motivations they had in adopting these practices, if they plan to adopt (or not) agroecological practices in the future and why. Finally, we asked them whether they will continue using the same production system after the COVID-19 crisis or if they plan to switch to agroecological or more sustainable practices and why.

The survey was designed focusing on aspects related to the adoption (or not) of agroecological practices by farmers (conventional and/or organic) and what factors affect this adoption. The survey was divided into 11 sections: (1) Characteristics of the farm; (2) Agroecological practices adopted until now; (3) Barriers to agroecological practices; (4) Accelerators of the adoption of agroecological practices; (5) Perception of the benefits of agroecological practices; (6) Intention to adopt agroecological practices in the future; (7) Trust in the different sources of information on agroecological practices; (8) Attitudes (preferences) to risk; (9) Attitudes towards the environment; (10) Perception of exposure to and risk from chemicals; and (11) Sociodemographic characteristics.

To measure the Attitudes towards the environment, we used the new reduced version of the Ecological Paradigm scale (NEP-R). Farmers were required to indicate their level of agreement with the statements in a 5-point scale (from 1 'Strongly disagree' to 5 'Strongly agree'). This scale allowed us to segment farmers into ecocentric and/or anthropocentric groups.

Data analysis was performed with the SPSS statistical program. We started with some descriptive analyses, which we represented in figures and tables. A factor analysis was carried out with the objective of reducing the elements of the environmental attitudes scale (NEP-R). Finally, bivariate analyses were carried out to describe the relationship between the variable "intention to adopt agroecological practices in the future" and various characteristics of the farmers and their farms, in order to identify the profile of potential adopters of agroecological practices in the future. The relationships between the variables are represented in figures. These analyses were performed using statistical tests (analysis of variance and Tukey) in order to detect which groups of farmers were more susceptible to adopting agroecological practices. It was not possible to conduct some multivariate analyses due to small size of the sample we used.

3. Results

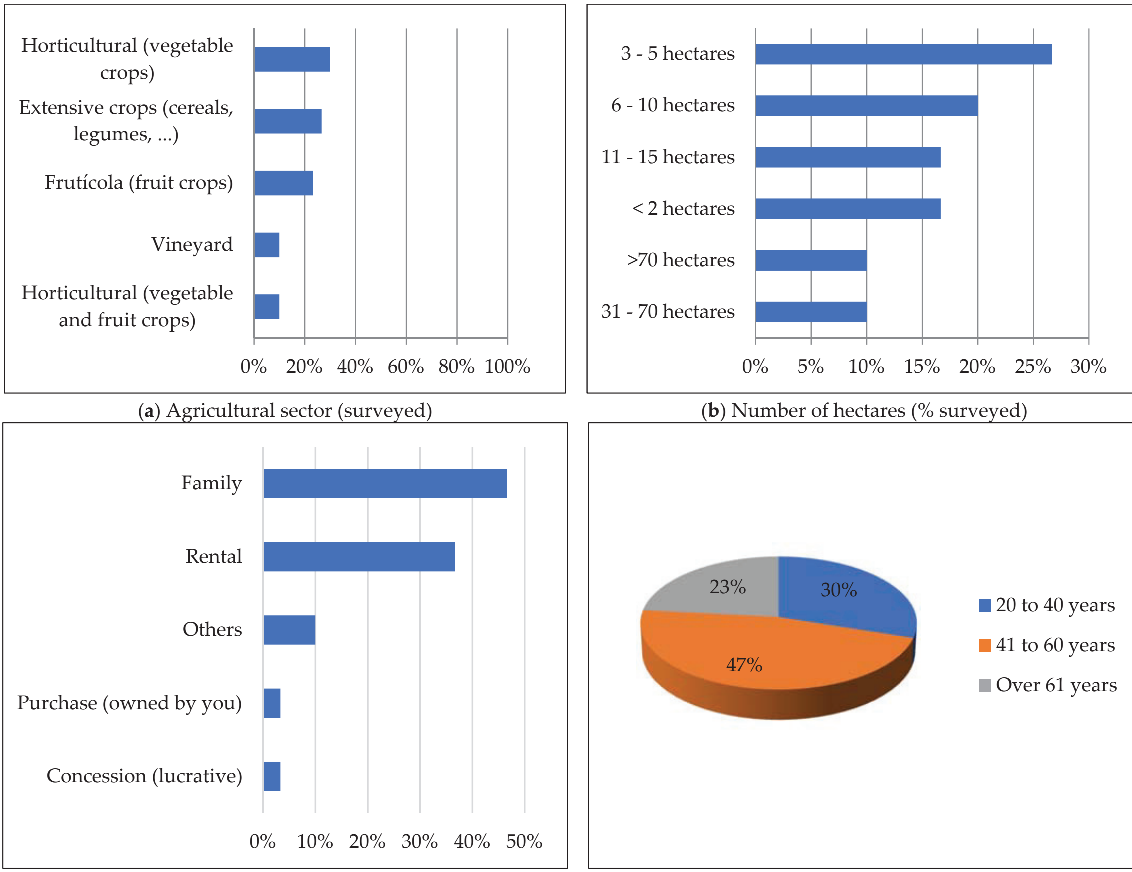
The results are presented in the following way: first we describe the results from the interviews, then we reported the results from the surveys. Those from the surveys are divided into the following sections: (1) Characteristics of farmers and their farms; (2) Level of knowledge, perceptions and farmers' attitudes towards pesticides and agroecological practices; (3) Main barriers, accelerators and perceptions of the adoption of agroecological practices; (4) Results related to the adoption of agroecological practices (profile of farmers who are potential adopters of agroecological practices in the future).

The results related to the interview are divided into: agroecological practices already adopted, barriers to the adoption of agroecological practices and accelerators of the adoption of these practices. Regarding the already adopted agroecological practices, the most indicated practices were: Do not abuse the land; Try to maintain high soil conservation in terms of low tillage and promoting biodiversity by leaving vegetation cover; Do not pretend to substitute ones' inputs for others but then decrease them; Seek the balance between plant-soil-adventitious herbs; Change agricultural practices to improve the health of cultivated plant species. The most cited barriers to the adoption of agroecological practices were: the lack of advice and technical support for the conversion to agroecology; the lack of agroecological training for farmers; the lack of knowledge on the application of biopesticides; the lack of research on new phytosanitary products; the lack of citizen awareness; and, Difficulty in the control of MH without herbicides, among others. Regarding the accelerators, the most cited are: the possibility of introducing technological innovation in organic production methods; Payment for the product at a fair price; Farmers' ecological groups to support each other and facilitate the transfer of knowledge of agroecological practices; Maintaining or increasing the viability of crops; Obtaining support and social recognition for the farmer's ecological work; Offering quality; Experimentation on their own farm with effective and more respectful methods with the environment; Gratification of success, etc. The results related to the survey are subdivided into:

3.1. Characteristics of Farmers and Their Farms

In Figure 1 it can be seen that 30% and 27% of respondents belong to the horticultural sector and extensive crops (cereal, hops, etc.), respectively. Furthermore, 27% of the farmers have exploitations of 3 to 5 ha, while 20% cultivate exploitations of 6 to 10 ha. Some 43%

of farmers cultivate family exploitation, while 28% rent their exploitations. The surveyed farmers ranged between 41 to 60 years of age.



(**a**) Agricultural sector (surveyed) (**b**) Number of hectares (% surveyed)

(**c**) Type of exploitation (% surveyed) (**d**) Percentage of farmers according to age

Figure 1. Farmers and exploitation's characteristics.

3.2. Level of Knowledge, Perceptions and Attitudes of Farmers towards Pesticides and Agroecological Practices

Farmers understood by agroecological practices those agricultural practices which are ecological and meet the daily demands of exploitation while enhancing the natural processes of crops' defense. They are environmentally friendly practices which maximize ecosystem services. It is also a symbiosis between profitability and sustainability. Agroecological practices are those that allow food to be produced without using pesticides from chemical synthesis, neither herbicides nor transgenics, maintaining the regenerative capacity of the soil (its fertility) and the ecosystem's biodiversity. Producing agroecologically is producing with care and respect, living together in harmony with the environment and its natural surroundings. On the other hand, the farmers most reluctant to change practices commented that using agroecological practices is simply going from having a conventional farm to an ecological one with agricultural practices following the regulations of the CCPAE, or even that it is a scam since producing this way would require more time and inputs to have pathogen-free plants. Furthermore, for those who do ornamental farming it is very difficult for them to carry out agroecological practices.

The level of knowledge that the farmers had about the aspects of agroecological practices, shown in Figure 2 were valued using a scale that goes from 1 (not informed) to 7 (very informed). The results show that farmers had a good level of knowledge about all aspects of agroecological practices. The aspects best known by farmers were the "cost of adopting agroecological practices", "Crop rotation", "crop diversification" and the general concept of "agroecological practices". The aspect that received the lowest valuation was "the production of agro-ecological products". Therefore, farmers need more information about the agroecological production system.

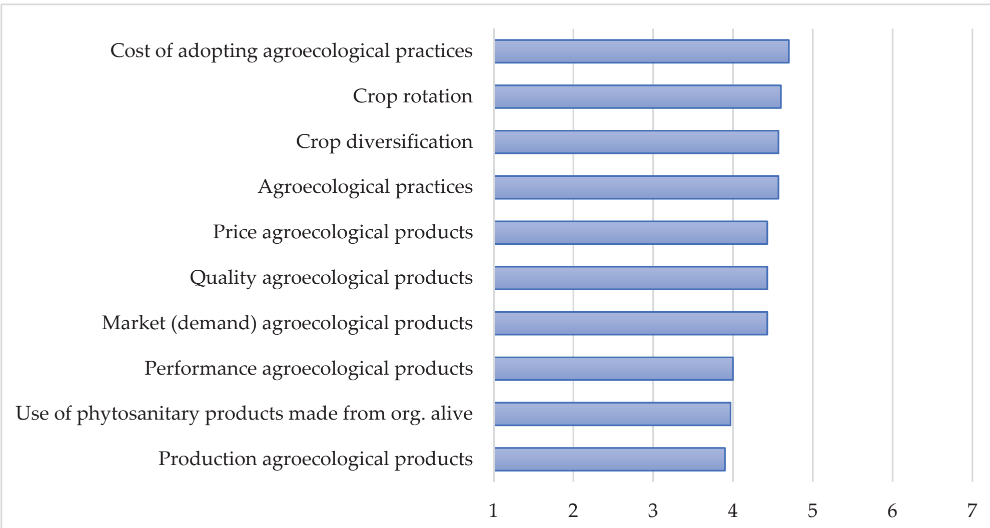


Figure 2. Scaled average according to the degree of knowledge about different aspects of agroecology.

53% of farmers had very little information on agrochemicals, 57% of farmers had very little information on the negative health effects of agrochemicals and, as Figure 3 shows, 83% of farmers affirmed that agrochemicals are a health risk.

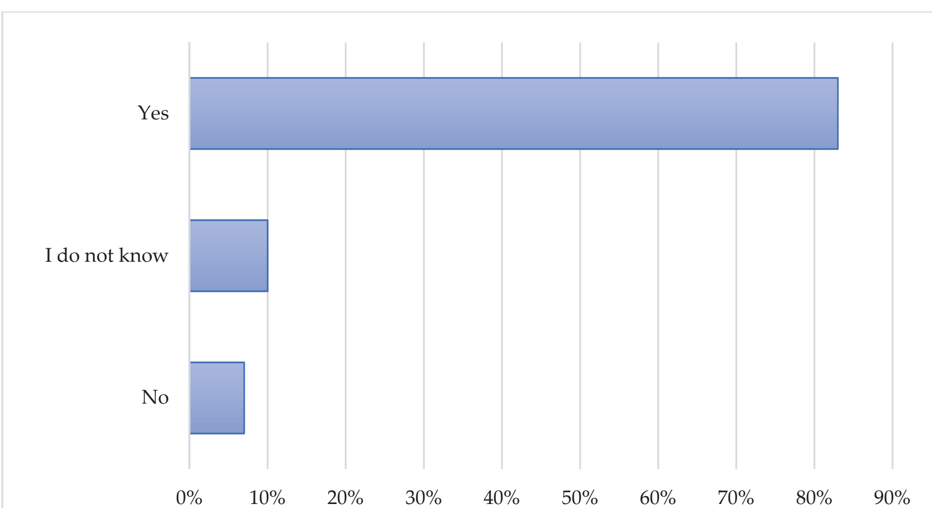


Figure 3. Percentage of farmers who affirm or deny that agrochemicals are a health risk.

In Figure 4 we can see how the media that offer farmers more information about the agrochemicals and their possible negative consequences on health are: 'agrochemical labels' with 28% of the respondents, 'Internet' with 25% and participation in 'Courses' with 17%.

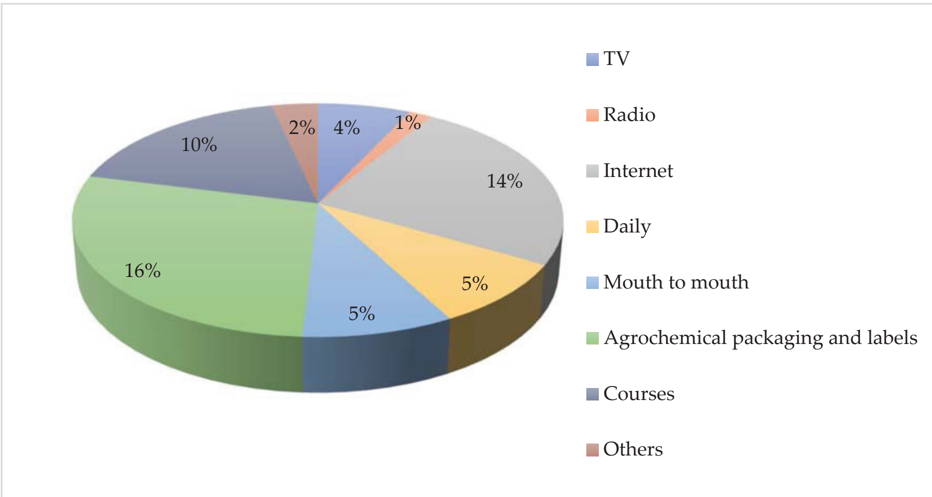


Figure 4. Percentage of farmers according to the communication medium observed.

3.3. Main Brakes, Accelerators and Perceptions in the Adoption of Agroecological Practices

In Figure 5 it can be seen that the most important brakes/barriers for farmers when it comes to adopting agroecological practices are: "Loss of producer income", "Lack of social awareness regarding the production of ecological products", "Low prices at origin and/or market", and "lack of agroecological training, technical and research advice". On the other hand, we have the less important barriers such as "low diversity organic products", "the economic situation does not allow to put agroecology into practice", and the "type of soil and relief of the farm". Thus, farmers tend to give more importance to those barriers that are more focused on the economic field (related to aid and payment for product), social (the ecological product or the production of organic products is not fully assimilated by the consumer), academic (lack of knowledge on the norms and use of ecological pesticides and advice by technicians) than those of an agronomic type (typology and soil relief, new varieties adapted to the conditions of the area, yields, etc.).

In reference to accelerators when adopting agroecological practices the most notable for the farmers were: to "Know experiences of other farmers", the "Rigor of legislation and product ecological standards" and a "favorable cultural environment to motivate the adoption of agroecological practices". Receiving the lowest rating was "Government Support (Grants)". Therefore, farmers demanded more rigorous exterior and interior policies in which the adoption of agroecological practices are favored. In addition, knowing the experiences of other farmers who practice organic farming is of vital importance since amongst themselves they understand each other much better than, for example, the administrators. Thus, exchanging experiences between groups of farmers in a specific area would facilitate the transfer of knowledge in agroecological matters, thus facilitating the adoption of these practices (Figure 6).

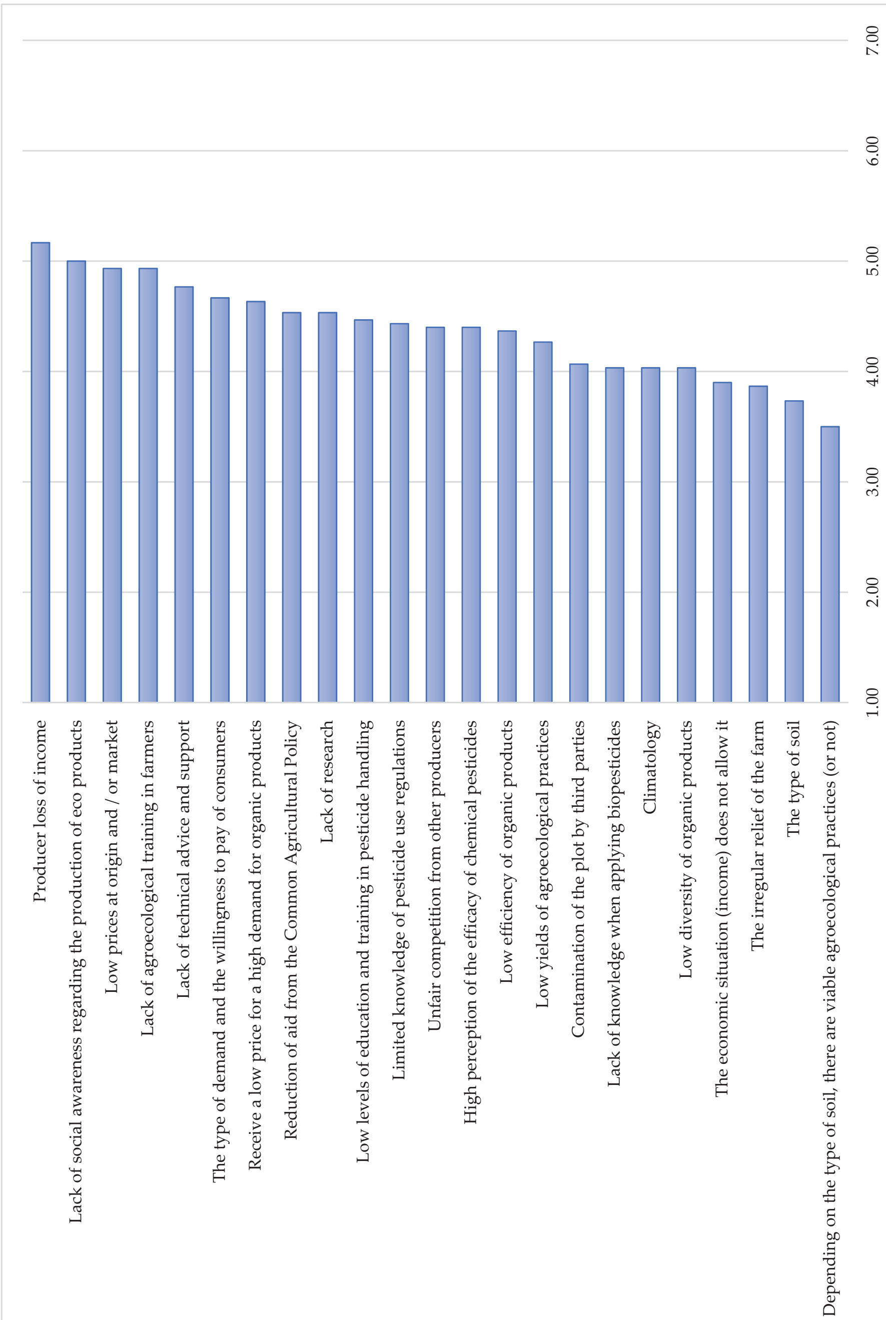


Figure 5. Average according to the different barriers when adopting (or not) agroecological practices.

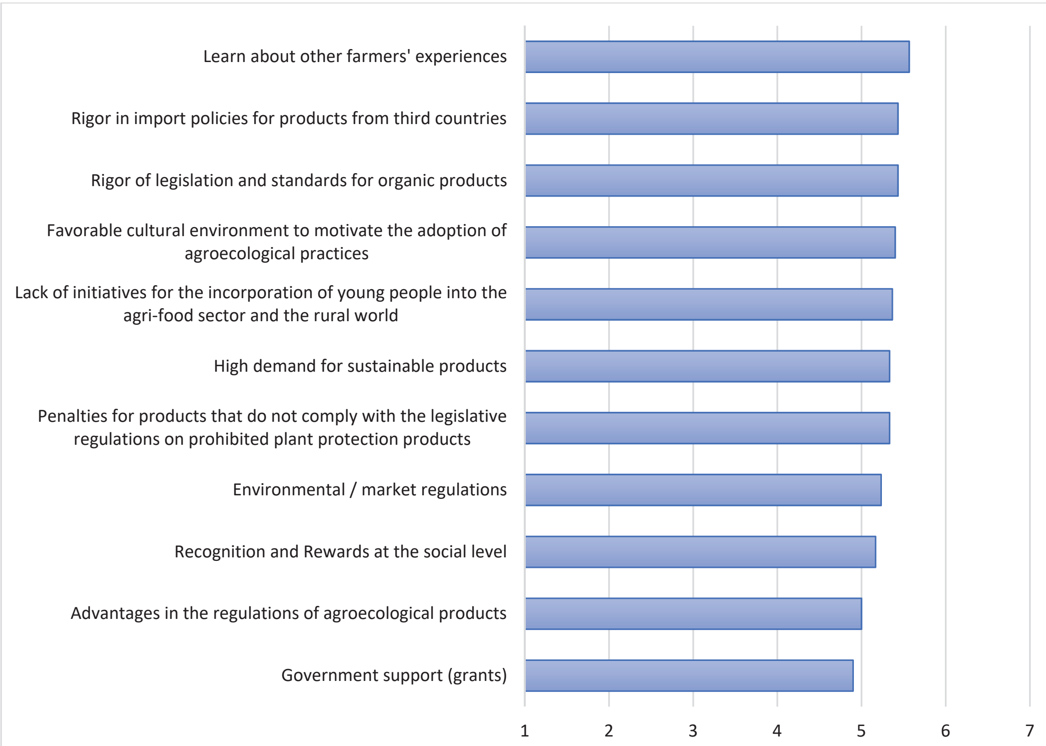


Figure 6. Scalar average according to the degree of importance of a series of factors on adoption of agroecological practices.

The benefits most perceived by farmers are "Agroecology reinforces the health and well-being of the soil, environment, producer and consumer", "Agroecology allows to protect and/or conserve ecosystems", "Agroecology reduces environmental deterioration" and "Agroecology incorporates ancestral values and knowledge of an avant-garde character". The aspects that received the lowest valuation were "Agroecology increases sovereignty of the farmer", "Agroecology allows the generation of medium-high benefits", "Agroecology eliminates hunger, poverty and negative consequences for the environment", "Government support" and "Agroecology empowers the farmer set the final price of the product". Therefore, farmers were clear that agroecology is not only based on the production of food without the use of synthetic chemical pesticides, but rather puts includes the value the ecosystem of the farm, that of its surroundings and that of the planet, thus contributing to the reduction of pollution and environmental deterioration. Besides, agroecology can be one of the agricultures of the future, with great weight in the development and research of new phytosanitary products of animal or natural origin for the control of pests and diseases. On the other hand, they did not see clearly that agroecology will allow them to have sovereignty over their products and ways of doing agriculture, or that it will be a practice that contributes to eradicating hunger in the world (Figure 7).

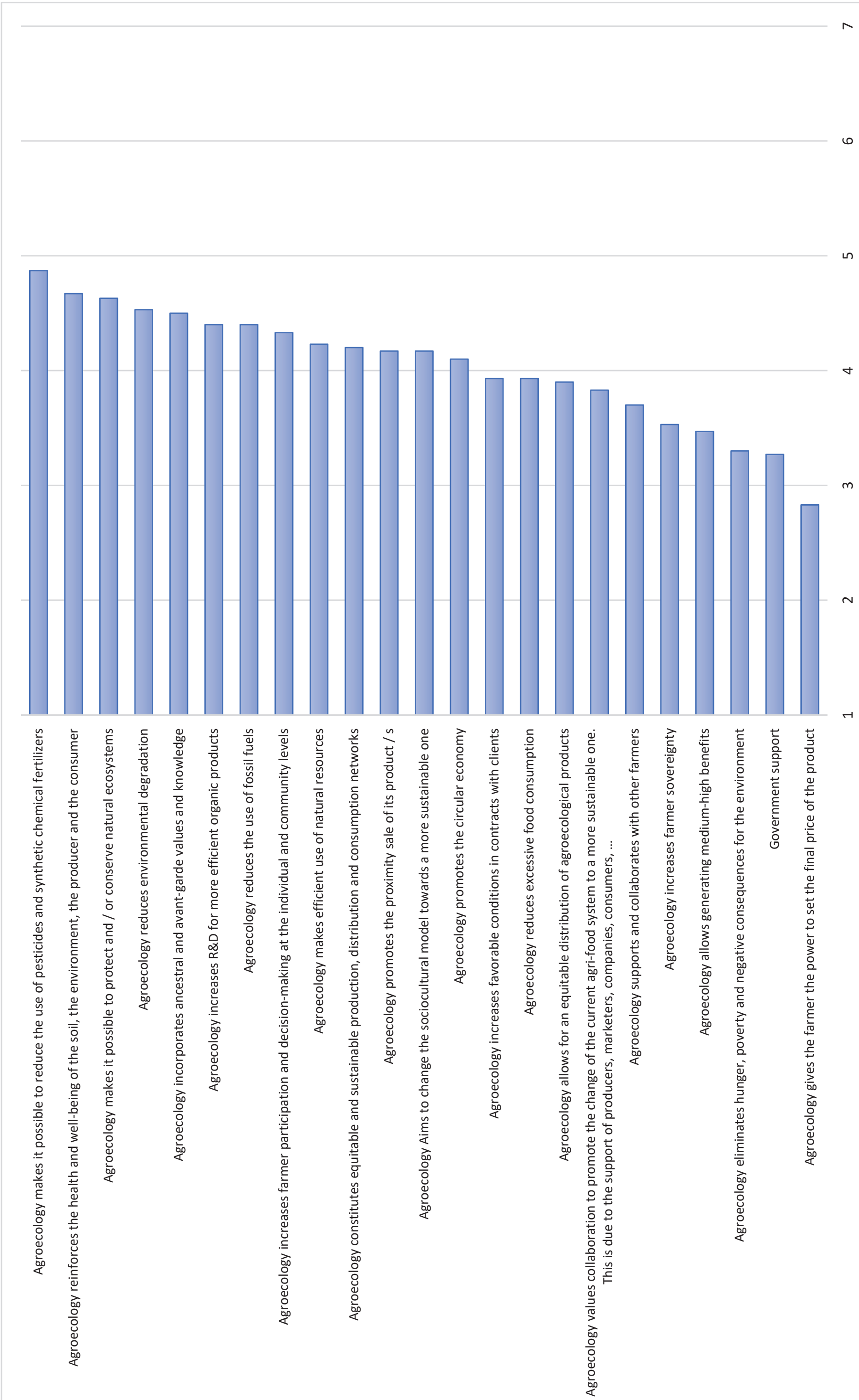


Figure 7. Scalar average according to the assessment of some statements related to agroecological practices.

3.4. Results Related to the Adoption of Agroecological Practices

The agroecological practices most adopted by farmers so far are "Organic fertilization", the "Reduction of the use of inputs harmful to the environment", "Conservation agriculture", "Biological control of pests", "Drip irrigation", "Split fertilization" and "Choice of crops and rotations". This is shown in Table 2.

Table 2. Number of farmers who have chosen each practice and number of practices who have chosen each of the farmers.

Practices	Number of Practices
Organic fertilization	19
Reduction in the use of inputs that are harmful to the environment	19
Conservation agriculture (soil protection through soil cover with plant remains from a previous crop, planting of plant covers, etc.)	18
Biological pest control	18
Drip Irrigation of Crops	17
Split fertilization	16
Choice of crops and rotations	14
Biofertilizer	13
Use of the soil's own organisms to promote the activity biological soil to increase crop yields and promote soil health	13
Create plant barriers around your crops, plots or the same farm	11
Polyculture; Diversification of cultivable species on the same farm	11
Production of organic fertilizers	12
Elimination of synthetic chemical pesticides	11
Choice of cultivars	10

With respect to the intention to adopt agroecological practices in the future, with an average adoption of 5.07, 40% show a high probability of adoption. In the short term, the most adopted practices will be: "Reduction of the use of inputs harmful to the environment", "Drip irrigation of crops", "Effective management of nutrients and biomass", and "Conservation Agriculture". In the medium term they will be the "Elimination of synthetic chemical pesticides", the "Choice of crops and rotations", the "Reduction of the use of inputs harmful to the environment" and "Tillage 0"; and, in the long term, the "Use of the soil's own organisms", the "Use of crops resistant to any stress", the "Use clean and efficient technologies", among others and will never be: "Agroforestry", "Tillage 0", "Divided fertilization", etc.

3.5. Profile of Potential Farmers Adopting Agroecological Practices in the Future

At this point, the variable "Intention to adopt agroecological practices in the future" was measured on a scale from 1 to 7, with the characteristics of the farmers and their farms. The graphs shown below were where the variable "intention to adopt" was statistically higher. Therefore, those farmers who had a higher intention to adopt agroecological practices in the future are those who engage in other types of sectors, that is, fruit and vegetable crops, extensive crops and vineyards as compared to horticultural and fruit crops (Figure 8), those who practice conventional and integrated agriculture compared to organic (Figure 9), those with a cultivable area of 11ha compared to those who have fewer ha (Figure 10), those who have more experience in the adoption of agroecological practices compared to those who have the least (Figure 11), those who have a lot of confidence in the different sources of information exposed in the questionnaire (Government, Producers, Associations or cooperatives of producers, Universities, Media (Newspapers, TV, radio), Neighboring producers or friends, Family, friends, colleagues, Social networks (Twitter, Facebook, etc.), and the EU) (Figure 12), those who have a lot of information with regard to agrochemicals compared to those who have little (Figure 13), and those who have a high concern for the health effects of agrochemicals (Figure 14).

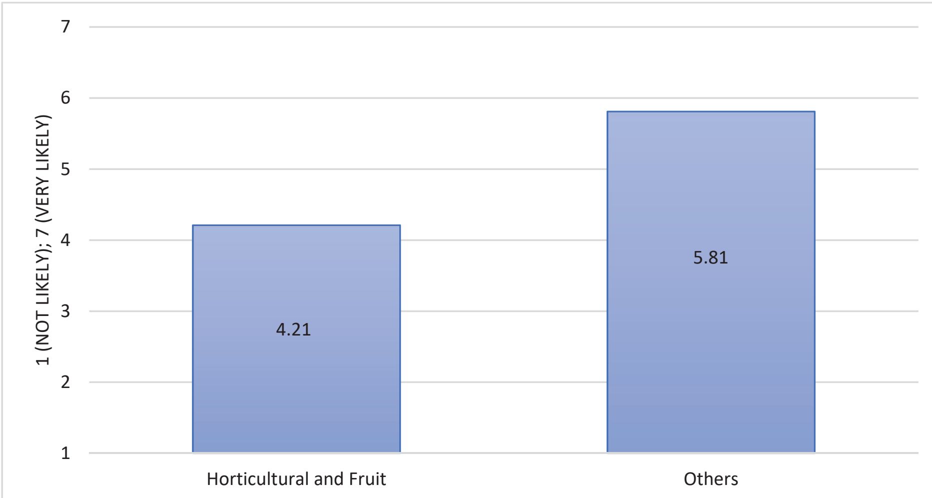


Figure 8. Probability of adopting agroecological practices depending on the sector that the farmers belong to.

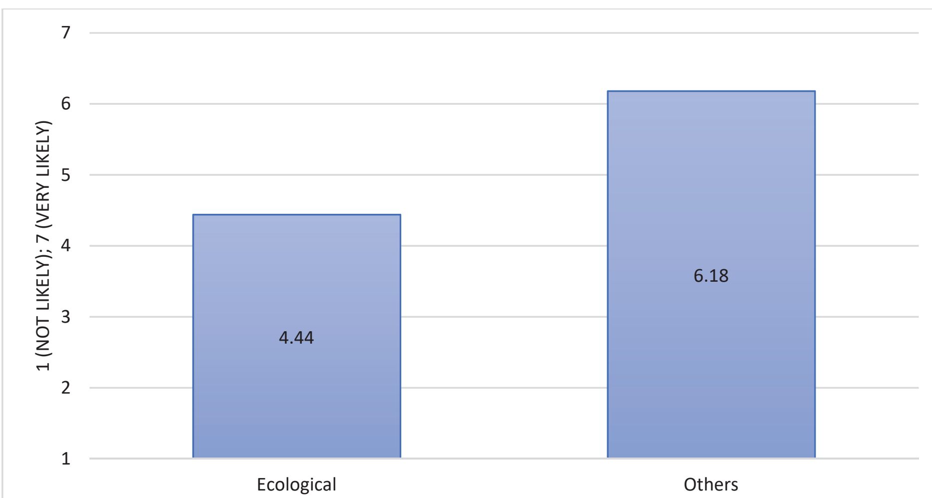


Figure 9. Probability of adopting agroecological practices in the future depending on the type of agriculture practiced by the farmers.

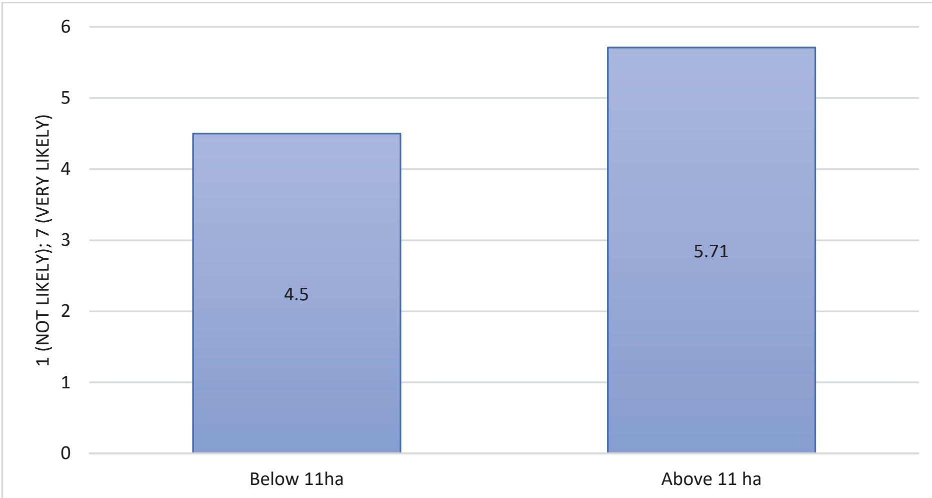


Figure 10. Probability of adopting agroecological practices in the future depending on the size of the farm.

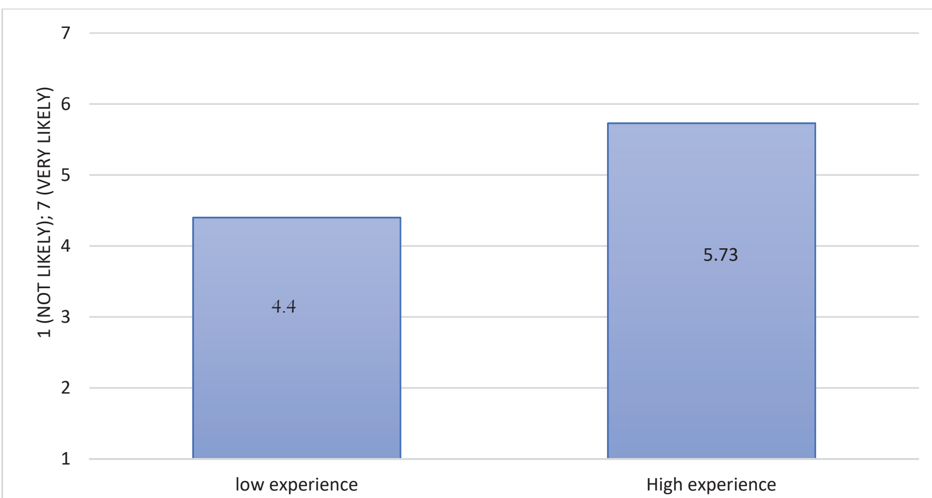


Figure 11. Probability of adopting agroecological practices in the future based on farmers' experience with agroecological practices.

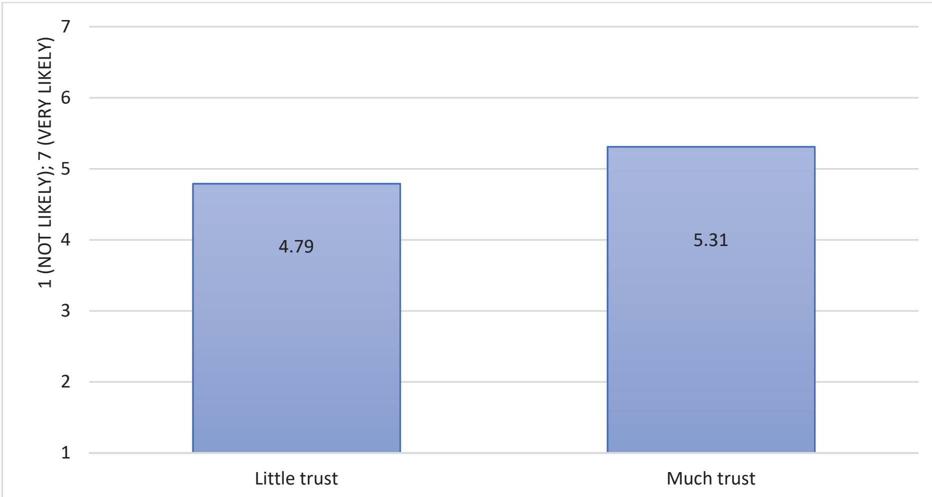


Figure 12. Probability of adopting agroecological practices in the future based on trust in information sources related to the adoption of agroecological practices.

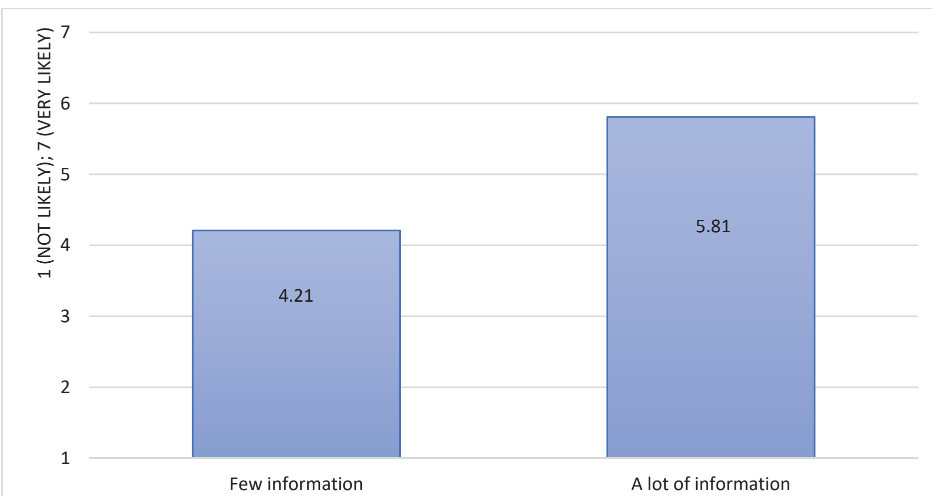


Figure 13. Probability of adopting agroecological practices in the future depending on the degree of information regarding the agrochemicals.

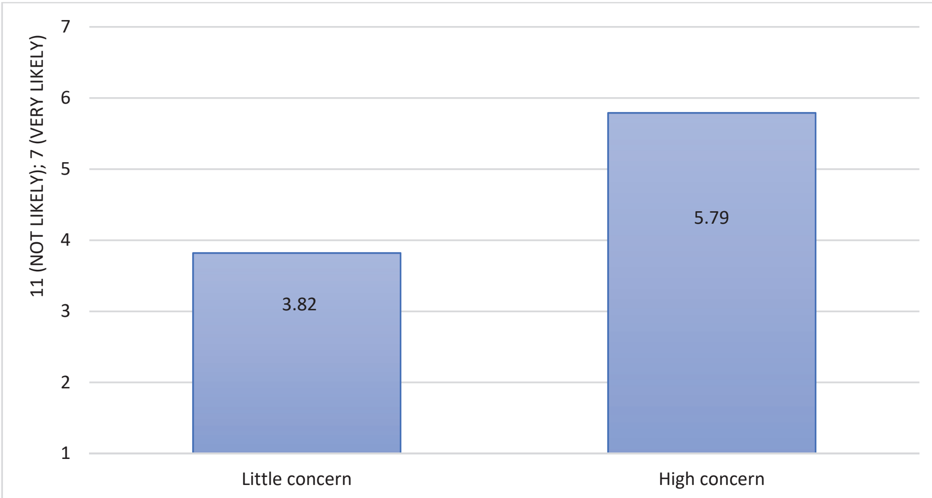


Figure 14. Probability of adopting agroecological practices in the future depending on degree of concern for the effects of agrochemicals.

4. Discussion

The results show that the main obstacles to the adoption of agroecological practices are focused on the economic sphere and are related to subsidies and low prices received for product at origin, coinciding with the results of other studies [11,14,19]. Other obstacles include social (organic products not fully assimilated by consumers), political (lack of attention on the part of institutions, as in [20]), academic (lack of knowledge of the norms around the use of ecological pesticides and access to advice by technicians that is essential to avoiding problems at the time of adoption [11,15,23]), and agronomic (typology and soil relief, new crop varieties not adapted to the conditions of the area, low yields of organic farming); all of these coincide with the results of other studies [14,20,24]. On the other hand, farmers do not see clearly that agroecology can allow them to have sovereignty over their products and ways of doing agriculture, or that its contribution is key to the eradication of hunger in the world. Horrillo et al. [12] showed that the production cost of ecological farms is high and highlighted the need for ecological farms to be compensated with subsidies for their contribution to territorial and biodiversity conservation and the provision of ecosystem services. Horrillo et al. [13] also reported that ecological livestock production is a sustainable model which benefits society by providing several ecosystem services, including carbon sequestration. They suggested that the imposition of a tax on CO_2 emissions will benefits ecological farms, improving their incomes.

Potential accelerators of the adoption of agroecological practices identified by farmers include the demand for more rigorous foreign and domestic policies in which they favor the adoption of such practices as good planning and policy management [14], and for the opportunity to learn about the experiences of other farmers who practice organic farming in specialized centers for the transfer of knowledge in agroecological matters. This, compared to the transfer of knowledge through public and/or private institutions, would guarantee greater successful adoption of agroecological practices due to the simple fact that there is greater trust among farmers. The lack of knowledge transfer is linked to the lack of stimulation to learn new agricultural practices [11,15,20].

The most adopted agroecological practices by farmers are: organic fertilization (reducing the use of inputs harmful to the environment), conservation agriculture, biological pest control, drip irrigation, divided fertilization (fertilization according to the demands of the crop and the growing period), choice of crops resistant to biotic and abiotic actions of the environment, and crop rotation. Other techniques adopted are cultivating according to the calendar and cycle moles, practicing solarization (a physical strategy to control soil pathogens), use of plastics to avoid water losses and reduce the use of herbicides, use of long-life boxes in the handling and sale of products, and the use of farm birds to combat pathogenic insects.

On a scale from 1 (Not at all likely) to 7 (Very likely), the intention to adopt agroecological practices in the future stands at an average of 5.07 points. Regarding the above, 60% of the farmers indicated a below average intention to adopt, which indicates that more than half are not considering adopting. However, the intentionality of adoption deepened for the choice of agroecological practices in the short, medium and long term. Therefore, the agroecological measures most adopted in the short term have been the reduction of the use of inputs that are harmful to the environment, drip irrigation of crops, effective nutrient and biomass management, and conservation agriculture; in the medium term, the elimination of synthetic chemical pesticides, the choice of resistant crops and rotations of crops, reducing the use of inputs harmful to the environment, and tillage 0; and, in the long term, taking advantage of the soil's own organisms, the use of stress-resistant crops, the use of clean and efficient technologies, and not depending 100% on external inputs from the farm.

Farmers, in general, have little confidence in the main sources of information on agroecological practices. The most prominent sources on the part of the farmers are "Family, friends, colleagues", other "producers" and "University".

The surveyed farmers who are dedicated to extensive crops, fruit and vegetables and integrated production have an intention to adopt agroecological practices in the future greater than those dedicated to horticulture and fruit culture. The same happens with conventional farmers and integrated production compared to ecological production; those with more than 11 arable hectares of land compared to those with less than 11 hectares; those who have already adopted more agroecological practices compared to those who have not; those who most trust the different sources of information on agroecological practices compared to those who least trust these sources of information; furthermore, farmers who feel highly informed about agrochemicals are more likely to adopt agroecological practices in the future (contrary to [9]), as are those very concerned about the negative effects of agrochemicals on the health compared to less concerned farmers.

The potential farmer adopting agroecological practices in the future can be described as: a farmer who is dedicated to the cultivation of cereals, fruits and vegetables and a practitioner of integrated production, with a background in conventional or integrated agriculture, who has more than 11 cultivable hectares, relies on different sources of information related to agroecology, has high experience with agroecological practices, and feels very informed about agrochemicals and very concerned about the negative effects they may have on both the health of the population and the environment. Parra López and Calatrava Requena [25] reported that compared to conventional growers, organic growers are younger, with a part-time dedication to agriculture, with less productive orchards, more involved in management and administration of the holding and more informed about organic agriculture. Läpple and Van Rensburg [26] showed that early adopters were the youngest to adopt organic farming. Djokoto et al. [27] found that being male, being from a smaller household and having access to credit was correlated with a tendency towards adopting organic cocoa production. According to Ashari et al. [28], the information and knowledge, economic and financial resources, technical and management skills, social aspects, environmental concern, institutional environment, and socio-economic and demographic characteristics of farmers are the key factors of organic farming adoption. Lohr and Salomonson [29] and Pietola and Lansink [30] demonstrated the role of subsidies in encouraging farmers to adopt organic conversion.

5. Conclusions

In general, farmers need to be provided with more information about the agroecological production system through means closer to them such as friends, other producers in the same sector, university trials in experimental fields and that these belong to an organic producer because this way it will serve as an example to gain a certain positive perspective for adopting agroecological practices.

On the other hand, there is no significant difference in the intention to adopt agroecological practices in the future among the farmers who have been working in the agricultural sector for more than 20 years and those who have been working in the agricultural sector for less than 20 years, among the farmers who have family or rental farms and those who have concession and/or purchase farms, among those who have indicated a greater number of barriers to the adoption of agroecological practices and those that have indicated a lower number of barriers, among farmers who perceive many benefits of adopting agroecological practices in the future and those who do not perceive or perceive few benefits, among risk-disliking farmers and risk-takers, among highly productive farmers environment and those who are not so protective of the environment, among farmers whose age is higher than the average age of the sample (48 years) and farmers whose age is lower than the mean age of the sample, and there is no difference in the intention to adopt agroecological practices in the future among men and women; nor among those who say that agriculture is or is not the only source of income their household receives. There is also no significant difference in the intention to adopt agroecological practices among those with university and secondary education and those with primary or simple studies.

With all the data collection, the profile of the potential farmer adopting agroecological practices in the future can be described as: farmer who dedicates to the cultivation of cereals, fruits and vegetables and a practitioner of integrated production, from conventional and integrated agriculture, who has more than 11 cultivable hectares, relies on different sources of information that provide information related to agroecology, with high experience with agroecological practices, feels very informed about agrochemicals and very concerned about the negative effects they may have on both the health of the population and the environment.

Producing in an ecological way implies higher production cost which forces farmers to sell the resulting product at higher prices than conventional ones. Consumers interest in organic products in increasing, however, the prices are a barrier. So, policymakers should support economically farmers paying them for the ecosystem services they provide to society. Our findings are in line with the theory. Farmers' knowledge and familiarity with the agroecological practices should be increase through informative campaigns; training and education. Farmers' access to technologies innovations should be guaranted. Consumers' awareness and knowledge should be also improved.

The present study is an exploratory study where a small sample size of farmers was used. This is the main limitation of this study. Future research should use the findings of the present study as a basis for more extended studies with a large and representative samples. Future research should also extend the research to more sectors. It will be interesting to estimate a model based on the Theory of Planned Behavior to better explain farmers' intention to adopt agroecological practices.

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Food Waste Behaviour at the Consumer Level: Pilot Study on Czech Private Households

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Abstract: The issue of food waste is a problem that affects the whole society. Food is wasted throughout the food chain. Households are great contributors to the problem. A detailed analysis of municipal waste from the production of 900 Czech households was performed. These datasets allowed for comprehensive insides. The analyses of mixed municipal waste were performed every quarter of the year (summer 2019–spring 2020). The method of municipal waste analysis was supplemented by questionnaire survey among households and 10 in-depth interviews aimed at identifying the main causes of waste. One of the periods in which food waste was measured was affected by the global COVID-19 pandemic. This finding has also been confirmed by findings from other countries. The climatic crisis multiplied by the impacts of COVID-19 has highlighted the need to actively address the issue of food waste.

Keywords: food waste; consumer behaviour; households; waste composition analysis

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1. Introduction

Food waste is a phenomenon with significant economic and, most importantly, social consequences. The inefficient end-use of food wasting creates significant environmental demands [1,2]. The amount of wasted food has been increasing over a time period [3] and it is estimated that one third of food produced for human consumption is lost or wasted [4–6].

Food is wasted throughout the food chain—from primary production, food processing, and production, through wholesale and retail to catering facilities and households. There are significant differences in the volume of waste and the end part of the food chain—households—are the most significant sources of food waste throughout the entire food chain [7–17]. According to Beretta et al. [18], the waste that is considered the most avoidable food waste is generated at the household level. Here, "avoidable" means food waste that can be prevented and that has the greatest potential in terms of possible reduction. According to a definition by the European Commission [19], food waste can be any food that: (1) entered the food supply chain, (2) was removed or disposed of from the food supply chain or consumed as waste, (3) was destined for treatment as waste. Thus, food waste may include edible food, as well as food that was not intended to be eaten, i.e., inedible food.

Although many authors agree that households contribute significantly to food waste, there are no detailed household-level data available to our knowledge in the Czech Republic nor within the EU that would systematically monitor waste production at the end of the food chain, for example, the FUSIONS study [20] has shown that the structure and the level of detail of EUROSTAT data are not sufficient for monitoring and evaluation purposes. Differences in household food waste estimates are caused by inconsistent methodologies [21,22]. This inconsistency results in that different numbers of food waste can be found in different sources, e.g., according to Food waste—causes, impacts, and proposals study [23], in Denmark food waste is estimated at 118 kg per person per year, in France 144 kg, in Luxembourg 207 kg, and in Sweden 227 kg. The households' contribution of food waste is 42%, according to this study. There are other studies, e.g., Preparatory study on food waste across EU27 [21], which states 7 kg per capita per year of household food waste in Denmark, 133 kg in Luxemburg, 47 kg in France, and 43 kg in Sweden [23], but if we compare this number with another study, different numbers are available: according to Naturvårdsverket [24], the amount of food wasted by Swedish households was 100 kg per person per year. Despite these differences, it is stated that European consumers, who have different shopping and cultural habits than American and Asian consumers [4] waste on average 76 kg of food per person per year [9].

The lack of relevant comparable data of household food waste led the authors to conduct an extensive survey among Czech households. The primary aim was to map in detail the structure and actual amount of food waste produced by households. The effort to obtain the most accurate picture of the volume of wasted food in households led to the implementation of a survey among a large sample of households. Data on food waste volumes were obtained by analysing municipal waste produced by a sample of 900 households. To capture possible seasonal fluctuations in food waste and monitor the possible impact of types of residential housing on the amount of food waste, the analysis of municipal waste was performed in three types of residential housing developments throughout the year; the authors analysed dustbin contents in quarterly intervals for one year. Given the fact that the Czech Republic was affected by the COVID-19 pandemic in the monitored period, the authors were also able to compare household food waste volumes before and during the first wave of the pandemic.

Although the primary aim of the research was to determine food waste volumes through waste analyses, the analyses were supplemented by an extensive household questionnaire survey on the causes of food waste. The purpose was to identify the causes of wasting and, thus, outline how to motivate households to reduce their waste. In-depth interviews were also conducted to identify in detail the causes and facts affecting food waste.

The goal of the study is to give exact numbers on food waste generated by Czech households, find out what the main causes of food waste are, and show whether the volume of the food waste is affected by the place where the household is located, and whether the volume of food waste is affected by the season—whether it is possible to observe seasonal effects. The findings were supposed to reveal how consumers behave in terms of food management and waste production.

Based on the goals, it is possible to define the main research questions of this study:

- What is the average volume of food waste generated by Czech private households per person per year?
- How does food waste amount change during the seasons in the observed year?
- Does the place where the household is located affect the volume of food waste?
- What are the main causes of food waste in Czech households?

2. Theoretical Background

Food waste can be analysed from various angles—ethical, economic, and environmental [25]. According to Swedish Environmental Research Institute [19], the majority of food waste is produced by households; this implies that end parts of the food chain are the most significant sources of waste. Kummu et al. [3], Griffin et al. [1], Gooch and Felfel [15], Parfitt et al. [2], and other authors agree with this statement and provide data that even in the US [7,26], in Canada [15], in Australia [27,28], or in other developed countries [8,29], the most food waste is produced by households.

However, gastronomic establishments are also a significant source of food waste as consumer decisions play a significant role here (the “plate waste” phenomenon—see Engström and Carlsson-Kanyama [30]). Many studies, such as FUSIONS [31], also point out that households are the riskiest parts of the food chain in terms of a possible waste increase. Although the UK Waste Reduction Initiative [32] led to a 14% drop in household food waste between 2007 and 2010, the same study shows that very little progress has been made in recent years. Evans [33] says that most people feel bad about wasting food and consider food waste an undesirable phenomenon, which leads to the question why the rates are so high.

Food waste-related behaviour is a relatively common topic in scientific studies. For example, Herath and Felfel [34] have been looking into possible links between food properties (influencing purchasing decisions) and waste-related behaviour. At the same time, consumers with better food and nutritional awareness tend to waste less food. Wasting itself does not have to result from purely rational behaviour, because it bears high economic costs—WRAP report [32] states that the cost of waste for households in the UK is about 15% of overall food cost, Buzby and Hyman [35] estimate that the cost of food waste exceeds USD 900 per household per year.

Herath and Felfel [34] emphasize that despite the growing interest in the issue, there is still a lack of empirical studies. Primary research based on direct food-waste measurement and objective data collection is still rather rare. Several different methodologies have been used to measure the amount of food waste, but all of them have certain drawbacks—see Thyberg and Tonjes [36] in Ilakovac et al. [14]. Grainger et al. [37] state that given the high cost of measuring household food waste, the conclusions of most studies have been based on questionnaire-based self-assessments by households. A good example of data collection based on diaries is Herzberg et al. [38], where authors collected dataset on household food waste in Germany based on a diary study, or Van Der Werf et al. [39] who present a four-season waste characterization study, which adopted a Pay as You Throw system. Giordano [40] points out the fact that, for example, in the years 2020–2021, it is possible to find ten studies dealing with food waste issues, but that most of them are based on questionnaires and come mostly from so called Global North countries. Primary research based on direct food-waste measurement and objective data collection is still rather rare. Next to attempts to quantify food waste, researchers also focus on causes leading to food waste production—see, for example [8,16,41–44].

Parfitt et al. [8] analysed various case studies on household food waste and identified several factors that may affect the amount of food waste. One of the main factors is the size and composition of the family (these findings have been supported by, for example [14,33,43,45]. According to Parfitt et al. [8], and Richter and Bokelmann [46], another factor is household members' ages, younger family members waste more than older ones. Ilakovac et al. [14] also concluded that older people tend to waste less food and this finding has also been confirmed by Stancu et al. [47]. Przezbórska-Skobiej and Wiza [48] also, in their study, showed that young people declare to waste more food than older people, this can also be found in studies [49,50]. Other factors influencing household food waste include household income (low-income households waste less food—see also Baker et al. [51], Stancu et al. [47] or Ilakovac et al. [14]), the sex of the family member doing the shopping (some research [52] also indicate that females show higher motivation in preventing food waste), and the frequency of discounted product purchases [45,53]). Bozdağ and Çakiroğlu [54] point out that many studies state that women generate more food waste than men; there are also some studies showing that men generate more food waste [55,56].

Stefan et al. [57] pointed out the importance of shopping habits in terms of food waste and emphasize the perceived degree of ability to influence the result (perceived control). Moreover, Krisjanti, Quinta [52] draw attention to the fact that food waste behaviour problems come from the food shopping behaviour; according to them, people tend to buy more food products than they need. Ammann [58] also points to studies [41,59] that prove that those who regularly buy too much food out of habit, or who tend to buy discounted products, tend to waste more food. Lebersorger and Schneider [60] examined the relationship between food waste and other factors, such as settlement structure (countryside or city), type of housing (single or multi-apartment houses), and distance to the nearest bio-waste sorting bins. The results of a case study by these authors showed a higher rate of food waste production in cities compared to villages, and in multi-apartment houses compared to single-apartment houses. Bozdağ and Çakiroğlu [54] point to the fact that their study showed a significant negative association between the amount of food waste in households and age or living place. Neff et al. [42] presents in their study that living in urban or rural areas does not have a significant impact on generating food waste. Richter and Bokelmann [46] and Tokareva [53] found in their research that households that wasted less were those of families living in villages. Research on household food waste also looks at what type of food is wasted most. The most significant source of food waste is perishable food, mostly fresh fruit and vegetables, bread, dairy products, meat and fish [8]. Food waste production is often related to household consumption behaviour, based on research on food waste at the retail and consumer level. Buzby and Hyman [35] identified three basic food groups that are wasted the most: meat, vegetables, and dairy products. Bozdağ and Çakiroğlu [54] state that most wasted food categories vary by country—e.g., home-made foods and milk products in Finland [61]; bakery products in Norway [62]; fresh vegetables and salads in England [32]; or pasta, fast food, previously-cooked meals, vegetables, fruits, and bread in Italy [63,64]. According to Bozdağ and Çakiroğlu [54], the different food cultures may explain the reason for the differences in food waste.

It is clear from the available studies that food waste is influenced by the number of socio-economic and behaviour factors; therefore, this study focuses not only on finding out the amount of food wasted in Czech households but also on finding out these key factors and causes of waste.

3. Materials and Methods

In this study, the authors adopted a concept defining food waste as disposed of edible food. This food waste does not contain cuttings, skins, bones, and other parts seen as a necessary waste. Another term used in the article is biological waste or bio-waste. The term encompasses kitchen waste of plant and animal origin, beverage residues, household waste (e.g., house plants and their residues, animal feed of plant origin, pet beddings, etc.) and garden plant waste (grass, leaves, branches, etc.). A detailed structure of bio-waste, as used in the study, is shown below.

Studies [32,39,65,66] show that subjective estimates of how many households waste food differ from objective data. Therefore, the authors decided to combine objective and subjective data. For a holistic view of food waste in households, it was necessary not only to find out the real amount of wasted food but also to discover what motives lead to waste. Therefore, the authors proceeded to the triangulation of methods.

For the study were used three methods: mixed municipal waste analysis, quantitative research in the form of a questionnaire survey, which was followed by a deeper explanation of the causes of waste in households by in-depth interviews. Many papers [42,46,53,54,67] confirm that the volume of wasted food varies depending on where households are located. Therefore, the waste analysis was divided into three specific locations—rural built-up areas, single family development and housing estates. The analysis of municipal waste was performed four times a year, in each season, in order to eliminate the effect of seasonality on the volume of food waste in households (the effect of seasonality is confirmed e.g., in [68]).

To capture possible differences in food waste in different types of residential housing, three types of residential housing developments were distinguished in the research:

1. Rural built-up areas consisting mainly of households living in family houses with local heating by solid fuels. Such households have better access to waste incineration in domestic fireplaces. They also have the possibility of garden composting their biological waste or feeding it to domestic animals. In this type of development, the share of service facilities and small trade establishments is insignificant.
2. Single-family developments, i.e., urban residential areas with floor or local heating by gas or electricity. These dwellings have also access to garden composting of biological waste. Heating with solid fuels is negligible. The share of service facilities and small trade establishments is insignificant.

3. Housing estates, i.e., apartment buildings with centralized heat supply. These dwellings have no possibility of utilising their waste. The share of service facilities and small trade establishments is insignificant.

The research was based on collections and analyses of waste produced by about 300 households from each of the above-mentioned housing developments. From each type of development, three different localities were selected in the city of Brno and its surroundings, where the waste was collected and subsequently analysed together, from 100 households from each locality separately. Thus, in total, waste from 900 households was analysed. The authors used secondary data on the permanent residence of persons living along the analysed collection routes (the data were obtained from the municipal office in Brno) and determined the amounts of waste per person.

3.1. Objective Waste Measurement—The Mixed Municipal Waste Analyses

The mixed municipal waste analyses took place in the city of Brno and the surrounding areas. The waste produced in each type of development was analysed separately. The composition of mixed municipal waste was determined through sub-sample analyses (a sub-sample accounted for about 200 kg of waste). The quaternation method was employed for sample collection. When using the quaternation method, the sample (each sample was collected from 100 households from one type of development) is divided into four equal piles, while two opposite piles are removed, and the remaining piles are mixed and divided into four equal piles again. This procedure is repeated until a representative sample weighing about 200 kg is obtained [69]. This representative sub-sample for the given housing development type is then examined in detail. Waste composition was determined by sieve analysis and manual sorting into predetermined substance groups (see below). 40 mm $\times$ 40 mm mesh-size sieves were used for the sieve analysis. The sub-sieve fraction was further divided into wasted food and other waste (therefore, in the sub-sieve fraction, waste components were not sorted in detail, see Table 1). Subsequently, the authors determined the real amount of food wasted in the given type of housing development.

Collections and analyses of mixed municipal waste (MMW) were carried out in each season (spring, summer, autumn, winter) so that the authors could assess the seasonality of food waste production. The seasonality perspective of the research corresponds to changes in the basic characteristics of waste—for example, changes between heating and non-heating seasons, changes reflecting the summer holiday period, or changes in vegetation conditions. Specifically, waste collected in the summer of 2019, autumn 2019, winter 2020, and spring 2020 has been analysed. The COVID-19 pandemic affected only one analysis—the one carried out in the spring of 2020 when the COVID-19 pandemic broke out in the Czech Republic.

Data on mixed municipal waste were classified into the following substance categories: paper/cardboard, plastics, glass, metals, textiles, mineral waste (e.g., porcelain, bricks, rubble), hazardous waste (e.g., medicines, batteries, protective equipment against COVID-19), electrical waste, combustible waste (e.g., nappies, tissues, etc.), and biological waste. The table below lists biological waste categories distinguished within municipal waste analyses.

Quantitative data on food waste obtained from MMW analyses were processed using basic statistical methods, such as absolute and relative frequencies or averages.

Table 1. Biological waste structure.

Food Category	Specific Foods
Kitchen waste of vegetable origin	
Fruits and vegetables	potatoes and other vegetables, fruits, and mushrooms for consumption or in the state of decomposition
Bakery products and their leftovers	bread, buns, baguettes, cakes, pies, and other baked and confectionery products, including their leftovers
Packaged ready meals of plant origin	ready meals (e.g., cooked vegetables, meatless soups) intended for immediate consumption, including packaging (food boxes)
Packaged foods of plant origin, including packaging	packaged (intact) food products: flour, sugar, legumes (uncooked), coffee, tea, cocoa, dried fruits, yeast, uncooked pasta, compotes, pickled vegetables, oil, vinegar, purées, dressings, honey, and salt, all including packaging
Ready meals of plant origin without packaging	prepared (cooked) meals (e.g., cooked vegetables) intended for immediate consumption
Foods of plant origin without packaging	food products completely or mostly without packaging, cereal products, sugar, legumes (uncooked), coffee, cocoa tea, dried fruits, yeast, pasta in the dry state (except bread), honey, and salt
Necessary waste	shells, nutshells, coffee grounds, coffee machine capsules, tea bags, citrus slices used in beverages (e.g., tea), used vegetable oils (including containers)
Kitchen waste of animal origin	
Ready meals of animal origin, including packaging	ready meals (cooked) intended for immediate consumption, including packaging (food boxes)
Packaged foods of animal origin, including packaging	packaged (intact) food products from animal tissues (e.g., sausages), all including packaging
Packed meat and eggs	raw meat (including fish and seafood), raw eggs, all including packaging
Packaged dairy products	cheese, yoghurt, and other dairy products, all including packaging
Ready meals of animal origin without packaging	ready meals (cooked) intended for immediate consumption, completely or mostly without packaging
Foods of animal origin without packaging	food products from animal tissues (e.g., sausages), completely or mostly without packaging
Meat and eggs without packaging	raw meat (including fish and seafood), raw eggs, completely or mostly without packaging
Unpacked dairy products	cheese and other dairy products, completely or mostly without packaging
Necessary waste	inedible animal tissues, fats, bones, casings of animal origin, eggshells, used animal oils (including containers)
Leftover drinks	
Leftover drinks	leftovers non-alcoholic and alcoholic beverages (weight without packaging—weight of packaging is deducted in the final balance)
Household waste	
Household waste of plant origin	house plants and their residues, animal feed of plant origin
Household waste of animal origin	litter of domestic animals, including excrement, animal feed of animal origin
Garden waste of plant origin	
Garden waste of plant origin	grass, leaves, plant tissue residues including wood (parts of trunks, branches)

3.2. Quantitative Research—Questionnaire Survey

In January 2020, the authors performed an electronic questionnaire survey to obtain subjective data on food waste. On the basis of the studies [22,50,70], a questionnaire was formulated, the main aim of which was to reveal the causes and the reason for wasting food in households. The authors decided to do the survey mainly because the MMW analyses did not capture links to the subjects producing the waste, nor did they reveal the reasons why food was wasted. It helped to find out what are the main causes of food waste in Czech private households and to answer a previously determined qualitative research question "What are the main causes of food waste in Czech private households?". As mentioned above, the level of waste can be significantly affected by household income, the number of households members, members' age, or the frequency of shopping. These data could be gathered through a questionnaire survey. Based on established research questions and findings obtained from the literary survey, the authors determined the set of following statistical hypothesis.

Analyses of waste showed certain differences in biological waste compositions and in food waste amounts depending on the type of development the respondents lived in. Tokareva et al. [53] comment on this in their study. Specifically, these authors talk about different attitudes of people in rural areas who live "closer" to food, often because they grow their crops. Similar observations were presented by Sosna et al. [67]. Therefore, the logical step was to verify whether the questionnaire survey results would also support this assumption:

Hypothesis 1a (H1a). *The amounts of food wasted by households living in a housing estate, a family house, a single-family development, or a rural-area family house differ.*

Previous research [8] suggests that the more often households make larger purchases, the greater the risk of food being wasted because the family does not have time to consume it. Therefore, the authors set the following hypothesis:

Hypothesis 2a (H2a). *There is relationship between the frequency of large purchases of food and the amounts of food waste.*

Food waste production is also affected by household income [8,14,47,51]; it comes as no big surprise that the higher the household income, the higher subjective estimates of food waste.

Hypothesis 3a (H3a). *There is relationship between the net monthly income and the amounts of food waste.*

It can also be assumed that with the growing number of household members the demands on food management increase and, thus, estimating the right amounts of food purchases becomes more difficult [46,47].

Hypothesis 4a (H4a). *There is relationship between the number of household members and the amounts of food waste.*

The generational difference is also a frequently discussed factor influencing food waste levels. Very often you can hear or read that younger people waste more [14,47]. The authors have also addressed this factor in their research. The following hypothesis was tested:

Hypothesis 5a (H5a). *The amount of wasted food varies depending on (the respondent's) age.*

Lebersorger and Schneider [60], Bozdağ and Çakiroğlu [54], Richter and Bokelmann [46] stated the influence of the place where the household lives on the volume of wasted food in their studies. Based on this, the last hypothesis was formulated.

Hypothesis 6a (H6a). *There are differences in the causes of food waste between different types of housing developments.*

Moreover, in a questionnaire survey, subjective data on perceived amounts of food waste (subjective estimates) can be obtained. Such data provide a comparative basis for the results of objective food waste analyses. This provides a deeper insight into the difference between the perceived and the objective amount of wasted food.

Due to the pandemic situation, the questionnaire was disseminated only in electronic form through the social network, and it was targeted at various city districts in Brno. The research team, thus, had to abandon the semi-structured interview conducted by the interviewer, which was intended, and the selection of respondents is conceived as a random selection. The questionnaires were fully completed by 395 respondents (households living in Brno) classified into the three housing development types described above. It should be noted that the questionnaire survey was not conducted in those specific households where the waste analysis was performed. The respondents were residents of the city of Brno and surrounding areas. The average Czech household has 2.43 members [71].

The basic characteristics of the questionnaire's respondents are shown in the overview Table 2.

Table 2. Basic characteristics of respondents.

Basic Characteristics of Respondents/Households	Questionnaires (*n* = 395) Absolute Freq.	Relative Freq.	Interviews (*n* = 10) Absolute Freq.	Relative Freq.
Gender of respondent				
Female	299	75.7%	6	60.0%
Male	96	24.3%	4	40.0%
Age category of respondent				
18 to 29 years	191	48.4%	3	30.0%
30 to 49 years	150	38.0%	4	40.0%
50 to 64 years	40	10.1%	2	20.0%
65 and more	14	3.5%	1	10.0%
Residence—type of housing development				
Housing estate	268	67.85%	5	50.0%
Family house—single-family development	97	24.56%	2	20.0%
Family house—rural development	30	7.59%	3	30.0%
Number of household members				
1	61	15.4%		
2	171	43.3%		
3	69	17.5%		
4	72	18.2%		
5 or more members	22	5.6%		
Net monthly household income				
less than CZK 30,000	108	27.3%		
CZK 30,001 to 45,000	115	29.1%		
CZK 45,001 to 60,000	82	20.8%		
CZK 60,001 to 75,000	37	9.4%		
more than CZK 75,000	53	13.4%		

The data obtained by the questionnaire survey were used for the statistical testing of research hypotheses. The authors employed the Kruskal–Wallis test for testing the hypothesis of distribution congruence between multiple independent samples (Hypothesis 1b, Hypothesis 5b). This test is suitable for ordinal quantities that do not have a normal distribution. Other hypotheses were tested by Spearman's coefficient of ordinal correlation. The coefficient is used for testing the dependence of ordinal characteristics. This test was employed for testing the Hypothesis 2b, Hypothesis 3b, and Hypothesis 4b [72].

3.3. Qualitative Research—In-Depth Interviews

As said above, only one of the MMW data collections (spring 2020) was affected by the pandemic. Therefore, to understand the deeper context of waste production, food management, and food waste in these specific conditions, the authors conducted in-depth interviews with respondents from different types of households. Fourteen people were contacted, and 10 agreed to participate in an interview. The basic characteristics of the interview's respondents are shown in the overview Table 2 above. The questions were determined based on the quantitative survey, to further clarify the causes and reasons for the findings of the questionnaire survey. During the interview, questions related to the respondent's behaviour, perceptions, and opinions were asked. The answers revealed how the households behaved during the pandemic and enabled the authors to assess the most significant changes.

4. Results

The presented research is unique, especially in the way it enables comparisons of subjective and objective data. The research aimed to reveal the actual amounts of food that end up in mixed waste. The subjects were anonymous and did not know about the measurements of food they threw away. This eliminated the risk of distortion of data. Simultaneously with the experiment, the authors have also conducted a quantitative questionnaire survey to clarify the causes of waste and the ways households manage their food. The survey also aimed at identifying people's willingness to address the issue of food waste, as well as finding appropriate support channels in the fight against waste. Based on the findings, the authors could compare whether the actual amounts (measurements) and reported amounts (questionnaires) of food waste corresponded. The qualitative data obtained through in-depth interviews helped the authors to understand the food waste behaviour in more detail.

4.1. *Objective Quantities—Actual Amounts of Food in Municipal Waste*

As was mentioned above, the experiment included 900 households from three selected types of housing developments, namely housing estates and single-family and rural developments. There were approximately 300 households from each type of development, where the analysis of mixed municipal waste was performed (see Figure 1).

(**a**)

(**b**)

Figure 1. Analysis of waste structure; (**a**) Manual waste sorting; (**b**) Quaternation method.

4.1.1. Individual Types of Housing Developments—Waste Quantities

The average amount of mixed municipal waste was 217.1 kg per person per year, of which 105.9 kg (49.0%) was biological waste. Most biological waste per person was produced in rural developments—121.6 kg per person per year (51.32% of mixed municipal waste). In housing developments, the biological component of waste accounted only for 45.3% of the total amount of waste (99.33 kg per person per year). However, a detailed look at the biological waste composition in rural and single-family developments shows that there was a significant portion of garden plant waste such as grass, branches, sawdust, leaves, etc., rather than food intended for consumption—see Figure 2. The research aimed at food waste (i.e., food intended for consumption) only. Therefore, the values have been adjusted for the necessary waste such as shells, bones, tea and coffee grounds, etc. The results showed that most food is wasted in housing estates, namely 53.6 kg per person per year (18.7% of total waste), then in single-family developments—32.7 kg per person per year (16.2%), and then in rural areas where food waste accounted only for 29.1 kg per person per year (14.1% of mixed waste). However, we cannot say the consumers living in housing estate are wasting more. The results probably point at different food storage conditions, as well as limited possibilities for further utilization of leftover food (feeding, composting etc.).

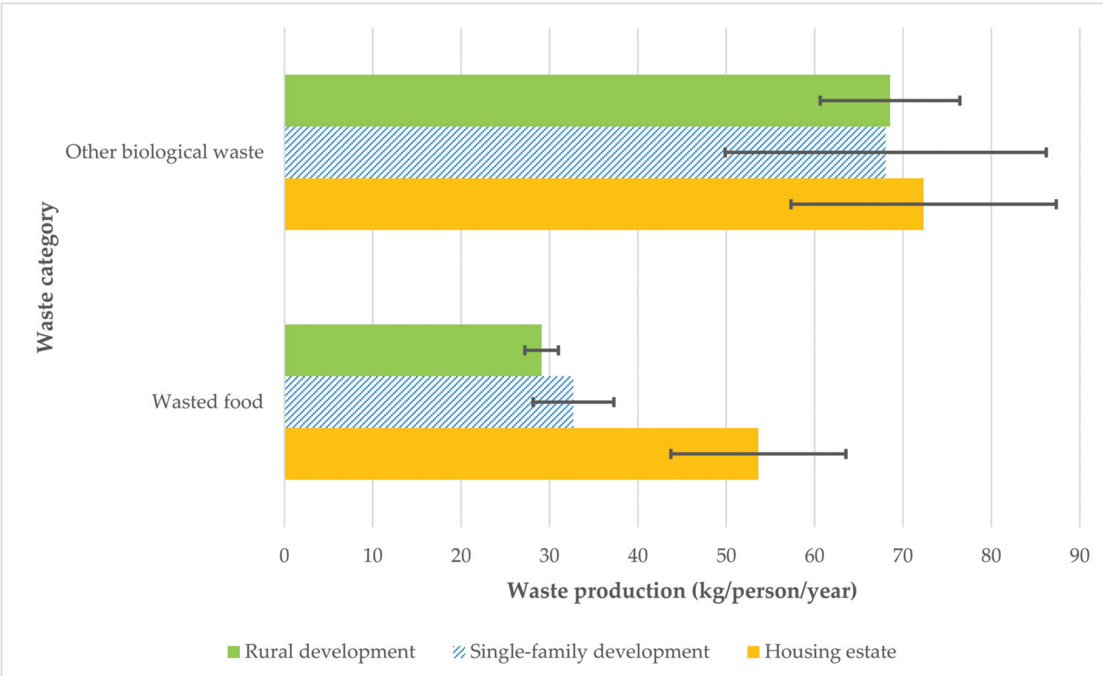

Figure 2. Biological waste structure in kg per person per year.

When taking into account all types of developments and averaging the amounts of food wasted in the entire sample (n = 900 households), the objectively measured amount was 37.4 kg of food waste (excluding necessary waste) per person per year. Similar results were published by, for example, Dutch researchers, who reported a slightly lower rate of food waste (30.4 kg per person per year—see Grasso et al. [73]). As for Danish consumers, Halloran et al. [25] speak of 42 kg of food waste per person per year. Another study into food waste in the Czech Republic even speaks of a lower waste amount (25 kg per person per year), however, these are only estimates based on Eurostat data [9].

4.1.2. Seasonality in Waste Production

One of the factors potentially affecting the results of research into waste is the season in which data are collected. There is a large number of seasonal aspects that can affect food waste amounts. Even though the impact of seasonality on food purchases and management is obvious, very little information can be found in scientific studies. Seasonality can be the reason why reported food waste amounts may differ during the year. In other words, research results may be affected by the time of year in which data collection took place.

To exclude seasonality, the authors collected data four times in one year. This gave them the idea of the variability of biological waste amounts during the year. The authors identified seasonal differences in food waste production (see Figure 3). This finding corresponds to the study by Adelodun et al. [68] who were also one of the few to address this factor. Apparently, food is wasted more during the harvest period. It may be because people do not have time to process the crop, because fruit and vegetables are cheaper at this time of the year, or because many people go on holiday and, therefore, do not care about food management so much.

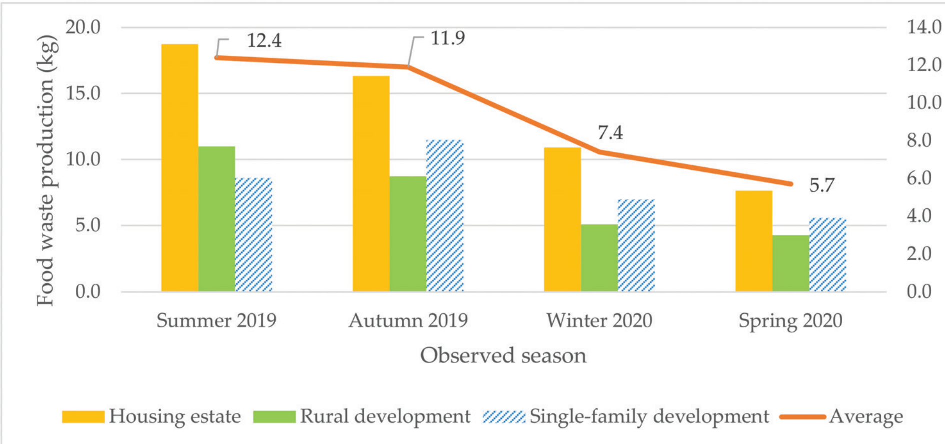

Figure 3. Food waste by season and different types of housing development (kg).

From the total amount of 37.4 kg of food waste per person per year, most food waste was produced in summer (33.2%, i.e., 12.4 kg of food waste found within summer collections), then in autumn (31.8%, i.e., 11.9 kg of food waste), in winter (19,8%, i.e., 7.4 kg of food waste), and the least food was wasted in spring (15.2%, i.e., 5.7 kg of food waste).

These proportions applied to all types of developments, except for single-family developments where a slightly higher amount of food was wasted in autumn (11.5 kg) than in summer (8.6 kg). An interesting finding was that households living in all types of developments produced the least waste in the spring season. Thus, we can observe a declining trend in the amount of wasted food (see Figure 3), but it is necessary to point out that the last observed period was a lockdown within the COVID-19 pandemic. Therefore, it is not possible to conclude that generally, people waste less during the spring. Since the amount of wasted food changed throughout the year, it was important to identify the causes of these changes and to examine the structure of food waste.

The total amount of collected municipal waste, which was analysed in the study, varied as follows in the individual seasons: in the summer of the reference year, it was 2360 kg, in autumn it was 1944 kg, in winter it was 1654 kg, and in spring it was 1795 kg. It can be seen from this data that not only the amount of food waste has changed within the individual seasons, but also the total amount of municipal waste that households produce.

4.1.3. Structure of Waste—Wasted Food

A key prerequisite for reducing household food waste is identifying the composition of waste and finding out what is wasted most. In addition, information on the composition of food waste allows for a better interpretation of seasonal fluctuations and identification of reasons for increased waste in the summer and autumn months. The following chart (Figure 4) shows food waste structures in individual seasons.

Overall, households waste fruit and vegetables the most (25.1%, i.e., 9.4 kg per person per year), then baked goods and leftover bakery products (18.7%, i.e., 7 kg per person per year), and ready meals (11.8%, i.e., 4.4 kg per person per year). For illustrative reasons, the authors converted the quantities into specific foods from individual categories. For example, an average person wasted about 28 eggs, 13 yoghurts, 163 rolls, 188 carrots, and 28 food servings (250 g per serving) during the year.

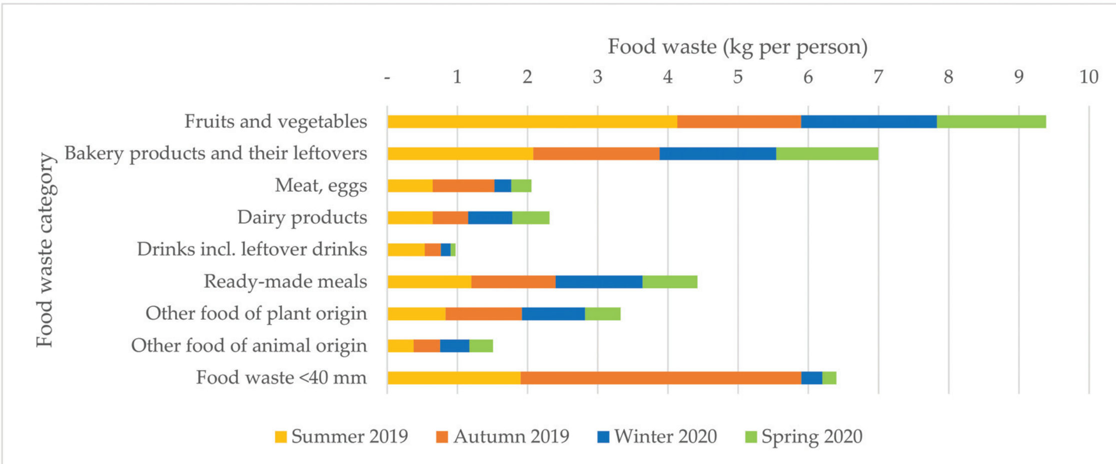

Figure 4. Selected food waste categories sorted by season (kg per person).

There was a significant share of food waste in the sub-sieve fraction (17.1%), but this waste has not been broken down into categories. It is because these are small pieces of food—mostly meal and side dish leftovers (Figure 5).

(a) **(b)**

Figure 5. Municipal waste analysis; (**a**) Bakery product and their leftovers; (**b**) Food waste <40 mm.

We can see dramatic seasonal changes in food waste structure, especially in the "Fruit and Vegetables" category where there was a significant peak in the summer period. Out of the total amount of fruit and vegetables wasted per year (9.4 kg), as much as 44% (4.1 kg) falls within the summer season. There has also been a notable seasonal difference in the meat and eggs category where the amounts of wasted food decreased significantly in winter and spring. This can also be attributed to the slower perishability of food in the colder months. Last but not least, there have been significant seasonal differences in food waste amounts in the sub-sieve fraction (a huge increase in autumn).

4.2. Subjective Quantities—Questionnaire Survey Results

As outlined in the introduction, there is a noticeable difference between how people perceive the amounts of food they waste and what the actual food waste amounts are. This assumption has been confirmed by a quantitative survey with 395 respondents—

households. The respondents were asked to estimate the amount of food wasted in their household per week. The average amount of food waste, as subjectively perceived by the households, was 12.3 kg per person per year. Seventy-eight percent of respondents said their household wasted up to 0.5 kg of food per week. However, the reality is different—the actual amount of food waste in mixed municipal waste was 37.4 kg per person per year. This means that an average household (2.43 household members—see [71]) wasted 1.7 kg of food per week. A further comparison of annual values shows that the estimated food waste amounts were almost two thirds (67%) lower than the actual amounts. People often do not realise they waste so much.

The following chart (Figure 6) shows subjective assessments of food waste rates, where respondents indicated the level of waste in their household on the Likert scale (1 = we do not waste food and 10 = we waste a lot of food). Most respondents (85.1%) said their waste rate was rather low (which corresponded to values 1–5 in the chart). The graph (Figure 6) also shows that the younger generation subjectively perceives themselves as more food wasting, however, their perception of their own food waste is very low, the mean value corresponds to a value of 3 on a scale of 1 to 10.

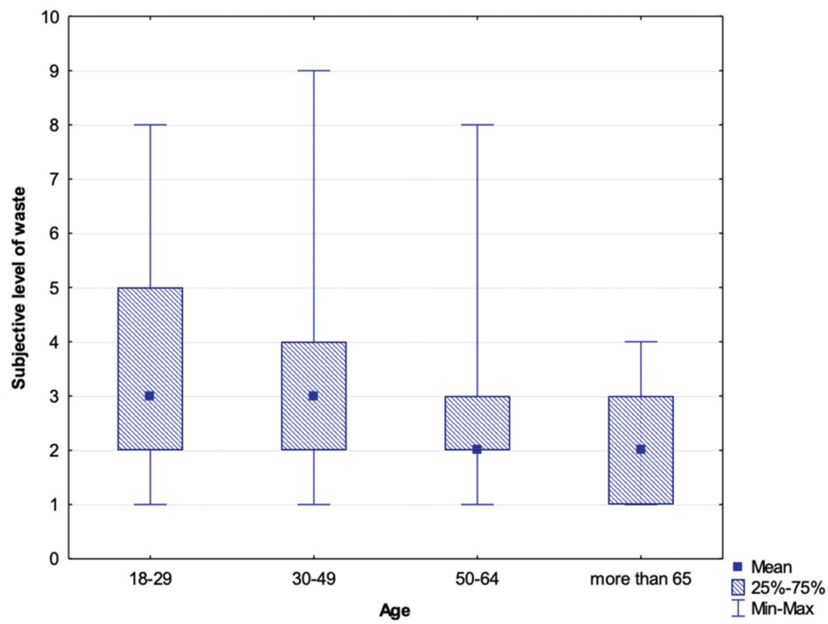

Figure 6. Food waste rates, subjective perception of respondents.

We comment on the issue of differences in food waste for different generations below (see testing of Hypothesis 5b).

4.2.1. Factors Influencing Waste Rates in Households

This sub-chapter evaluates variables that may affect subjective perceptions of weekly food waste amounts. Waste analyses showed some differences in the composition of bio-waste and in the amount of food waste depending on the type of development in which the respondents lived, household income, the size of purchases made, the age of the respondents. The authors determined the set of hypothesis (see Methodology part, Section 3.2) and the following null hypotheses were statistically tested:

Hypothesis 1b (H1b). *The amounts of food wasted by households living in a housing estate, a family house, a single-family development, or a rural-area family house do not differ.*

The respondents gave their estimates on the weekly amounts of food they wasted. The hypothesis was verified by the Kruskal–Wallis test (Table 3). The null hypothesis, however, could not be rejected at the 5% level of significance, $p = 0.2315$. Even though the data on the actual food waste showed differences between individual types of development (Figure 2), in the case of the subjectively perceived amounts of waste the differences were statistically insignificant.

Table 3. Tested hypotheses.

Hypothesis	Test	*p*-Value	Spearman's ρ
H1b	Kruskal–Wallis	0.2315	-
H2b	Spearman's coefficient	0.0001	0.27
H3b	Spearman's coefficient	0.0077	0.20
H4b	Spearman's coefficient	0.0000	0.25
H5b	Kruskal–Wallis	0.0056	-

Other variables included in the research related to households' shopping behaviour. The households were asked how often and where they made purchases and how large their purchases were. The results showed that smaller purchases were much more frequent—48.9% of respondents even said they never made large purchases (above CZK 1500). Small purchases (up to CZK 200) were a common part of households' routines as 71.6% of respondents said they made such purchases several times a week. By far the most food purchases were made in supermarkets and hypermarkets (89.6%), which is in line with other research—see, for example [74]. Online purchases came second (5.3%), which may have been a somewhat surprising finding, ahead of shopping in smaller specialized shops (3%). This trend is likely to intensify in the future, as the pandemic accelerates the shift from traditional to online shopping.

Hypothesis 2b (H2b). *There is no relationship between the frequency of large purchases of food and the amounts of food waste.*

The dependence was tested by Spearman's rank correlation coefficient (Table 3). The authors have rejected Hypothesis 2b at the 5% level of significance ($p = 0.0001$) and accepted the alternative hypothesis. The more often a household makes large purchases, the higher their estimate of average weekly food waste production. However, Spearman's rank correlation coefficient is low (0.27) and, thus, this is a weak dependence.

Hypothesis 3b (H3b). *There is no relationship between the net monthly income and the amounts of food waste.*

Moreover, in this case the authors have rejected the null hypothesis (Table 3). Spearman's coefficient of rank correlation (0.20) showed a weak dependence. Specifically, there was a direct proportion between increasing net monthly income and amounts of food thrown away.

Hypothesis 4b (H4b). *There is no relationship between the number of household members and the amounts of food waste.*

Since the resulting *p*-value was 0.0000, the authors accepted the alternative hypothesis. Spearman's coefficient of rank correlation (0.25) showed a weak dependence between the variables. It means that the more members a household has, the higher its average weekly food waste production.

Hypothesis 5b (H5b). *The amount of wasted food does not vary depending on (the respondent's) age.*

As you can see (Table 3), this dependence was tested by the Kruskal–Wallis test. Moreover, in this case, the null hypothesis was rejected at the 5% level of significance. Therefore, the authors proceeded to *p*-value comparisons. The results showed differences in average weekly food waste levels depending on the respondent's (household representative's) age. While in young people's households (aged 18–29) and middle-aged people's households (30–49 years), the most commonly reported weekly food waste amount was "up to 0.5 kg", in households of seniors (the age category of 65 and above) the most frequent answer was "less than 50 g". Furthermore, no senior reported they wasted more than 0.5 kg of food per week, while this option was chosen by about a quarter (24%) of young people aged 18–29 and a quarter (25%) of middle-aged people aged 30–49.

4.2.2. Waste Structure—Bakery Products vs. Fruit

The detailed analysis of food waste found in mixed municipal waste showed that the most wasted category were fruits and vegetables (Figure 4). As for the subjective waste rate perception, the respondents said they wasted pastry most (Figure 7). As many as 14.1% of respondents said they threw away bread at least once a week, and another 25.6% of respondents said they wasted bread two to three times a month. However, vegetables and fruits were right after pastry (19.6% of households said they threw away vegetables and fruits at least twice a month). In the third place—like in the primary measurements—was home-cooked food (16.4% of households said they threw it away at least twice a month).

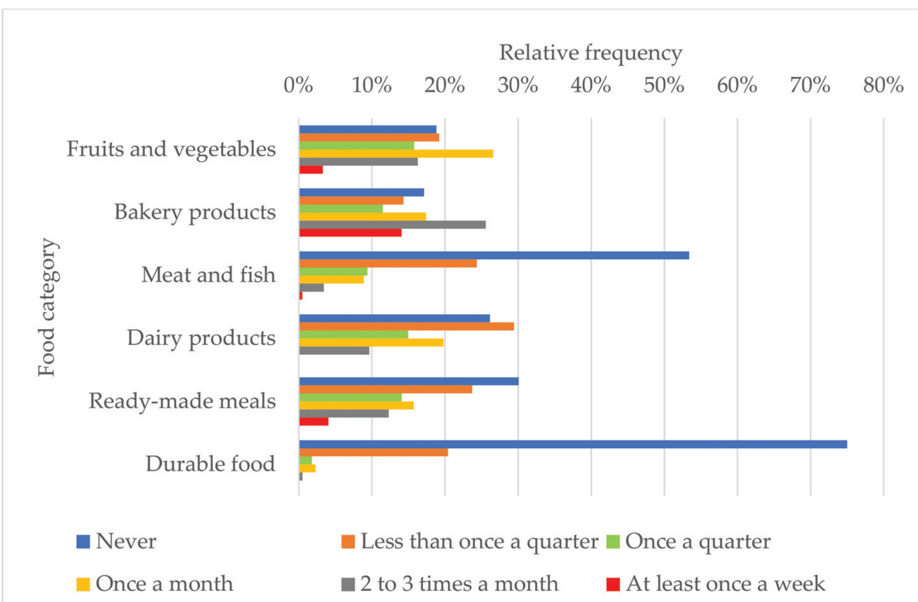

Figure 7. Subjective evaluations of food waste levels in selected food categories.

Most studies into the subject of food waste confirmed the findings of the primary research (direct analyses of municipal waste). Due to their perishable nature, fruits and vegetables are generally the most wasted food category [8,14,61]. The fact that bakery products are relatively cheap may also be one of the reasons why this food category is the second most wasted one. As for home-cooked meals, the thing is it is often very difficult for households to estimate the appropriate amounts to cook.

4.2.3. Causes of Food Waste

Giordano and Franco [40] said there was no other use for food thrown away by households and, therefore, prevention was the only way how to combat the issue of food waste and its effects. To make prevention possible, it is essential to know the causes of food waste. For this reason, respondents were also asked what waste-related factors they considered most critical.

Figure 8 shows that the most frequently reported factor was the spoilage of food during storage—it was reported by 58.7% of respondents, mostly belonging to the younger age group (18–29 years). Other frequent factors included exceeding the date of minimum durability or shelf life, and the fact that households often cook more food than they consume. This food then ends up in mixed municipal waste. The survey also shows that the cause of food waste is very rarely deterioration before food storage or damaged package. On the contrary, one of the important sources of waste is the inadequate quality of purchased food.

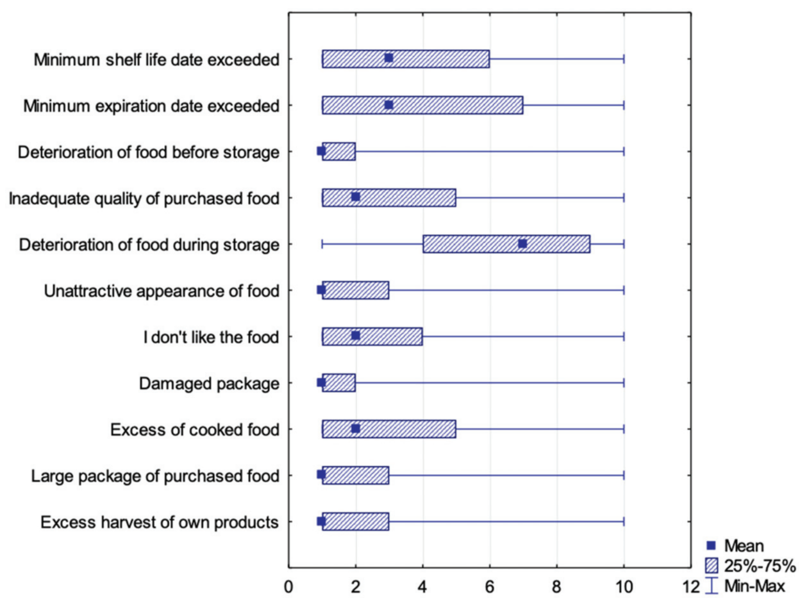

Figure 8. Causes of food waste.

However, is it possible to distinguish between the causes of food waste in housing estates and rural areas? The authors set the following hypothesis:

Hypothesis 6b (H6b). *There are no differences in the causes of food waste between different types of housing developments.*

All the reported causes of wasting were tested by the Kruskal–Wallis test (rated on a scale of 1–10 where (1) was the least common cause and (10) the most common cause). Only for the "Excessive yield of own crops" the null hypothesis was rejected ($p = 0.005$) and a statistically significant difference was found. This cause of waste was more common for households living in rural areas (median value = 3) than for households living in housing estates (or in single-family developments, median value = 1). As for other causes, no differences in evaluations were identified between households living in housing estates, single-family developments, and rural areas.

Of households, 85.3% said food waste was an important issue, and 77.6% of these households feared that this would be a major threat in the future. As many as 76.2%

of respondents believed that food waste should be given more attention, and 65.8% of respondents said they were interested in the topic and would welcome more information, including guidelines on ways how to reduce household waste.

Regarding the specific forms of consumer support in this field, the households would prefer the following ones: recipes and tips on what to do with leftover food (67.9%), better information about the appropriate storage of various types of food (59.8%), better awareness of meanings of minimum shelf life and usability (54.4%), and better awareness of impacts of food waste on the environment (49.1%). The data also showed that a change can be achieved, above all, through the planning of purchases by the family needs for the following week, and through checking the condition of already purchased food. Households that check their food stocks before they go shopping produce less waste.

4.3. Impact of the Pandemic

As mentioned above, part of the data collection was affected by the COVID-19 pandemic. This fact could, therefore, also affect the actual measured amounts of household food waste and, thus, affect the results of the survey. The questionnaire survey took place in the winter of 2020 when the impact of the pandemic on the Czech Republic was not yet noticeable. People were often unaware of the danger and, therefore, the subjective assessments of waste levels were not affected by the pandemic situation. On the other hand, the last measurement (spring 2020) took place during the lockdown and this fact most likely affected the last analyses of waste. There have been many studies into how the pandemic affected food waste [75–78].

The primary data clearly showed that food waste levels decreased compared to other seasons. Only 15.2% of the total annual food waste was produced in the spring season. The obvious question was whether the structure of food waste also changed. As regards this point, no significant deviation was found, i.e., food waste structure remained the same—see Figure 9.

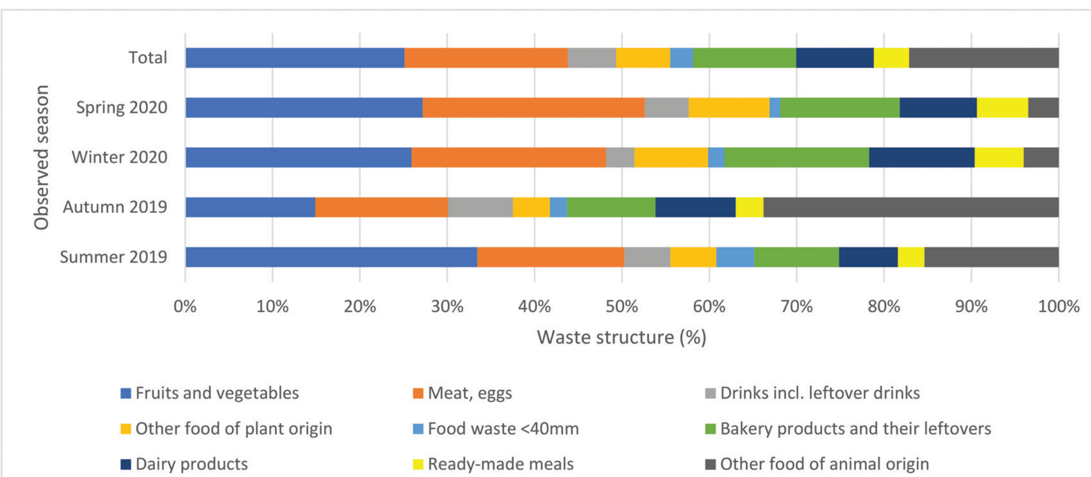

Figure 9. Waste structure during the seasons.

The analysis of municipal waste showed that in the spring of 2020, there was a change in the amount of food waste. It was necessary to look for the causes, so the authors used online in-depth interviews to learn about the significance of changes the new regime brought to the households—the results of the online interviews are summarized below. Ten respondents from different families living in different developments were contacted.

The greatest changes reported concerned the frequency of shopping. Most households that used to shop every day or every other day have limited their shopping to once or twice a week. (Only one respondent said they did not change their shopping behaviour and went shopping as often as before). The lower frequency of shopping led the households to think more about the food they needed, i.e., to plan their consumption. The respondents said they made shopping lists more often so that they would not forget anything. Due to this, on the other hand, they started making larger purchases than before. The respondents said they spent more time cooking and had a better overview of food they had at home, including better awareness of the expiration dates of their stock of food.

The most popular shopping venues have still been supermarkets, mostly because they offer convenient parking, larger assortment of goods, and advantageous special offers. Nevertheless, online food sales increased as well and seven out of 10 respondents said they had bought food online at least once. The pandemic also affected preferred methods of payment—three respondents out of 10 said they paid in cash before the pandemic, now only one in 10 respondents uses this method of payment. In addition, some respondents said they started to save more and reduce their costs. Respondents bought more durable food but said they kept only small food stocks. Most often, they kept extra sugar, flour, rice, pasta, and long-life milk. Last but not least, some respondents said they bought more canned food, such as beans or tuna, and also frozen foods.

4.4. Research Limitations and Further Study

In this study, triangulation of methods is used to gain a holistic view of the issue of food waste. However, the study also has some limitations. Firstly, it could be mentioned, that our measurements are still based on a large number of assumptions. As already mentioned in the methodology, data on food waste volumes were obtained by analysing municipal waste produced by a sample of 900 households in three types of residential housing developments, i.e., 300 households from every type of development. From each type of development, three different localities were selected in the city of Brno and its surroundings, where the waste was collected and analysed together from 100 households from each locality separately. This number of households was determined according to the number of natural persons who have permanent residence at the given address. However, we cannot guarantee that this number is exactly in line with reality. Furthermore, it is not possible to filter out phenomena such as the possible departure of some families away from home (they do not produce waste in the monitored area) at the time of the experiment. As well as the fact that they regularly take out waste every week. Furthermore, we only know the total quantities for every 100 households from the nine waste collection routes, but we are not able to measure the amount of waste for each household separately.

Due to the complexity of collecting objective data, it was not possible to perform the analysis in areas further away from the larger city. The company that collected the waste for the experiment does not cover remote locations with the collection routes. Families living here may then show other eating habits.

It is also difficult to distinguish the effect of the season and the COVID-19 pandemic, as spring 2020 was affected by the pandemic situation. It is not possible to reliably describe how the amount of food waste develops during the year because we do not know to what extent the seasonal change has manifested itself and what weight the reduction of waste in the spring can be attributed to the lockdown during a pandemic.

Last but not least, for each questionnaire, the reliability and accuracy of the data can be compromised by various limitations, such as the honesty of the participants. In addition, the participant may unconsciously improve.

Our study provides an opportunity to expand knowledge on food waste only at the regional level. Consumer behaviour across different cultures could be highly inconsistent about food.

The issue of food waste still raises many unanswered questions, the authors continue to collect data through the analysis of mixed municipal waste in the next two years. Longer collection times may help to better understand household behaviour, identify the causes of waste and find suitable methods to reduce food waste.

5. Discussion and Conclusions

Many studies point to the fact that households are the main producers of food waste [7,8,11,13]. As the need to address the issue of food waste grows, food waste produced at the household level is being examined from various angles. According to Giordano and Franco [40], the number of Scopus-registered research studies into food waste produced at the household level has increased 10-fold in the last 10 years.

As mentioned above, it is very important to realize that there are many methodologies for measuring amounts of wasted food, and, therefore, values presented by different institutions may vary considerably. In terms of parts of the food chain, the last one—i.e., the amount of food wasted at the level of final consumers and households—is generally the hardest to measure. Some of the studies aimed at objective identifications of food waste in municipal mixed waste—mainly through analysing mixed municipal waste [39,60,62,67]. Other studies were based on subjective monitoring of food waste, mainly through questionnaires [79–82]. The authors of these studies often discuss the advantages and disadvantages of the methods they used. The reported amount of food wasted by households is often only an estimated value calculated based on information from a set of respondents, thus, the estimates tend to be inaccurate [39,65]. Consumers tend to make themselves look better—whether knowingly or not—and undervalue the amounts of food they throw away by up to 40% [32]. The abundance they live in prevents them from seeing how significant their contributions to the overall alarming amount of food waste are. A more accurate form of research are diary records in which consumers put detailed information on the food they do not consume and throw away. The fact that respondents have to make the records can affect their consumer behaviour and the results tend to be skewed to a certain degree. Undistorted results can be obtained only by empirical measurements of leftover food found in the garbage—see Ilakovac et al. [14]; Elimelech et al. [83]. It is also very important to ensure that the observed subjects are not aware of the measurements taking place in their area. However, the financial, time, and also personnel demand of such empirical research often pose a problem for researchers [37]. Studies based on subjectively ascertained data predominate in the scientific literature—Herath and Felfel [34] pointed out that studies based on objective data collections and direct weighing of food waste are still rather rare. Grainger et al. [37] added that given the high cost of measuring household food waste directly, conclusions of most studies stem from questionnaire-based self-assessments by households. The subjective surveys are most criticized for underestimations of food waste amounts by consumers [39,65].

This study is unique because it is based on high-quality, objectively determined primary data obtained by mixed municipal waste analyses. Subjective data not detectable by this method (e.g., reasons for wasting food or linking the issue of food waste to characteristics of those producing the waste) were obtained by questionnaire surveys and in-depth interviews. In this study, triangulation of methods was used.

Based on the mixed municipal waste analyses the authors found out that on average 105.9 kg of biological waste per person per year ends up in the bins, of which 37.4 kg per person per year is wasted (this means edible parts of food, i.e., the avoidable food waste). According to Beretta et al. [18], most avoidable food waste is produced at the household level, and avoidable food waste can be prevented and has the greatest potential in terms of possible reduction and usability in tackling environmental problems. Giordano and Franco [40] added that the only way to address this problem and its effects is through prevention. Based on the identified causes of wasting and the in-depth interviews, the authors concluded that the search for effective intervention modes has to take into account households' preferences. Furthermore, prospective media strategies will have to reflect target groups' ages. There is no universal way to reach all households as each household has members belonging to different generations, and every generation has their specific needs. Despite this fact, short videos broadcast through online formats appear to be one of the most effective forms of disseminating information. This is because short videos are best for attracting viewers' attention and the online environment is a low-cost alternative enabling reaching a wide audience even in the current pandemic times. The videos should have a positive and motivating tone, but also be instructive. Consumers prefer specific tips and advice on how to reduce household waste production.

When taking a closer look at the issue of food waste produced by households, we can see that households living in urban developments—especially housing estates—produced the most waste. The reason is these households have limited possibilities of utilizing their biological waste and, therefore, almost all their food waste ends up in mixed municipal waste. On average, this means 53.6 kg of food (avoidable food waste) thrown away per person per year. The least food is wasted by households living in rural areas. These households waste about 29.1 kg of food per person per year. The fact that more food is wasted in towns and cities than in rural areas has also been proved by Lebersorger and Schneider [60], Hanssen et al. [62], and Tokareva et al. [53]. Our results are consistent with the findings by these authors. There are several possible reasons for this—for example, the possibility of composting leftover food or feeding it to domestic animals. According to Tokareva et al. [53], the reason for lower rates of food waste in or near rural areas is a closer relationship people living there have to their food—they can see the crops grow and know how much effort it costs to grow their food. These findings apply to the general concept of a European consumer and are in line with the results found for Czech households.

As for the structure of the foods that are thrown away the most, these are mainly fruits and vegetables, bakery products, and ready-made home-cooked meals. These results correspond to the findings by Parfitt et al. [8] and Silvennoinen et al. [61]. The reason food belonging to these categories is wasted so much is mainly its perishability [8,61]. Parfitt et al. [8] add that the structure of food waste is largely related to households' consumption habits. When considering seasonality, most food waste is produced in autumn and summer. However, there are only a tiny number of studies mapping seasonality factors in food waste production. The reasons are the complexity of data collection and high costs. This is why the extent of data and results presented in this study are so unique—the data on food waste creation cover all seasons, which allows for identifying seasonality in food waste production. The influence of the measurement period on the identified amounts of food waste has been proven by, for example, Wenlock et al. [84] who monitored food waste production in summer and winter. They found out that more food was wasted in summer than in winter, which is in line with our findings. The Korean study [68] also describes the different amounts of food waste depending on the season and also points to lower wastage rates during winter and spring. In our research, on average 12.4 kg of food (per person) was thrown away in summer and 7.4 kg in winter. Higher food waste in the summer months could be associated with limited storage options during these higher temperature months. It is, therefore, possible to point out the importance of proper storage and equipment for proper food cooling in households. That means knowledge of how to keep fresh food longer is essential [85]. There are several possible reasons for higher food waste in autumn, households switch from the "holiday regime" (households with children eat at home more often) to the "eating-out school regime" and before families switch to the new regime and set up their food management properly, they may buy unnecessarily large amounts of food, which is then wasted. This is also the season when, for example, apples and pears ripen and, therefore, crop surpluses end up in the rubbish bin more often—this especially applies to rural and residential areas. People wasted food the least during the spring, 5,7 kg. However, households' consumer behaviour was most likely influenced by external circumstances, as the COVID-19 pandemic broke out during the spring.

Why do consumers waste food? This question could not be answered through analysing mixed municipal waste—this method provides objective data (which is its great advantage), but does not encompass the link to the household, i.e., the producer of waste [83]. Therefore, to identify the reasons behind food waste, we have conducted an additional questionnaire survey. The survey results showed that the main reason was food deterioration due to exceeded dates of minimum durability or shelf life. The other reason was that households often cook more food than they consume.

The questionnaire survey results also revealed how well Czech consumers are able to estimate the amount of food they throw away. Figure 7 shows that households' estimates of the amounts of food they wasted were very poor. Subjective estimates differed from the objective primary data by about 67%. This corresponds to the findings by van Herpen et al. [65] and van der Werf et al. [39].

The effect of the pandemic on households' food management is indisputable. The changes, which have been observed and discussed with selected households, are in line with the results of the spring measurement. This measurement was affected by the first wave of the pandemic and was characterised by a significant decrease in the amount of wasted food (5.7 kg per person, 15.2% of the total annual total waste). Qian et al. [77], and Schmitt et al. [76] also pointed out lower waste rates during the pandemic. On the other hand, as regards the structure of waste, no statistically significant deviation from the period before the outbreak of the pandemic has been found. All households reported they planned their purchases more thoroughly in the pandemic—they thought more about what they needed to buy and made purchase lists. However, planning often requires advanced experience as it is not always easy to estimate the amount of food needed, especially with the growing number of household members. Skills in food management often come with experience—in some cases, older people are better at planning the required amounts of food and, therefore, waste less (see Hypothesis 5b). The elderly generally spend more time at home and, thus, have more time to manage their food supplies and process those approaching expiration dates [77]. Shopping habits are also changing with households shopping less often and buying more or buying food online.

The status and composition of food waste generated by Czech households included in the measurement were investigated by examining two important influencing factors of seasonality and housing types. The study indicated that food waste production differs significantly according to housing development and the seasons. Of the three different types of housing considered, the highest level of food waste production was in housing estates. Likewise, the amount of discarded food varies depending on the season. The most food is wasted in summer and autumn, regardless of the type of housing development. During the COVID-19 pandemic and lockdown (spring 2020), the food-wasting was significantly lower. Qualitative research points to changes in food management of families in this period. The findings of this study also indicate that there is a significant difference between subjectively perceived and objectively measured amounts of wasted food. The results of this research can, thus, become a valuable basis for the development of intervention strategies to prevent waste.

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A Systematic Review of Factors Affecting Food Loss and Waste and Sustainable Mitigation Strategies: A Logistics Service Providers' Perspective

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Abstract: This study investigates the causes of food loss and waste (FLW) from the perspective of logistics service providers (LSPs) and provides sustainable options for the Chinese market. To this end, this study reviews the literature on FLW and cold chain logistics published from 2008–2021. Until recently, little attention has been paid to understanding FLW drivers from the LSP perspective. This critical systematic literature review (SLR) aims to identify the potential drivers of FLW and provide a coherent and integrated knowledge base regarding these factors. A configurative SLR was performed, and after a filtering process, 43 articles were analyzed. Potential factors were identified and categorized into four groups: (i) poor management, (ii) inappropriate operational practices, (iii) high cost, and (iv) restrictions. The results reveal that technical inefficiency and facility costs are the most serious risks, and the lack of legislation and standards constitutes the second most serious risk for FLW. Sustainable solutions are recommended to address these risks. Finally, the study findings provide guidance for LSPs to achieve sustainability in social, economic, and ecological dimensions.

Keywords: agricultural (Agri) products; food loss and waste (FLW); logistics service providers (LSPs); cold chain logistics (CCL); systematic literature review (SLR); sustainable mitigation strategy

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1. Introduction

China is regarded as an agricultural country and is a leading fruit and vegetable producer in the world [1,2]. With the expansion of trade, a major challenge is to maintain and protect food quality, and many factors affect food quality [3] and result in food loss and waste (FLW). FLW is a vital topic because of its expensive socioeconomic costs, which further affect three bottom lines of sustainability. FLW contributes to huge losses of precious resources while causing environmental deterioration [4]. In summary, FLW occurs at each stage of the food supply chain (FSC) and impacts the three dimensions of sustainability: economic, social, and environmental (Table 1) [1].

Table 1. Impacts of FLW on the three dimensions of sustainability.

Economic	Social	Environmental
Reduced profit Decreased financial resources for investment in other sectors [1] Decreased customer value and repurchase intention	Harm to LSP reputation [5] Reduced labor productivity and wages [1]	Increased emissions of greenhouse gas methane [6] Waste of non-renewable energy

Various studies investigating the causes of FLW revealed that inappropriate logistics is a significant reason for FLW in China. There is a huge gap between China and developed countries in terms of cold chain logistics (CCL). The loss rate is approximately

25–30% [7], and the value of products is nearly CNY 280 billion (about USD 40.55 billion) in transportation every year [8]. The seriousness of broken CCL is especially evident in the distribution process [7], which arises from problems concerning management and regulation mechanisms [9]. Logistics-related FLW drivers are worth identifying but still have not been thoroughly studied [10].

Most studies identified causes of FLW from various streams; the first stream deals with enlisted drivers that result in high FLW emerging in FSCs [11–14]. The main causes of FLW, following these studies' findings, include poor forecasting, overproduction, lack of training/worse processing ability, poor packaging, logistic constraints mismanagement of cold chain (CC), inadequate cold storage facility, errors in quality checks, inappropriate precooling, a large number of participants, the lack of post-harvest precooling and handle, the lack of regulation, technology inefficiency, and loss of innovations that lead to FLW. The second stream relates to special issues in FSCs, such as CCL brokenness [9,15], stochastic demand and supply [11], poor temperature control [16] and management, and policy and industry standards. Third stream compares developing and developed countries in FLW, occurring in stages with regard to developing countries and FLW mainly emerging in the upstream of food supply chain. However, in developed countries, consumption stage is the significant driver of FLW [17]. Even though extant findings provide various drivers of FLW, it is hard for LSPs to review their errors and challenges directly.

As for the field of causes of FLW in CCL, scholars make an effort on academic studies, especially through quantitative research. One study measures risk assessment using a catastrophe progression method and choosing two cold chain logistics companies to conduct a case study. Even though the result mentions technology application in cold chain logistics, this method limits the control within four variables related to only one state variable [18]. The other study evaluates reliability of CC distribution system by Bayesian network [8], and the limited data may affect the accuracy of research findings.

Although there are many authors show interest in the topic of causes of FLW, most of them mention food supply chain stages and debate which stage significantly affects FLW. There are few scholars that study the drivers of FLW from the perspective of LSPs. On the other hand, each method that seeks to explore causes of FLW has its own features and advantages, but most of them lead to subjective bias in the process of decision making and the final results [18].

This study identifies causes of FLW and ranks these causes based on extant findings and provides a comprehensive explanation using a systematic literature review (SLR) from the LSPs perspective. The method of SLR is selected because it helps to understand the breadth and depth of the extant findings and identify gaps to explore in order to push knowledge advancement [19]. Causes and sustainable mitigation options were identified by systematically analyzing the research published from 2008–2021. Our results reveal that LSPs face critical challenges of technical and technology inefficiency, high facility cost, and lack of legislation and standards. Findings provide valuable insights for both practitioners and policy makers on how to optimize CCL operations and management in order to improve efficiency and sustainability.

The traditional understanding of FLW refers to food that is disposed of or left unused. Currently, the understanding of what causes and constitutes FLW is fairly complex. Five dimensions make up the definition of FLW: FSC stages, human edibility, food quality, nature of use, and food destination, which are also the features of FLW [4]. In a wider definition adopted by the authors, according to the stages of FSC, food loss occurs upstream of the FSC, that is, from farm to processing. In comparison, food waste emerges downstream of the FSC [14,15]. However, there is still no single agreed-upon definition of food loss and waste [16,17], and the terms food loss (FL) and food waste (FW) are used interchangeably [4,18]. We adopted the definition proposed by FAO (HLPE, 2014) that refers to FLW as reduced quality of food originally intended for human consumption at all stages of the food chain, no matter the cause [19]. In this study, LSPs act as intermediaries connecting different stages in the total cold chain, actively working from the origin to end customers, and FLW is the preferred term to use. This study focuses on identifying causes of FLW and ranks the drivers without considering the interrelationships of these factors.

The remainder of the paper is organized as follows: Section 2 provides the related literature review and value of this study. Section 3 discusses the systematic literature review approach. Section 4 presents our results. Section 5 discusses the results. Section 6 presents the conclusion, contributions, and limitations.

2. Literature Review

This paper is related to risk factors that affect the deterioration of agricultural products. We first review related articles and then compare our study to others to highlight differences and describe our contributions to the literature.

The analysis of FLW in supply chains must be region-specific because the relative significance of causes that restrain CC efficiency differs by region [1]. China's agricultural products are developed at the expense of the logistics industry. Actually, many logistics operations are inefficient in China. Even though the study findings hinted at some causes of FLW from a different point of view, LSPs as intermediaries were not fully explored. Researchers evaluated FLW through food cold chain logistics from different perspectives. More details are provided as follows:

(1) From the CCL perspective: Han et al. (2021) compared the current status of cold chain logistics regarding special issues of infrastructure, digital development level, and national policies and legislation between China and developed countries. The findings revealed a huge gap in these three areas [14].

(2) From the logistics companies' point of view: Tian et al. (2007) evaluated the performance of Chinese agri-food cold chain logistics companies, and the results showed the strengths and weaknesses of these operations. Specifically, the authors found that cold chain logistics companies were effective at customer service, especially in service processes and delivery. Conversely, companies performed poorly in learning and development, especially with regard to the lack of storage and technical innovation [20]. The performance of finance and internal processes was satisfactory, which was inconsistent with currently official reports, such as CCL suffering high logistics costs and having difficulty earning profits. However, factors excluding infrastructure and facilities and research time in 2007 studies could not represent the current status.

(3) Based on food characteristics: Liu et al. (2019) assessed meat safety by collecting 135 samples from 45 online stores in China and recording the shipment conditions, such as delivery time, distance, endpoint temperature, and package model. The results showed that endpoint temperature control was the most important factor to ensure the safety of meat products sold online in China [12].

(4) According to different geographic units: Lan et al. (2020) evaluated the inefficiency rate and total factor productivity (TFP) of logistics in 36 Chinese cities from 2006–2015. The findings revealed that the inefficiency rate of logistics systems in the eastern region was the highest, followed by the western and central regions [11].

(5) Focusing on the cold chain stage: Liu (2014) reported that the main loss happened during the storage and transportation stages in China, and the main reason was the incomplete infrastructure of the cold chain. However, Wu and Hsiao (2021) emphasized that the top five food quality and safety problems occur in the product-receiving step [3].

The authors identify different causes of FLW from various points of views. There are still some shortcomings among the extant findings, such as the stage that significantly leads to FLW, which is inconclusive and inconsistent in the measurement of logistics companies' performance with recent CCL yearbook; currently, LSPs are not performing well in agricultural product protection and financial aspects. The reason why this condition occurs has to be excavated. This study identifies the critical causes of FLW and driver categories capable of being used to develop strategies for delivering more efficient and effective CCL solutions in China.

While a number of studies concentrate on mitigation strategies, studies have attempted to improve supply chain efficiency through different methods, such as enhanced supply chain management [21,22], optimized distribution networks [23,24], enhanced monitoring [24], increased traceability [23,25], reduced logistics costs [26,27], waste management [26], and sustainability [28]. Even though previous research provides suggestions on how to mitigate the risk of FLW and shows an increasing trend in concentrating on sustainability and sustainable solutions as a good way to release FLW [29], practically, LSPs face specific FLW risks that are not easily addressed. After analyzing the risks and challenges faced by LSPs, this study provides solutions while deeply considering their sustainable development. The findings of this study can help managers solve practical problems as well as improve their sustainability and core competence.

Value of This Study

From the research point of view, Figure 1 shows that numerous studies have focused on the topics of food supply chains (FSCs), cold chain logistics (CCL), logistics service providers (LSPs), management, and third-party logistics. According to a cluster analysis of terms by CiteSpace, most studies on CCL and FLW show indirect relationships between CCL, LSPs, and FLW; there are relatively few studies on FLW in LSPs; and FSC plays a mediating role.

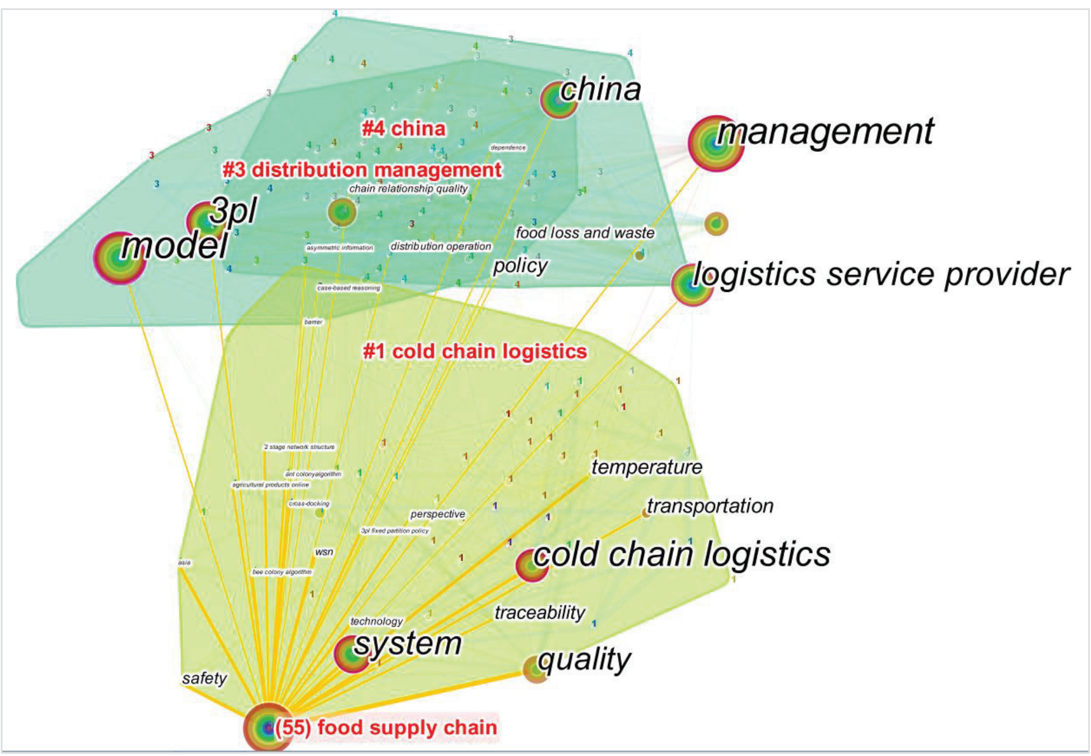

Figure 1. Cluster analysis of terms based on CiteSpace.

The main contributions that differentiate our study from other works are as follows:

(1) This study provides a comprehensive understand of FLW in LSPs, identifies 18 causes related to FLW by SLR, and shows a detailed summary of the current situation for LSPs. It establishes a direct connection between FLW and LSPs.

(2) The stated causes of FLW broaden the current research scope, including operation, management, cost, and policy.
(3) Solutions are provided that consider the three bottom lines of sustainability and mitigate the most challenging problems that LSPs frequently face.
(4) Managerial insights and policy contributions are provided, which should help LSPs involved in designing and managing CCL and explain policy gaps in the CCL industry.

3. Methodology

3.1. Systematic Literature Review (SLR)

The SLR process is "a systematic, explicit, and reproducible design for identifying, evaluating, and interpreting the existing body of completed and recorded work produced by researchers, scholars, and practitioners" [30]. This helps researchers to precisely analyze the current status of their topic of interest. In addition, the SLR follows a search strategy to pick out relevant literature that relates to the research question [31] and enables a strict, fair, and full assessment of findings, quality, and design. However, previous findings lack a connection between FLW and LSPs because of the complex feature of the topic. SLR is beneficial for absorbing and analyzing current outcomes within the discipline or across disciplines in order to establish a comprehensive research framework that can be instructive for both academia and industry [4]. Excavating deep insights from current findings to promote our comprehension of FLW at the level of LSPs is the highlight of our work.

The SLR process places some delimiting criteria to provide a comprehensive review, and the information is organized and provides meaningful insights. For this purpose, our steps were as follows [31]: (1) definition of the study: defining the issue topic, database selection, and filters to be applied for the research; (2) data collection and treatment: selecting, collecting, merging, and duplicating data after the first step filter; (3) data analysis: using CiteSpace 5.7.R5W for bibliometric and science mapping; and (4) interpretation: interpreting and disseminating results. Figure 2 shows the SLR method used in this study.

CiteSpace is open-source software that provides an alternative method to analyze an ever-changing knowledge domain based on our own datasets. It has three characteristics: first, it provides comprehensive, systematic reviews of topic history, thematic foci of research questions, landmark studies, established methods and techniques, and remaining problems. Second, it helps to continuously match the scientific literature with the knowledge domain and identifies emerging field of studies. Third, it is based on a wide spectrum of disciplines and publications [32].

3.2. Planning the Review

This review analyzes the causes of FLW from the perspective of LSPs. This study does not demarcate between FL and FW, which is in accordance with the existing studies in the domain of FLW [4]. The Web of Science databases were chosen for data collection. The following criteria were used: (i) inclusion: research articles or review articles, studies related to cold chain logistics and logistics service providers, studies on cold chain logistics management and practice, studies focused on food cold chains, studies that present causes of FLW, studies that connect upper criteria, and studies written in English; (ii) exclusion: studies not associated with the research objective, studies that do not present a research method, and studies that do not show results in the paper abstract.

The authors determined an initial set of keywords to use in searching the databases. Our keywords list led to 446 results in the Web of Science. In the next step, a search was performed by country. In order to assure rigor in the selection and profiling of publications, a review panel was established. It was extremely important to establish the review panel in order to set the conceptual boundaries of the review. Three experts in FLW causes (one professor and two researchers) constituted the review panel. This panel consulted to reach a consensus over the selection of keywords for the final list (Figure 3).

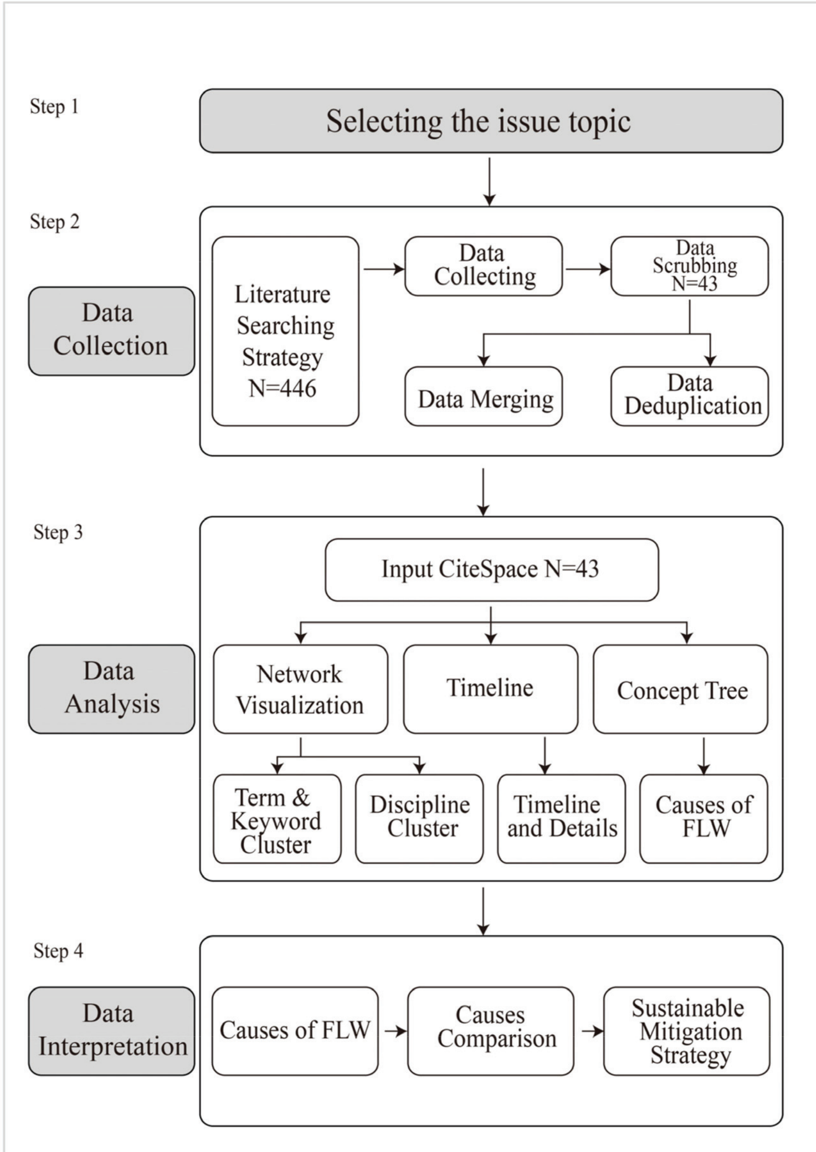

Figure 2. Process of SLR.

The time period used in this study was 2008 to 2021, mainly due to the policy and practice background. First, in 2008, the Ministry of Commerce of the People's Republic of China launched a policy aimed at developing third-party logistics (3PL). Second, from the practice perspective, in 2008, the scale of the logistics industry grew rapidly, and logistics infrastructure was enhanced (Logistics industry adjustment and revitalization plan, 2009). Third, from the academic point of view, growing interest in the topic of the environmental sustainability LSPs arose in 2008 [20].

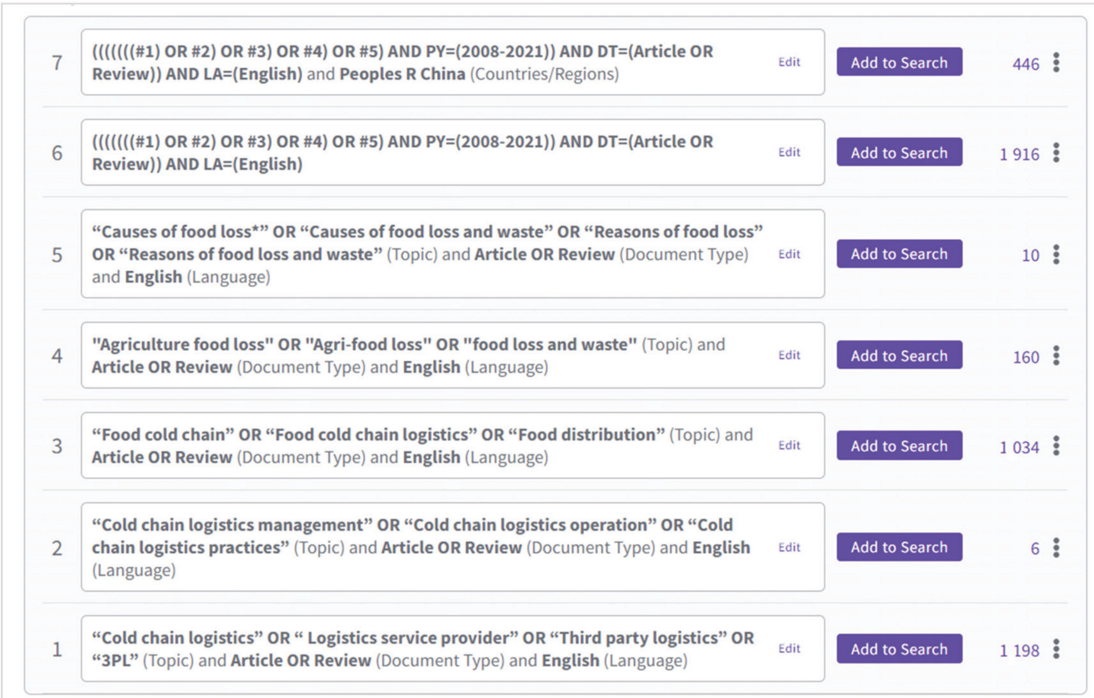

Figure 3. Topic search queries used for data collection.

3.3. Data Collection

First, an initial SLR was performed manually, using the main terms related to cold chain logistics and food loss and waste, resulting in a total of 446 files. All keywords resulting from this review were systematized and analyzed. The keywords with the highest occurrence in previous studies were identified and used to perform the SLR on the WOS database. All keywords were used as a search string, and 446 documents were found on the Web of Science platform.

3.4. Data Extraction

The final sample of 43 articles in the period 2008–2021 was used in the extraction stage because they had a close relationship with the main topic, they connected FLW and LSP management and operations, and the target country was China. Data analysis using CiteSpace software was conducted, relying on three functions: cluster analysis of terms and keywords of studies, display of timeline of terms of studies, and the discipline. The publication year of each article, list of FLW causes, and important risk factors were also provided.

3.5. Factors

Figure 4 depicts the 18 factors identified by the systematic literature review, which were divided into four groups for better understanding. These groups are displayed in Figure 4.

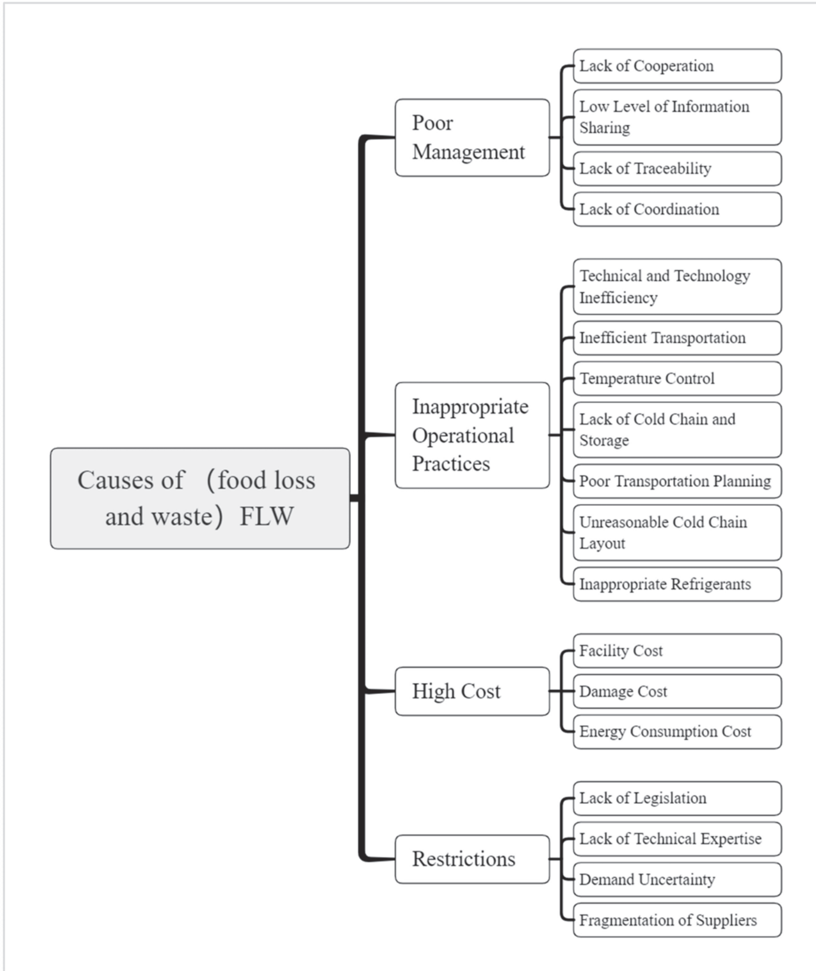

Figure 4. Groups of factors.

4. Result

4.1. Data Execution: Research Profiling

In Figure 5, the main features of the 43 articles are displayed by CiteSpace. According to the cluster analysis of term and keyword in 43 articles, the parallel research topics were classified into seven clusters. The most frequent keywords are labelled as the cluster. Moreover, the connection, development, and evolution of topics are illustrated by timeline visualization, showing some details of the term and keyword cluster analysis (Figure 6). Year of publishing distribution and discipline distribution and connection are also explained (Figures 7 and 8).

The distribution of term and keyword clusters illustrate the seven main clusters and their labels from the 43 articles, and the result is shown in Figure 5. The topic of food waste received the most attention from authors, followed by food safety and waste prevention. Logistics service capability and customer satisfaction occupy the fifth and sixth clusters, respectively. Cluster 6 focuses on outsourcing. Even though previous studies showed different interests, these topics lack a connection. This study fills this gap and builds connections between clusters.

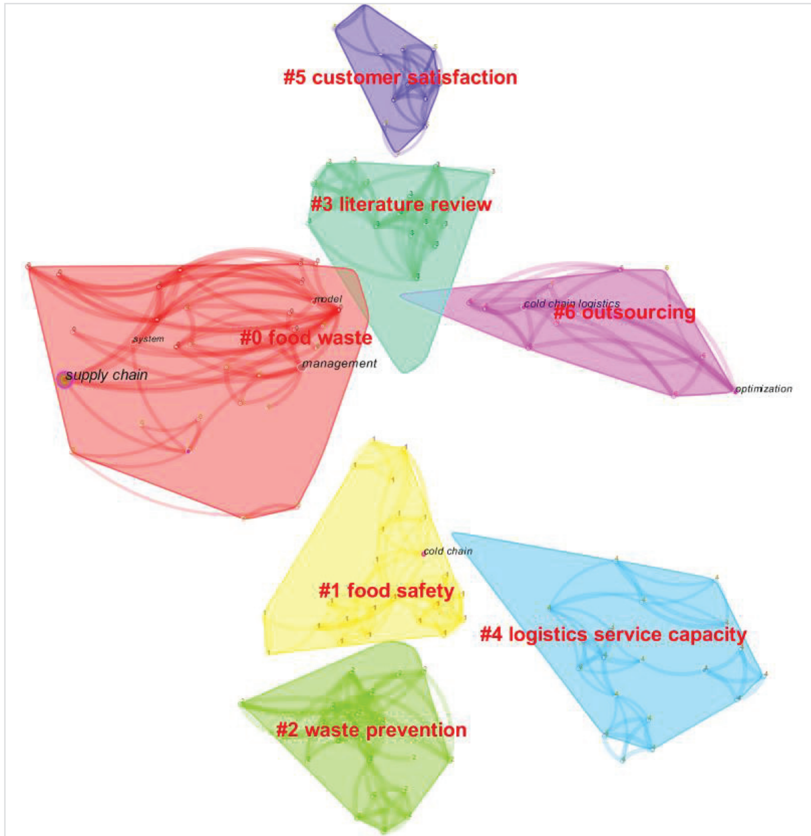

Figure 5. Landscape view of term and keyword network generated as 50 per slice between 2012 and 2021 (LRF = 3.0, LBY = 5, e = 1.0).

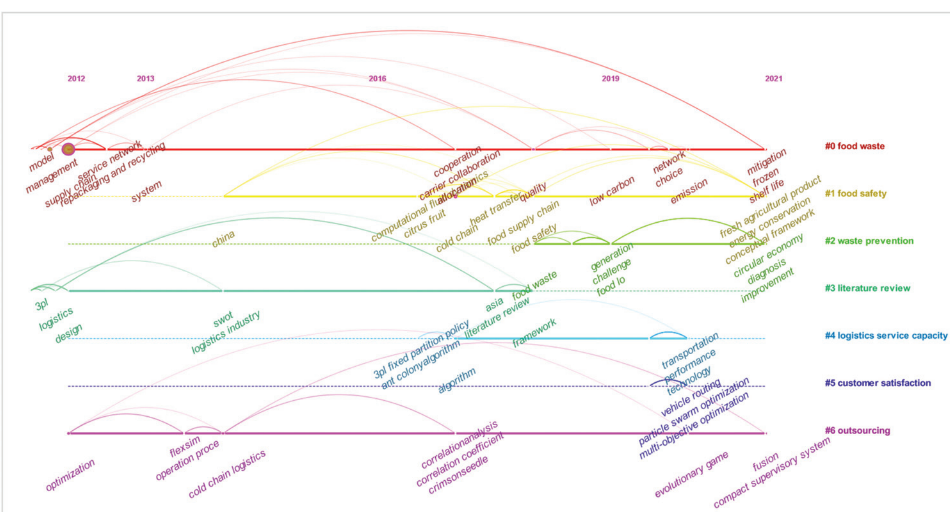

Figure 6. Timeline visualization of clusters.

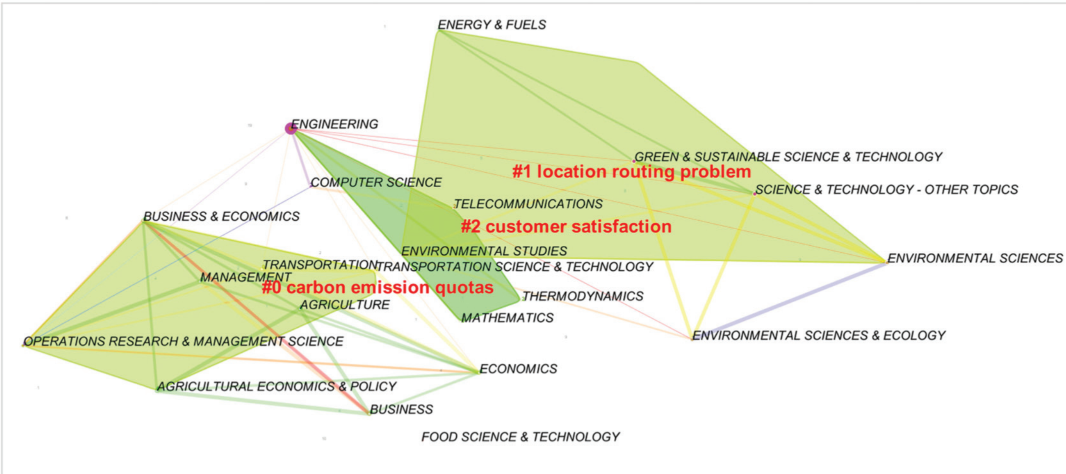

Figure 7. List of studies across disciplines.

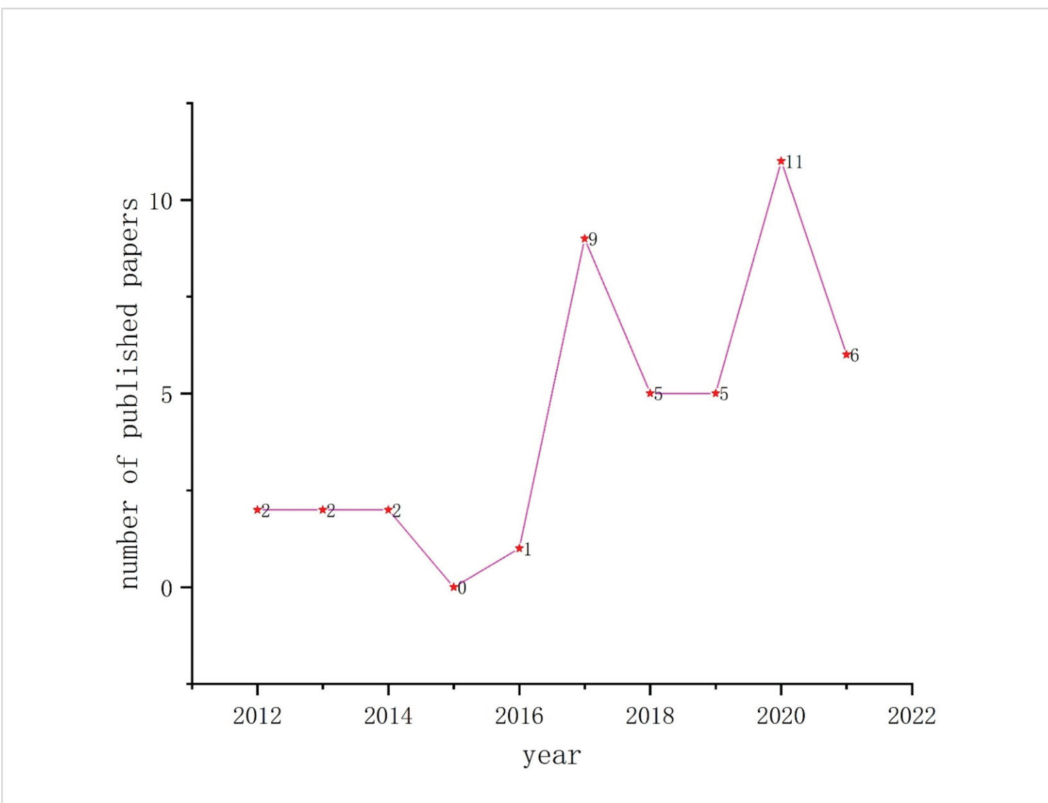

Figure 8. Distribution of selected papers by year of publication.

A timeline visualization in CiteSpace explains the details of term clusters in Figure 5 (see Figure 6). The clusters are displayed from left to right. The publication years are shown at the top of the figure in different colors. The clusters are distributed vertically depending on their size. Large nodes are particularly important, as they represent either high frequency or bursts or both. Under each timeline, the three most frequent terms and keywords in a particular year are displayed. The label for the highest frequency is placed at the lowest position. Terms and keywords that occurred in the same year are arranged so that the less frequent ones are shown on the left.

Cluster labels were numbered starting with 0, representing the largest one that included the most studies from the timeline overview, varying by active time period and existing published topics of studies. Some clusters, such as 0 and 6, cover a total time period and keep active, whereas others cover relatively short periods, such as 1, in which studies started in 2014 and continue until now. Clusters 1 and 4 cover the same period; however, 1 is still active. Some clusters include emerging topics until 2021, the most recent year of publication for a cited reference in this study.

Figure 7 shows the disciplines of 43 articles and their connections. The most important publishing outlets were those with a focus on environmental concerns and on food waste and food safety. There were 19 articles published in engineering and accounting, making up the largest portion (see Figure 7). Studies related to food science and technology had the second highest rank, and the authors showed an increasing interest in green and sustainability topics.

Regarding the distribution of year of publication (see Figure 8), the first article was published in 2012, when two articles were published, and the number remained stable until 2014. The number of publications grew from one article in 2016 to nine articles in 2017. In December 2017, China established the world's largest national carbon emissions trading market [33]. Moreover, in this period, China's cold chain logistics entered a stage of rapid growth, and foreign cold chain LSPs developed in the country. The second boom occurred between 2019 and 2020, and publication peaked at 11 articles. Authors concentrated on reducing the externalities of cold chain logistics activities, such as low carbon processes [34], and optimizing cold chain logistics systems with environmental concerns [33].

4.2. Causes of FLW from LSPs

The main group factors, sub-risk factors, sub-risk factor evidence, sources, and importance are listed from findings in the Appendix A (Tables A1–A4). Importance is divided into high, medium, and low based on frequency of previously published studies. Table 2 explains the main risk sub-factors associated with poor management of LSPs, with the evidence and sources listed and counted to show their importance. The table also lists inappropriate operational practices of LSPs and sub-factors with more details about their wrong activities and includes the main high cost of LSPs suffered and which cost is the highest. The table also considers obstacles for LSPs when operating CCL and shows more details and importance.

Based on our findings (Table 2), technical and technological inefficiency, facilities cost, and lack of legislation and standards are the top three challenges for LSPs in protecting agri-product quality; most importantly, technical inefficiency and high facility cost lead to food loss and waste (FLW).

Technology in CCL is mainly adopted in traceability, temperature control, and information systems, which is supported by the results of timeline visualization (Figure 6). The current research in 2020–2021 mainly focuses on the topics of vehicle routing problems, FLW mitigation, energy conservation, and circular economy, which are high-technology-related research directions. In addition, the discipline with the most publication is engineering, which also reflects the importance of technology. Technical and technology inefficiency significantly leads to FLW from few perspectives. First, inefficient IT compatibility occurs in forecasting, order purchasing, inventory replenishment, and life-cycle management [27,35,36]. Moreover, a new technology can have uncertain reliability when newly adopted by LSPs, with similar outcomes for current technology transferred to serve in a new condition without familiarizing users with its failure rate [16,35]. Third, agricultural products need to have real-time monitoring, tracking, and temperature measuring;

current tools, such as Radio Frequency Identification (RFID) tags and Wireless Sensor Networks, provide accurate and convenient service, but these tools have some drawbacks, such as sensor signals always being attenuated by a humid environment in delivering agri-food [35]. Last, lack of specialization and interdisciplinary talent also contribute to technical and technology inefficiency [14]. Technical inefficiency includes poor capabilities, security, and reliability. Therefore, this result is supported by previous studies reporting in which IT-related challenges are critical for third-party logistics providers [37]. This also illustrates the cause of high FLW in China.

Table 2. Comparison of factors.

Major Factors	Related Sub-Factors	Article Studied	Value		
			High	Moderate	Low
Poor management	Lack of cooperation	5	3	1	1
	Low level of information sharing	3	2	0	1
	Lack of traceability	2	2	0	0
	Lack of coordination	1	1	0	0
Total		11	8	1	2
Inappropriate operational practices	Technical and technological inefficiency	10	9	0	1
	Inefficient transportation	8	5	2	1
	Temperature control	6	6	0	0
	Lack of cold chain and storage	6	6	0	0
	Poor transportation planning	5	2	3	0
	Unreasonable cold chain layout	4	2	2	0
	Inappropriate refrigerants	2	1	1	0
Total		41	31	8	2
High cost	Facility cost	10	9	1	0
	Damage cost	2	2	0	0
	Energy consumption cost	2	1	1	0
Total		14	12	2	0
Restrictions	Lack of legislation and standards	9	6	1	2
	Lack of technical expertise	5	4	0	1
	Demand uncertainty	3	1	2	0
	Fragmentation of suppliers	2	2	0	0
Total		19	13	3	

Fierce competition and high facilities costs account for the second-largest risk. Ten studies mention that Chinese cold chain LSPs encounter high costs, such as for purchasing refrigerated vehicles [2,38] and building cooling warehouses [24], refrigeration facilities [39], special equipment, and IT facilities [40]. Many small- and medium-sized cold chain LSPs have gone bankrupt, and 82.76% of logistics companies have suffered low profits [41,42]. Changes in consumer habits and economic growth have resulted in the growth of the cold chain logistics market since 2016. Thus, additional investment has been made in CCL facilities and equipment in China; the number of refrigerated vehicles reached 164,000, with 24,000 new ones added annually. This represents a year-on-year increase of 33% [35].

The lack of legislation and standards has been frequently analyzed by researchers and practitioners, such as the shortage of laws [38] and the lack of industry standards, especially in mandatory standards [2]. Current standards have low enforcement operability and inadequate regulatory oversight [14]. Actually, existing laws mainly focus on food safety requirements and ignore the role of the cold chain in China [20]. There are still some problems regarding cold chain standards in China compared with developed countries:

(1) There are 13 different authorities, and many local governments are currently working independently in the process of drafting, organizing, approving, and issuing stan-

dards regarding cold chains rather than collaborating with stakeholders. This causes inefficiency in implementing policies and regulations [2,32,43].

(2) Existing standards do not cover the total cold chain.

(3) Most standards are at the local or industrial level and are recommended standards rather than mandatory laws.

(4) It is difficult to implement standards.

5. Discussion of Findings and Sustainable Mitigation Solutions

5.1. Findings

Through the analysis in the previous section, the first three drivers of FLW in LSPs with high importance are technical and technology inefficiency, high facility cost, and lack of legislation and standards. The results build direct connection between FLW and LSPs. In general, the above conclusions are consistent with reality. Thereby, SLR can be well applied in the field of drivers of FLW.

The first three factors affecting customer satisfaction further influence customers' re-buy decision because customers seek high quality of service and timely delivery, especially for perishable food, and technological inefficiency means that temperature, time, and traceability cannot be well managed. LSPs that are cost-oriented and unwilling to invest in infrastructure and technology, within lack of legislation and standards, limit the development of LSPs capability and business.

The findings of this study suggest both managerial and policy implications. Regarding the former, it concludes various challenges that limit LSPs efficiency and capabilities to protect agricultural product quality and safety. LSPs have to improve the technical and technology efficiency by decreasing the cost and familiarizing the function, advantage, and disadvantage of each tool, making full use of its advantages and escaping its disadvantages. Regarding the governments and policy makers, it is better to redistribute the responsibilities of 13 different authorities and combine current issues of LSPs for drafting international, easy to implement, full cold chain and mandatory regulations.

5.2. Sustainable Mitigation Solutions

Sustainability emphasizes a balance between the economy, the environment, and society. Based on a resource-based view (RBV), resources and capabilities affect firm performance. According to RBV theory, internal integration (operational ability) and external integration (cooperation and information technology abilities) are treated as resources that benefit distribution performance and encourage LSPs to increase their sustainability.

5.2.1. Mitigating Risk of Technical and Technology Inefficiency

There are two methods for solving problems of technical and technology inefficiency. First, traditional CCL has been transformed and upgraded to automatic, visible, digital, and intelligent supply chains by the new generation of information technology (e.g., the IoT, cloud computing, big data, blockchain, AI, WSN) and communication technology (e.g., WIFI, 5G, RFID), ensuring that CCL operations are safer, more efficient, and sustainable. However, there is no cold chain technology that fits everything [44]. The key success metric is strategic technological complementarity.

The second method involves employee training within logistics companies, making sure practitioners are familiar with current tools' features and drawbacks in order to reduce human error, such as WSN lacking robustness and RFID lacking reading range and having limited sensing systems. However, IoT provides a platform of information exchange between items that makes RF technologies and WSN better interconnect the data and items and helps them utilize databases relating hardware and software [44]. The right use of technology can effectively reduce FLW, improve operational efficiency, and simplify processes of CCL.

5.2.2. Mitigating Risk of Facility Costs

Facility costs include investment in cold storage, refrigerated transportation, and cooling infrastructure. It was claimed in [44] that less developed countries have to invest more to modify facilities in order to reduce FLW, while focusing on reducing facility costs, collaborating with peers, supply chain players, and stakeholders is the best appropriate solution. In [39], the authors studied collaboration with peers and found that resource sharing with peers can reduce the operation costs of cold chain logistics and also that collaboration with supply chain players can cut down delivery time by eliminating unnecessary links within the logistics process. Collaborating with stakeholders and developing collaboration among the facilities of cold chain logistics systems to reach agreement between stakeholders on transport equipment purchases, maintenance, use, and other aspects could improve the equipment utilization rate. Third, collaborating with the government, the government, as the leader, arranges and guides the diversified input investment mechanism and needs to encourage increased capital investment by multiple participants, such as logistics companies and wholesale and distribution centers [45].

Freight villages (FVs) create benefits of sustainability and are defined as areas "within which all activities relating to transport, logistics, and distribution of goods both at the domestic and international level are carried out by various operators" [27]. According to the three principles of sustainability, the functions of FVs include: (1) economic benefits, e.g., reduced transport cost and promotion of regional economic development; (2) environmental impacts, e.g., reduced freight emissions by consolidated transport; and (3) social effects, e.g., job creation, public transport connectivity, and improved urban planning. A freight village breaks the logistics bottleneck by sharing access to logistics infrastructure, facilities, and equipment [27].

The reduction in total logistics cost offsets facility costs. Optimizing vehicle routing problems can reduce total costs and energy costs [37], using a hierarchical hub network can reduce transportation costs [21], and solving the vehicle-routing problem involves a trade-off between total cost reduction and increased customer satisfaction by an improved artificial fish swarm (IAFS) algorithm [46]. A variable neighborhood search (VNS) approach is proposed to solve the multi-compartment vehicle-routing problem with time window and, considering carbon emissions, can reduce total travel costs and fixed, refrigeration, and carbon emission costs and further achieve a higher level of logistics services [47].

Qian et al. (2019) explored the relationship between LSPs' low-carbon supply chain integration (SCI) and firm performance in China. The findings proved that LSPs' low-carbon SCI significantly promotes their environmental and financial performance. Moreover, their environmental performance is positively related to their financial performance [43].

5.2.3. Mitigating Lack of Legislation and Standards

Government policies should make sure they cover the total cold chain and do not have duplicate and broken issues. Government also lead LSPs to control carbon emissions by introducing caps and fines. In this regard, policies by regulatory authorities should be framed in a manner that encourages LSPs to voluntarily reduce their carbon footprint. Policies should also impose standards that ensure environmental protection [48].

From the macro-environmental perspective, for a policy to be effective, it needs to be comprehensive and flexible to motivate LSPs and should reference international standards. Policymakers should have to clearly inform the public that (1) emission standards, (2) vehicle types, and (3) selected refrigerants (R717 or in combination with R744) have proven to be safe, environmentally friendly, and efficient [36], and (4) modified-atmosphere storage (MAS) for refrigeration is used to adjust the composition of the storage atmosphere (e.g., high carbon dioxide and low oxygen) to prolong the shelf life of food [14].

From the internal perspective, firms' eco-friendly norms enable them to enhance their brand image and increase sales as well as gain a competitive advantage [48]. LSPs have to formulate standards inside their company, establish regulatory systems to monitor, and supervise the behavior of employees, measure the performance of sustainable practices, and publish official reports that enhance both managers' and employees' awareness of sustainability.

6. Conclusions

This study evaluates the causes of FLW from the LSP perspective because LSPs act as intermediaries between CCL and food safety, and agri-food quality relies on their conduct. The contributions of this study fill a gap between academia and practice. LSPs have important responsibilities and face risks while delivering agri-food; they urgently need to identify and explore the causes of FLW to prevent economic, social, and environmental losses by concentrating on internal management and practices, high costs, and restrictions. Surprisingly, technology, transportation inefficiency, and facility costs account for the highest risk factors, and the lack of legislation and standards is the most serious constraint. Other causes include incomplete logistics infrastructure and maldistribution, unreasonable resource allocation, non-normalized logistics operation, and lack of supervision. According to these factors, cold chain logistics are regarded as a bottleneck for agri-food delivery in China. However, reducing FLW can solve the difficulties encountered by LSPs. This study considers capacity and sustainability issues and provides sustainable solutions from multiple dimensions.

6.1. Theoretical Contribution

The findings of this study fill a gap in previous research from the following perspectives. First, the risks of FLW, especially in developing markets, were examined. This study presents the most urgent risks in FLW in China from the LSP perspective and reveals representative problems of LSPs activities in developing countries, especially with regard to the biggest agricultural producers. Second, sustainable solutions based on a natural resource-based view, focusing on integrating resources and capabilities with the internal and external side and improving competitive advantage and sustainability [49,50], were discovered.

6.2. Practical Contribution

This study identifies serious risks for practitioners as a reminder of upcoming challenges and opportunities and gives them sustainable suggestions to mitigate their risks. Challenges include technical and technology inefficiency, lack of legislation and standards, and high facility cost. Methods mainly involve becoming a member of a freight village [27], encouraging peer cooperation [39], and reducing total logistics costs [37] in order to escape a huge investment in facilities and promote individual service and customize service that is hard to imitate and build up competitive barriers.

For internal operations, as a first step, LSPs should familiarize themselves with the competitive challenge by analyzing their firm's internal and external conditions. After diagnosing the competitive challenges, LSPs have to formulate effective policies, such as making investments and implementing changes to the organization's incentive and reward system. As a last step, the policies need to be implemented with a set of coherent actions that support further steps.

6.3. Political Contribution

The cold chain industry lacks supervision, and rigorous and normative standards need to be introduced. Due to the demand for international trade in fresh food, international standards are worthy of consideration. There are two main suggestions for legislation. First, encourage LSPs to be involved voluntarily in reducing their carbon footprint. While identifying drivers of green practice adoption, one study showed some evidence that mandatory norms were the main driver [51], and green supply chain practices can improve company performance, more specifically, actions such as developing distribution and transportation strategies, reverse logistics, and eco-design and packaging, which will benefit the company's environmental, economic, and social performance [52]. The second method of implementing mandatory industry standards and regulations, which can be ensured through the promotion of environment-oriented efforts, is detailed below [48].

Previous studies proved that government pressure prompts LSPs to change their operation [53], and LSPs are always cost-oriented. Whatever government subsidies or punishments can heighten LSPs' awareness of reducing FLW, the government can issue relevant policies or regulations according to their pain points and urge them to make reasonable changes. More details are listed as follows:

(1) Revise the role and responsibility of 13 authorities and many local governments in the drafting, organization, approval, and issuing of standards so as to avoid policy duplication and cross-phenomena [2].
(2) Formulate a specific and effective procedure or requirement that provides good guidance for implementation.
(3) Revise and combine current cold chain logistics standards to meet the demand for complete, networked, traceable, informative, newly patterned, highly efficient, and strict standards (State Council, 2017).

6.4. Limitation and Future Directions of This Study

While this study promotes the development of research in both developing and developed countries and identifies causes of FLW from the LSP perspective, it still has some limitations. First, the causes of FLW are regionally based, and the findings of this study may not apply to other countries. Second, the causes of FLW may be correlated with each other. However, this study does not investigate the interaction of factors. Future research could utilize the ISM method and construct a hierarchy of risk factors. Third, the exact quantity of FLW in China is unknown, which could open a new area for future research.

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Appendix A

Table A1. Factors in the literature relate to poor management.

Sub-Factor	Evidence	Source	Importance
Lack of cooperation	Brokenness	[14]	High
		[6]	High
	Cooperation difficulties	[37]	High
	Lack of reasonable cooperation mechanism	[22]	Moderate
	Lack of overall planning and coordination	[14]	Low
Low level of information sharing	Lack of information sharing from origin to end	[54]	High
	Lack of intelligent management, information integration, and information sharing	[54]	High
	Inadequate agriculture information systems	[55]	Low
Lack of traceability	Hard to trace agricultural products during delivery	[56]	High
	Inadequate tracking and tracing of agri-food products from farm to folk	[55]	High
Lack of coordination	Weak coordination of government organizations	[57]	High

Table A2. Factors in the literature related to inappropriate practices.

Sub-Factors	Evidence	Source	Importance
Technical and technology inefficiency	Experience-based operation	[58]	High
	Current tools have drawbacks; attenuation of signal	[35]	High
	Poor information technology	[8]	High
	Poor or low-tech approaches; lack of available cooling technology	[26]	High
	Many technologies have not been thoroughly implemented in agri-food logistics processes	[55]	High
	Inefficient temperature sensors	[24]	High
	Cold-chain infrastructure limits the application of related information technology	[14]	High
	Input congestion	[59]	Low
Inefficient transportation	Different transportation requirements of perishable food-product categories	[60]	High
	Ordinary mechanical refrigerated trucks	[56]	High
	Inefficient transportation network	[8]	High
	Poor delivery strategy; inappropriate traveling speed	[61]	High
	Derailment of intermediate links and untimely delivery	[54]	Moderate
	Limited transport mode	[14]	Moderate
	Low cold chain circulation and transport rate	[14]	Low
Temperature control	Temperature abuses	[60]	High
		[35]	High
		[62]	High
	Inability to control/monitor temperature	[44]	High
	Shortened cooling periods	[24]	High
	Temperature fluctuations	[22]	High
Lack of cold chain and storage	Serious shortage of transport fresh product	[42]	High
	85% of meat, 77% of aquatic products, and 95% of vegetables and fruits are still transported by regular trucks without refrigeration	[2]	High
	28% of LSPs can provide cold chain transportation, warehousing within 111 e-commerce firms; low CCL service under self-operation mode	[56]	High
	Only 15% of all perishable products are transported in refrigerated vehicles	[55]	High
	China has 0.132 m^3 of cold storage capacity per urban resident, which is far below the level of developed countries	[14]	High
Poor transportation planning	Low efficiency of equipment	[63]	High
	Numerous allocation mesh points	[42]	High
	Poor design of CCL facilities and uneven temperature distribution	[35]	Moderate
	Long-distance transportation	[26]	Moderate
		[64]	Moderate
Unreasonable cold chain layout	Inappropriate postharvest handling; uneven distribution of refrigerated warehouses and vehicles	[14]	High
	Lack of integrated CCL system	[55]	Moderate
	Incomplete cold chain facilities	[2]	Moderate
Inappropriate refrigerants	Less use of natural refrigerant R744 and R290	[54]	High
	Low level of refrigeration applied	[60]	Moderate

Table A3. Factors in the literature related to high cost.

Sub-Factors	Evidence	Source	Importance
Facility cost	Facilities cost	[39]	High
	Cost of trucks, drivers, and machine maintenance	[42]	High
		[65]	High
	Investment in specific equipment, IT facilities, and management systems	[40]	High
	High technology facility cost based on sophisticated technical requirements	[55]	High
	Investment in employees training	[40]	High
	Deployment cost; depot cost	[24]	High
	Investment in information transformation of cold chain infrastructure	[14]	High
	Higher refrigeration facility costs	[65]	Moderate
Damage cost	70% of sold price needs to make up for FLW	[2]	
	Huge resource waste when packaging and transporting of goods deviates from the superiority that saved the cost from e-commerce and manpower	[2]	High
Energy consumption cost	Energy costs account for a significant portion of storage costs	[66]	High
	Cooling costs	[55]	Moderate

Table A4. Factors in the literature related to restrictions.

Sub-Factors	Evidence	Source	Importance
Lack of legislation and standards	Low adoption of international standards; of 185 cold chain standards in China, only 7 are mandatory	[2]	High
	No regulation or no enforcement of regulation	[26]	High
	Despite reforming and perfecting of statutes, there is still a huge issue about agriculture safety in China compared with developed countries	[35]	High
	Government regulations	[67]	High
	Current standards have overlapping national, local, and industry standards and low enforcement operability	[14]	High
	Shortage of laws	[42]	Moderate
	Current regulations have inconsistent standards	[14]	Low
	China's national policies and legislation and regulatory oversight are inadequate	[14]	Low
Lack of technical expertise	Poor perception of multi-source online information, poor stability, high error rate, and, in particular, lack of a dynamic perception of product quality	[14]	High
	Lack of appropriate logistics infrastructure and knowledge	[14]	High
	Lack of interdisciplinary talent	[42] [14]	High High
	Low digital development level	[14]	Low
Demand uncertainty	Massive demands and limited transportation resources	[65]	High
	Too much transportation	[63]	Moderate
	Rapidly changing consumer demand	[55]	Moderate
Fragmentation of suppliers	Fragmented and small scale of farm structure	[28]	High
	Numerous small-scale suppliers	[55]	High

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Article

Agricultural Holdings' Impact on the Rural Development. Case Study: Romania

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Abstract: Associative forms represent a part of the agricultural producers' manifestation, with long-term impact on rural development. Considering the current dimension and the cultural-organizational baggage, the authors aim to carry out an impact study on the contribution of agricultural holding companies to rural development. This objective is to be achieved through prospective analysis methods based on a structured questionnaire, which allows for statistical tests of the variables' frequency and representativeness and econometric modelling of rural development efficiency in relation to independent variables related to the organizational custom and economic outputs of organizations. The results of the study aim at identifying the vulnerabilities that hinder the maximization of the function of the agricultural holding companies (the economic development) and treating these vulnerabilities through some concrete measures according to the modelling results. The study is useful for rural policy makers and trainers in any country in the world.

Keywords: rural development; agriculture holding; econometric model; vulnerabilities; sustainability

1. General Approach

Associative forms represent an approach to agricultural management that aims at both rural development and increasing performance at the branch level by applying production management and marketing procedures adapted to the mechanisms of the modern economy, with global trade flows and connections on the stock management and production. Although it is an innovative concept, cultural differences can have a significant impact on these forms of organizing agricultural activity, differences that can make the distinction between failure and success. Interconnection with the administrative apparatus was used in Romania as a way of support to compensate for the material and management deficiencies of the branch. With integration into the European common space, a number of rules and principles have been adopted and have somewhat limited the application of these aid schemes.

In Romania, rural development is a combination of economic and administrative activities that seek economic, social, cultural development against the background of

European funding under the CAP's Second Pillar (Common Agricultural Policy) and government funding.

In this equation, the associative forms play a productive regulatory role, using by association resources for productive purposes. They have a social role by ensuring the absorption of the labor and contribute to the national and regional budget by paying taxes and duties.

This paper aims to analyze the efficiency of the associative forms and their direct impact on the rural economic dimension at the qualitative level (by influencing the policies of cooperation, cohesion and harmonization of the legislative framework necessary to carry out these types of activities). The quantitative dimension reflects the market economic capacity, the study revealing that the contribution of some economic agents can be measured by financial indicators (such as turnover of over 1 million euros per year, profit made), by participating in the foreign trade and by providing logistics chains between Romanian producers and processors.

The objectives of the study are:

O1: Determining the result elements regarding the efficiency of the associative forms, which contribute intrinsically to rural development in Romania;

O2: Evaluating the efficiency of these elements by conceptualizing an econometric model of correlation regarding holding efficiency and rural development;

O3: Identification of vulnerabilities that affect the function of maximizing the development of holdings on rural development;

O4: Quantification of the rural development measures that reduce the identified vulnerabilities and maximize the development function;

O5: Identifying the role of financial support for the development of holding companies and rural development.

The motivation of this study lies in identifying the main vulnerabilities which prevent this form of organization from maximizing its economic function as a pole of rural development, as happens in advanced economies such as France and Germany.

2. Literature Review

In order to determine the theoretical foundations of the present study, the literature is extremely useful. The topic itself is interesting and topical for researchers, who approach it from different angles.

A first innovative approach is that of the role of the Expert Knowledge Broker (EKB) in rural development. A case study was conducted in Greece and focused on Neo-Endogenous Development. In this context, an EKB is able to bring local and 'extra-local' actors together. Moreover, the EKB is able to choose the most appropriate type of rural development for a given region. The research itself was focused on the Renewable Energy projects in Greece and highlighted the need to use local and extra-local funding in order to achieve rural development [1].

Another article of research aims to assess the determinants of the development through the application of Common Agricultural Policy measures (through a case study on the spatial distribution of the rural development in Poland). The study has showed that the European Union rural development policy continues to remain far-centering and to favor regions where agricultural structures are better represented, strengthening regional disparities with rural areas with agricultural potential [2].

Rural development in China is analyzed on the basis of the concept of urban expansion, which has accelerated the phenomenon of economic and social development but has had a negative effect on the environment and social development. From 1970 to the present, there has been a regression of the rural areas in China, visible when a Cobb-Douglas type model is applied to measure the effect of urbanization on rural development using characteristics in a spatial distribution. This paper is interesting for Europe as it reflects a current global trend of increasing urbanization and reducing rural demiography amid the development of processes such as digitalization, global trade, the IoT (Internet of Things), etc. The research results marked the elements of the sustainable development strategy in the context of increasing urbanization and environmental degradation [3].

Sustainable rural development is the subject of an analysis with reference to Romania. The authors present a viable alternative for the economic development of rural areas and increasing the living standards of communities by strengthening rural tourism in the North West region of Romania, based on enhancing factors such as preserving traditions, landscape attractiveness, hospitality, security and the safety of tourists. The results of the study reflect the fact that there is, in the Romanian rural area, a potential for sustainable development of the tourism sector, but this potential cannot be realized without the involvement of the community [4].

The performances of local management in the rural development are analyzed in an investigative study of the relational type between their performance and the active participation of the rural communities in sustainable rural development. In this context, it is noted that social capital can become an important source for contemporary rural development, which, together with the community, can become a successful recipe (social trust in execution of socio-economic plans) [5].

A strategy to revitalize rural areas and rural development itself in China highlights that agriculture, farmers and rural areas are the pillars of the new approach in the field. A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis of the rural areas in China highlights the fact that rural revitalization eliminates poverty, improves the quality of the environment and superiorly mobilizes the available resources to the rural environment [6].

An interesting connection between rural development and the reduction of migration flows is analyzed in a paper by some American researchers. According to them, this connection can be a help in limiting the migration phenomenon, given the differences in perceptions of the population in urban and rural areas. The authors believe that the agricultural sector and its development can be a catalyst for the migrants' absorption, giving to the economic development a sustainable status, through the development of the agricultural technologies and limiting the unskilled labor in agriculture [7].

In the current conditions of food overproduction due to increased productivity in developed countries, some authors consider that the new food supply is of lower quality, but with lower prices, and favors overconsumption in developed countries and diseases such as obesity, diabetes, etc. At the same time, malnutrition is manifesting itself in developing countries due to the global competition in food procurement. These developments are accompanied by environmental degradation and produce long-term negative effects on producers and consumers. The authors propose a refocused approach on the criteria of a productive and efficient food system, able to support health and sustainability, including through the development of rural areas [8].

Foreign investments in agriculture may be, in the opinion of other authors, a solution for rural development, especially for developing countries, countries where the access to technology is limited [9,10].

International trade is a driving force for the development of agricultural areas as long as the agricultural production in these areas is efficient and competitive. In order to achieve this goal, it is necessary to identify proactive measures to shape an agricultural model based on market functionality and adaptability to global trade. The comparative analysis of Romanian agriculture's competitiveness vs the agriculture of the other Member States revealed that the concentration of trade relations in the EU (European Union) area attracts competitiveness, but also that there are Member States that have an advantage in this equation. Romania has managed to increase the competitiveness of its agricultural sector by diversifying the food processing industry, an aspect that is a premise of rural development [11].

On the other hand, agricultural farms produce non-agricultural goods and services, even in the current period. They use different inputs than those used to obtain agricultural goods, which they sell on the market, thus increasing the farmers' incomes. Finally, the technical and financial performance of these farms were analyzed in the case of family farms in Italy. Obtaining additional income in these farms cannot be achieved without diversifying activities and income sources. Another factor with a positive effect on farms and rural development is education [12].

The problem of association in agricultural holdings has led to the finding that there are large disparities between agricultural regions (in this case, in France) in relation to the size and the frequency of the association's forms. Moreover, contemporary conditions have supported the separation of agricultural producers into large holdings (such as Groupement Agricole d'Exploitation en Commun—GAEC) and family farms (EARLs—Exploitations Agricoles a' Responsabilite'Limite´e). Currently, GAEC owns 7.6% of the total agricultural farms and 15% of the adult labor factor in agriculture. These different evolutions in the development of agricultural farms are largely due to historical evolution, globalization and the need to protect the environment [13].

A meta-analysis on economic behavior and the transfer of performance to agriculture has been performed by a group of authors which analyzes the correlations between the economic and the demographic phenomena, the technological characteristics and the size of the development over time of agriculture and economic behavior. Moreover, they seek to identify future research topics in the field in order to assist the agricultural policy makers and stakeholders in developing a sustainable strategy for rural development [14]. The need to plan and modernize the associative model is addressed in a paper regarding Greek agriculture. The author identifies the small Greek farmer as a small entrepreneur who tries to survive in the economic environment through specific forms of cooperation and rural association. This demonstrates that these associative forms represent a solution for rural development in other countries, as well [15].

The research of specialized literature reflects the fact that rural development is closely related to the agricultural producer. The interaction of this producer with economic flows and the social and environmental factors represent aspects that are the object of the sustainable development policies and that generate ample strategic development programs in this field. In this context, the efficiency of the associative forms becomes a challenge because they can represent the fruition of a comparative advantage (accumulation of resources), but at the same time they can be real sources of misunderstandings or economic dissensions that curb the beneficial potential of these associations. In the absence of coherent policies, the vulnerabilities tend to outweigh the benefits, and rural development suffers.

These aspects motivate the delimitation of the role of the associative forms in the concrete conditions of the organizational standards in Romania [16], which often demonstrates a quantified specificity in terms of cultural and economic baggage of the organization, which makes its mark on the economic result of the associative forms: rural development.

In the view of [17], regional development of agriculture represents critical points in the overall stability of population welfare. This is also reflected by the growing demand for food and fiber. The author point out that, in the context of a dynamic climate and demographic and economic changes, ensuring the agricultural sector's sustainability is a key factor for socio-economic stability. The author proposes some directions for action based on strengthening the commercial capacity of agricultural farms by providing infrastructure, increasing the efficiency and effectiveness of the agricultural bodies through Research& Development (R&D), improved management models in agriculture and addressing trade barriers in a favorable way to these entities (product traceability). This model confirms that government policies are a supporting factor that can mitigate the risk to associative forms in order to ensure a sustainable balance in regional agricultural markets.

The correlation between sustainable agricultural development, profit and uncertainty is studied in the case of cereal production using a dynamic model developed by [18]. The model provides scenario-based optimization of production estimated up to 2030 (triangular distribution between costs, prices and quantities obtained per year over the period 2025–2030). Although we have reservations about forecasting profit histograms with uncertainty, we consider the idea of evaluation based on five scenarios useful for estimating the regional capacity for productive expansion through strategic agricultural production planning. Thus, the prerequisites for strengthening the administrative capacity of the associative forms in agriculture are achieved.

A theoretical approach, based on the econometric modeling of dynamic correlations of randomized impact factors assimilated to agricultural development, is carried out by [19] in a scientific study assessing the behavioral paternity of agricultural development in Ukraine during 1996–2018. The results of the study show that this approach allows forecasting the decline in the economic growth of the agricultural sector according to the separate evolution of influence factors so that peaks of growth and periods of economic recession in the agricultural sector can be predicted.

In order to assess the impact of agriculture on the development of the regional economy, input—output analysis was applied in a study carried out by [20]. Furthermore, the authors developed a regional model capable of quantifying the contribution of the primary sector to the regional economy as well as the contribution of the Common Agricultural Policy to the development of the local economy. The results of this research point out that agriculture is an important factor of regional development and it is able to support the increase of the local gross output.

In a study on the Russian economy, the small and medium-sized associative agricultural forms are deprived as regional entities that benefit from the ability to associate in a small area, with limited capacity and little stability from external influence. In times of crisis, these organizations can be easily destabilized in the absence of innovative development directions [21], which consist, according to [22], of improving the fiscal climate and the input supply system and the introduction of a new taxation system for these operators. Given the national size of the agricultural associations, the opportunity to adopt such a package of measures is high.

Two important articles in clarifying the issues of the production value forecasting as a factor in the sustainable development of the agricultural sector are realized by [23] and [24]. In an impact study, the authors demonstrate that the SARIMA model (Seasonal Autoregressive Integrated Moving Average) can be used in relation to factors such as access to the transport network, import and export volumes of products, logistical redistribution of cargo, changes in agricultural policy, changes in consumer demand to identify price saturations and forecasting production volumes in a sustainable manner.

The development of agriculture from another topical perspective takes into account the information systems according to the land configuration. The authors show that the systematization of production by bringing non-productive land into the productive circuit, part of the extensive development component, can be achieved through CIM (Computation Independent Model) and MDA (Model Driven Architecture) models in a sustainable way which technically supports the agricultural management decisions and repositions the development strategy in line with the reality on the ground [25,26]. We consider this approach to be complementary to the forecasting model presented earlier [23], and consider that it can contribute to increasing the sustainability of agricultural sector development by combining the two methods. This was also considered in our present study.

Following a rigorous meta-analysis, it was concluded that the exchange of best practices in agriculture is not topical because the production conditions, climatic conditions and logistical facilities vary significantly from a regional point of view, so that common practices represent an aspect that must at least be adapted to by deepening the knowledge of the influencing factors that determine sustainability in integrated farm management [27].

A new approach to sustainable agricultural development strategy takes into account aspects of cooperation between the agricultural entities operating in the agricultural micro-environment as well as in the economic macro-environment [28]. The authors show that the success of the associative forms depends both on the organization and management of the associations, on the individual characteristics of the associating entities and on external conditions, market factors, agricultural policies and other macroeconomic characteristics in such a way as to ensure that social, environmental and economic criteria are met, in turn ensuring the sustainability of the association and the acceptance of collaboration.

Considering the complexity of the issue of associative forms, the areas of development and the potential that this branch has as a support for national and regional economies, we adapted our approach to carry out an impact study on associative forms and their ability to contribute, in a sustainable way, to economic well-being as being timely and necessary. This approach is intended to clarify, on the basis of feedback from managers of associative forms, aspects that will vitalize the regional and national strategy to boost this economic branch.

3. Methodological Approach

The present study was conducted on the basis of a questionnaire applied to 233 agricultural cooperatives during June 2020-March 2021, throughout Romania, obtaining a representation of over 95% of the sample at the level of such entities in Romania. It validates the information collected through the questionnaire as a reference point in drawing development models based on the connection to the associative capacity of the agricultural producers in Romania.

The procedure for obtaining responses from the questionnaire went through the following steps:

- contacting potential respondents by e-mail and informing them about the purpose and objectives of the research;
- Google forms design of the questionnaire;
- sending the questionnaire to the entities in the target group, i.e., agricultural holding companies in Romania;
- collecting data and re-contacting non-respondents by e-mail in order to obtain information by their completion of the questionnaire;
- statistical consolidation of the data;
- use of data for modelling.

The procedure was used in a pandemic context, which did not allow physical contact but only contact by e-mail or telephone.

The structured questionnaire aimed at identifying the characteristics of the associative forms (the sector of activity in which it mainly carries out its activity, the level of education and training of the association's members and the age of the association's members). The second section was represented by the evaluation of the economic dimension of the activity, the respondents being asked questions regarding the turnover, the supply structure and the sales processes and the detailing of the market shares depending on the level of market coverage. Another question in this section was on access to finance. The third section of the questionnaire was represented by the connection with the rural development dimension both as a provider of stability and as a beneficiary of the impact measures promoted by the authorities, which should benefit the associative forms (see Table 1).

Table 1. The questionnaire map.

Question	Answer's Options	Symbol	% of Representativity in Total Responses	Question	Answer's Options	Symbol	% of Representativity in Total Responses
Activity	Production	AGQ	54.74%	The top of the governmental policies	Incentives	GPI	77.59%
	Agricultural production processing	AGPRO	10.34%		Microfinancing	GPM	68.53%
	Trading	AGTR	30.17%		Development	GPD	53.45%
	Services	AGS	1.72%		Support	GPS	40.95%
	Others	AGO	3.02%		Base	GPB	21.12%

Table 1. *Cont.*

Question	Answer's Options	Symbol	% of Representativity in Total Responses	Question	Answer's Options	Symbol	% of Representativity in Total Responses
Education & training	Without education	EDWE	1.92%	Holdings' promoting	Contribution to the food security	HPFS	50.43%
	Basic	EDB	15.80%		Improving the farmer's role on the agricultural and food chain	HPF	86.64%
	College	EDC	42.60%		Decreasing poverty	HPDP	30.17%
	University	EDUN	35.41%		New jobs generating	HPNJ	43.53%
	Post-University	EDPU	4.27%		Financial services	HPFS	27.59%
Age (years)	21–30	AGEY	10.47%		Socio-Economic development	HPSCD	45.69%
	31–40	AGEAV	23.60%	Opportunities in promoting agricultural holdings	No	OPAH	0.86%
	41–50	AGEAC	34.47%		Yes		71.98%
	51–60	AGEAD	20.11%		No opinion		27.16%
	>60	AGEO	11.36%	Measures regarding the rural development	Strategical joint with the public authorities	RDSJ	23.71%
Turnover (euros)	1: <10,000	TUVL	60.34%		Promoting the benefits and costs of the association	RDBC	32.33%
	2: 10,000–100,000	TUL	12.07%		Incentives, including financial measures	RDI	25.43%
	3: 100,000–1,000,000	TUM	15.52%		Rural development	RDRD	41.38%
	4: >1,000,000	TUH	12.07%		Regional partnership	RDRP	33.19%
Inputs	Producer	IP	34.61%		Shorting the logistic chains	RDLC	18.97%
	Distributor	ID	65.39%		No opinion	RDNO	33.62%
Goods market	Domestic market	DM	45.16%	The public intervention in supporting the rural development	Promoting transparency and trasability for the agricultural job	PITT	27.59%
	External market	EM	4.00%		Concrete economic incentives	PICI	25.86%
	Domestic traders	DT	24.63%		Financial support and fiscal facilities	PIFS	55.17%
	Domestic processors	DP	12.23%		Viable regional development programmes	PIRP	21.55%
	Domestic consumers	DC	8.75%		Strategical partnership	PISP	21.55%
	Export EU	EEU	4.90%		Developing coherent agricultural policies	PIAP	19.40%
	Export non-EU	ENEU	0.33%		Improving the law approach	PILA	25.00%
Access to financing	Yes	AF	42.24%		Particular measures for rural development	PIRD	30.60%

These three sections allowed a complete radiography of the associative forms in Romania, radiography that highlights at the structure level the fact that:

- most associative forms have concerns in the agricultural productive sector; there are some entities concerned with services or trade;
- the level of education is mainly secondary and higher education, which means that, through entrepreneurship and rural development programs carried out at governmental or European level, it has been possible to attract young people with specialized training in the agricultural sector, which is an advantage for rural development;
- from the age structure of the sample point of view, the respondents are mainly aged between 41–50 years, with a homogeneous left-right distribution around the median interval, respectively, on the age levels of 31–40 and 51–60 years. This represents the fact that most of the respondents are part of the adult population, the young labor force being less attracted by the agricultural sector. This is a long-term disadvantage for rural development;
- the evaluation of the economic dimension generated results at the level of the sample, as follows: the median range of the turnover is located at the level of the annual economic performance of up to 100,000 euros / associative form, which is a disadvantage for rural development in the sense that most economic agents fail to obtain superior yields, which would allow them a sustainable economic growth and which would effectively contribute through the four functions (economic, social, contributions to the public system, and environment) to rural development. This aspect generates the need to improve the efficiency conditions through several policies and actions to support the associative forms;
- from the use of internal resources or imported resources for the activity point of view, it is found that the share of purchases from distributors (imports or retailers) is double the share of use of domestic resources, which contributes to the balance of payments deficit and slows rural economic development;
- regarding the sales market, the analysis based on the questionnaire highlighted the fact that the sales market of the associative forms is mainly the internal market, on the retail component. A share of 5% is destined for exports, most of which targets the European Union market. Other production destinations are to processors (18.2%) and direct consumers (13.7%). This structure of the sales markets does not favor rural economic development, because the exports' limitation intrinsically slows down this development;
- a share of 42% of the associative forms declared the fact that they benefited during the financing time through European projects or national programs, which presents a quite good percentage in terms of accessing funds and adhering to the financing programs;
- the analysis of the third part of the questionnaire highlighted the fact that at the level of associative forms the need for the governmental support measures and policies is known and realized. The majority of respondents (78%) state that they feel the need for incentive policies regarding specific activities, policies that should be coordinated at the governmental level. Secondly, the need for microfinance is perceived at the level of 70% of the sample, an aspect that completes the reduced efficiency of the economic activity expressed by the average turnover of up to 100,000 euros achieved at the level of the sample. At the same time, over 50% of the respondents stated that government policies should be oriented towards the development of the agricultural branch, and 40% towards the support of activity through government policies;
- regarding the promotion of agricultural holding companies, promotion actions would aim, in the opinion of the majority of respondents (87%), to consolidate the role of the farmer within the agricultural and food chain. A total of 50% of the respondents appreciate that promotion of holding companies would contribute to ensuring food security, socio-economic development and job creation. Poverty reduction and access to accessible financial services represent promotional outputs in the opinion of only 30% of respondents;

- over 70% of respondents consider promotion as a viable opportunity for economic recovery. In terms of rural development impact measures, over 40% of the respondents believe that effective rural development measures would influence the proper functioning of holding companies, while over 30% believe that promoting the benefits and obligations of the association or regional cooperation is a way of increasing economic development efficiency. Only 25% of the respondents appreciate strategic cooperation with the authorities or concrete incentive measures as alternatives to economic development. In addition it resulted through the questionnaire that economic operations performed within the existing logistics chain are optimally represented (80% of respondents), while the reduction of the logistics chain is agreed by 20% of respondents. Regarding the ways of state intervention in supporting rural development, the majority of respondents (over 50%) opt for financial support and the provision of fiscal facilities. This aspect does not contribute on the long term to sustainable rural economic development because the dependence on funds is an element of economic regression in any field, especially in the agricultural field. The second measures regarding state intervention in supporting rural development are the specific measures adopted in the field, and lower weights aim at strengthening legislative framework, adopting viable regional development programs, strategic cooperation, developing coherent agricultural policies or promoting transparency and traceability of the profession.

Considering the above and the study of literature, we define the following *working hypotheses* for the conceptualization of the rural economic development model regarding the economic efficiency of associative forms in the agricultural sector of Romania:

H1. *The specific measures of rural development represent an effective approach to the state intervention in supporting local economic development if and only if they offer concrete measures of economic stimulation for at least 40% of the economic agents / associative forms in the region;*

H2. *The adoption of specific measures of rural development becomes efficient if the regional development programs are accessed by at least 50% of the economic agents/associative forms in the region and has as the effect of development of coherent agricultural policies, with an effect on the turnover of the holding companies.*

H3. *The specific measures for rural development are all more effective as the provision of financial support and fiscal facility is better regulated.*

H4. *Regional cooperation is an element of vulnerability in the current context and must be maximized through specific government programs.*

Consolidation processes of the databases resulting from the collection of the answers from the questionnaire were used through XL (Microsoft Excel) and SPSS (Statistical Product and Service Solutions) software. A procedure of quantitative quantification of qualitative data and data standardization procedures was applied, thus resulting in a model-able database with over 11500 records. The data were modeled using the least squares method and linear regression, using as a dependent variable specific measures of rural development (noted as PIRD) and the impact measures on rural development (noted as RDRD) in relation to the *regressors*:

- Measures of impact on rural development (strategic cooperation with the authorities—RDSJ; promoting the association's benefits and obligations—RDBC; concrete incentive measures, including financial—RDI; regional cooperation –RDRP; reducing the logistics chain—RDLC; alternative impact measures—RDNO);
- Ways of state intervention in supporting the rural development (promoting the transparency and traceability of the profession—PITT; concrete measures of economic stimulation—PICI; financial support and provision of fiscal facilities—PIFS; viable regional development programs—PIRP; strategic cooperation—PISP; developing coherent agricultural policies—PIAP; strengthening the legislative framework—PILA).

The modelling results (obtained by applying the linear regression function) of the evaluation with the Enter method allowed the introduction of all regressors in the equation, the estimated model being adequate according to a coefficient of determination of 82% for a Durbin-Watson test that tends to 2 and a degree of freedom of the regression variables of 14 out of a total of 231 degrees of freedom.

The model equation is of the form:

$$Vd = \sum_{i=1}^{15} \alpha_i \, r_i + \varepsilon \quad (1)$$

The dependent variable (Vd) represents the possibility of implementing impact measures on the rural development (RDRD) in the opinion of the interviewed holdings, the logical variable with two response steps for the possibility and impossibility of adopting impact measures.

ε represents the residual value left after the design of the regression equation, in our case being assimilated to a sum of the residual squares from the total sum of the squares of 16% or to 217 degrees of freedom from the total of the 231.

The regressive variables (r_i) represent the rural development modalities through the state intervention in supporting rural development, respectively:

- strengthening the legislative framework—PILA;
- financial support and granting of fiscal facilities—PIFS;
- alternative impact measures –RDNO;
- regional cooperation –RDRP;
- promoting the association's benefits and obligations—RDBC;
- concrete incentive measures, including financial ones—RDI;
- opportunities to promote holding companies—OPAH;
- concrete measures of economic stimulation—PICI;
- strategic cooperation with the authorities—RDSJ;
- promoting the profession's transparency and traceability—PITT;
- strategic cooperation—PISP;
- viable regional development programs—PIRP;
- development of coherent agricultural policies—PIAP;
- reduction of the logistics chain—RDLC.

The coefficients of the regression variables (α_i) are determined based on Pearson correlation, their value being determined by the non-standardized value (β) in the table of coefficients, a value that is presented below and which reflects direct or indirect proportionality with the dependent variable. All of the above reflects a homogeneous distribution of the model for a coefficient of determination of 82% and a standard estimator error of 0.2. The Sig value of the F test tends to 0, which proves that the model is valid and representative for the studied phenomenon. The data are presented in Table 2.

Table 2. Model Summary [b].

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	0.913 [a]	0.834	0.823	0.208	0.834	77.695	14	217	0.000	2.202

a. Predictors: (Constant), PILA, PIFS, RDNO, RDRP, RDBC, RDI, OPAH, PICI, RDSJ, PITT, PISP, PIRP, PIAP, RDLC
b. Dependent Variable: RDRD

The histogram distribution performed by the residual normality test reflects homogeneity under the Gaussian curve, with the accumulation on the ascending slope near the maximum of the median interval (see Figure 1).

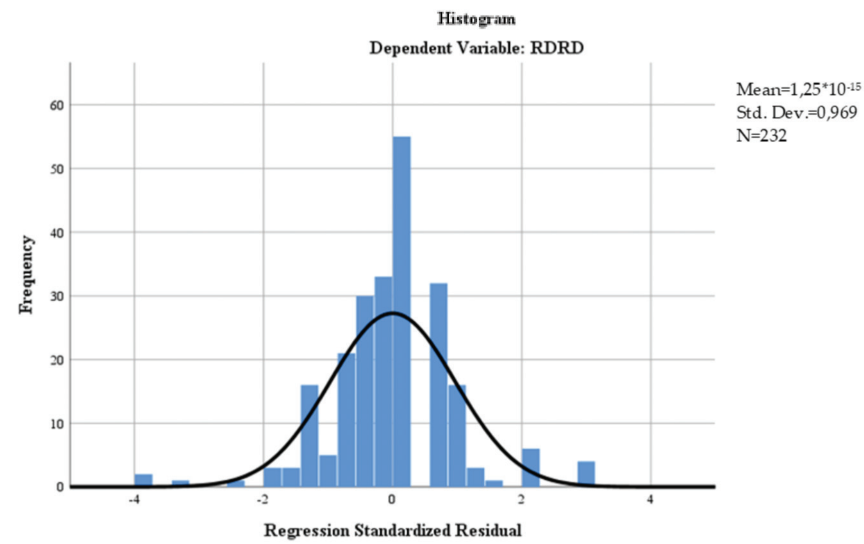

Figure 1. Histogram distribution for RDRD.

According to the P-P Plot distribution for the trend line forecast in relation to the observational values, it results that the biggest variations are found in the cases of 3- trade and 1-production, sectors that experience the biggest dynamics at the level of Romanian agriculture. These sectors attract the highest turnover, which explains the distribution of the P-P Plot (Figure 2).

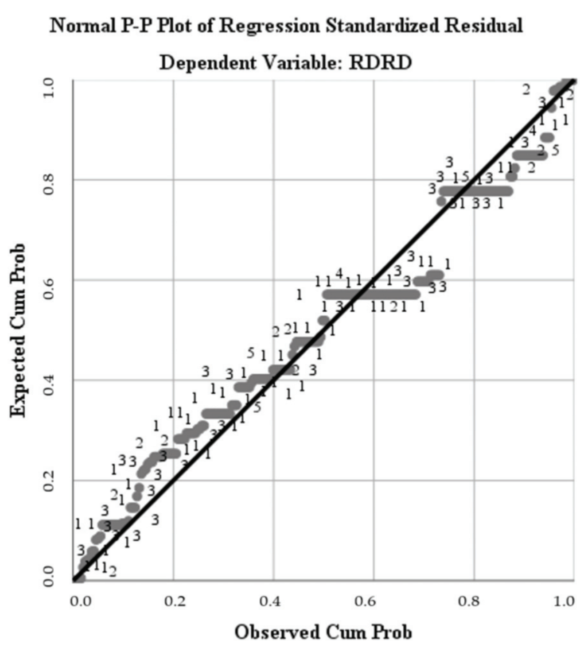

Figure 2. P-P Plot distribution for RDRD.

The ANOVA test confirms the statistical results of the model by the relatively small percentage of the sum of the residual squares (16%) of the total, the small number of degrees of freedom of the regression variables (14) and the value Sig → 0 for Test F (see Table 3).

Table 3. ANOVA Test for RDRD.

ANOVA [a]						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	46.916	14	3.351	77.695	0.000 [b]
	Residual	9.360	217	0.043		
	Total	56.276	231			

a. Dependent Variable: RDRD
b. Predictors: (Constant), PILA, PIFS, RDNO, RDRP, RDBC, RDI, OPAH, PICI, RDSJ, PITT, PISP, PIRP, PIAP, RDLC

The proposed model is valid and quantifies the poor development of the associative forms in the Romanian agriculture based on the elements of associative history and inconsistency of the regulatory framework. These aspects affect the rural economy through the qualitative component of the cooperation and cohesion policies, but also through the quantitative dimension, according to which the access to financing is only used in some cases in representative financial indicators such as turnover or profit.

The development measures, as a result of modelling, must be based mainly on the components whose correlation with rural development is in direct proportionality and of high statistical significance. The rest of the components represent the vulnerabilities that hinder the economic potential of these associative forms in reaching their maximizing function and represent significant impact factors on rural development.

4. Results and Discussion

The report for the purpose of this study revealed that, although the concept of associations could have beneficial effects on the holdings and rural development as a whole, there are several vulnerabilities (deduced by calculating the regression of the independent variables from the dependent variable) able to affect the holding companies' efficiency in Romania and to represent punctual realities and not a system reality at this time.

In this sense, we consider opportune the analysis of the regression coefficients in parallel with the partial diagrams represented on the coordinated system with the dependent variable as residual standardized diagrams.

The first regression coefficient assigned to the variable (strengthening the legislative framework—PILA) has the value of 0.575. The coefficient indicates a significant correlation between the effective ways of the rural development and the strengthening of the legislative framework, respectively, that the measure will generate a superior effect at the level of rural development. It is found that the distribution of partial regression is bipolar (2 clusters), which means that there is different legislative adaptability for the entities in the same economic sector marked on the graph with 1 for productive agricultural entities, with 2 for entities with agricultural products processing activities, 3 for the entities active on the segment of commercialization of agricultural products, 4 for service entities in the agricultural field and 5 for other entities.

Thus, there is bipolarity in sectors 1, 2 and 3, the services sector being less reflective in relation to the legislative changes. This adaptability is a characteristic attributed to the entropy for the associative forms and represents an indicator of vulnerability correction, implying at the same time active measures regarding counseling, coordination, cooperation and transparency (see Figure 3).

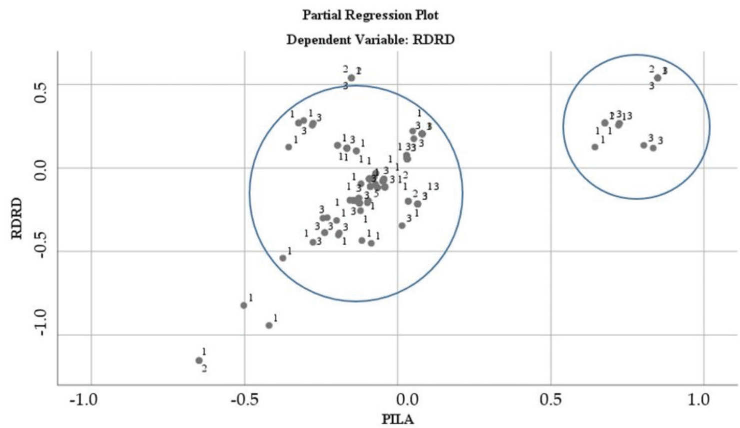

Figure 3. Regression analysis for PILA.

The second coefficient attributed to variable financial support and fiscal facilities—PIFS, has a value of 0.467 and represents an average correlation between the effective ways of rural development and the financial support and fiscal facilitation, which means that there are vulnerabilities both in the structuring programs of financing as well as in their fructification by the beneficiaries of the financing. This demonstrates that strengthening the regional capacity of the agricultural structures can generate an improvement as notes [2]. The partial diagram reflects a linear trend without polarization but with significant distances from the trend line. The largest deviations from the trend line are found in the case of the entities in the fields of marketing and processing of food products, which means that these entities do not automatically benefit from the given support to producers or service providers (e.g., management companies, water and irrigation). As a result, these segments turn into segments more exposed to the market risk, which strengthens the systemic vulnerabilities and slows down rural development. These aspects motivate the H2 and H3 hypotheses of the research, as follows:

H2. *The adoption of specific measures of rural development becomes efficient if the regional development programs are accessed by at least 50% of the economic agents / associative forms in the region and has an effect the development of coherent agricultural policies with effect on the turnover of the holding companies.*

H3. *The specific measures for rural development are all more effective as the provision of financial support and fiscal facility is better regulated (see Figure 4).*

As some authors [22] have presented as part of the package of revitalization measures, fiscal policy can ensure the improvement of the conditions of association and increase the life span of these associative forms, along with improving their economic efficiency.

Another indicator represented by the alternative impact measures—DRNO was introduced in the modelling as an independent variable, and the non-standardized coefficient β resulting from the modelling is −0.588. As a result, the alternative measures have a significant indirect correlation with the dependent variable, motivated by the fact that they are by definition antagonistic. The same bipolar trend is noticeable, which for the first three categories of economic agents (production, processing, marketing) reflects the fact that the associative forms fail to maximize the development function in the current context. As such, alternative rural development measures are needed. This approach is in line with objective 1 of the research: ***O1:*** *Determining the result elements regarding the efficiency of associative forms, which contribute intrinsically to rural development in Romania.* According to this objective, the analysis reveals that the agricultural associative forms, through their development, are not able to ensure overall rural development today, alternative measures being necessary (see Figure 5).

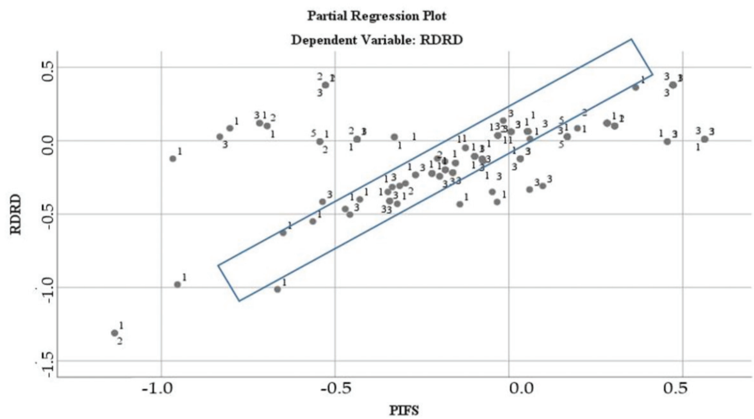

Figure 4. Regression analysis for PIFS.

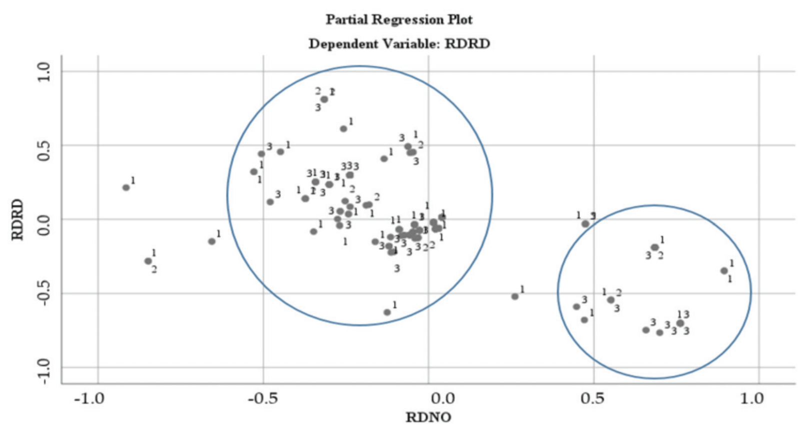

Figure 5. Regression analysis for RDNO.

A controversial output of the analysis is the regional cooperation—RDRP, a variable whose value is negative (−0.800). It highlights a strong indirect correlation regarding regional cooperation, which is motivated by the poor perception of the advantages of cooperation and the recent history of this type of cooperation much of which have ended with disputes and bankruptcies of the holding companies. Our proposed study is based on the premise that the redirection of development efforts should be undertaken after identifying vulnerabilities, so that government programs can achieve maximum results with minimum effort [19]. On the other hand, strengthening the management capacity of agricultural holdings, in addition to the representative aspects of vulnerability reduction, brings a viable addition to the sustainable development. This is likely to economically strengthen the region and generate on the medium and long term an advantageous repositioning of the market shares in favor of the agricultural holding companies [4,5,7,14,15,17,18,24].

According to the partial diagram, there is a reverse evolution trend (with impact on the first three forms: production, processing and marketing), an aspect that reflects the vulnerabilities assumed by objective 3 of the research: *Identification of vulnerabilities that affect the function of maximizing the development of holdings on rural development*, and motivating H4, as follows: *H4: The regional cooperation is an element of vulnerability in the current context and must be maximized through specific government programs* (see Figure 6).

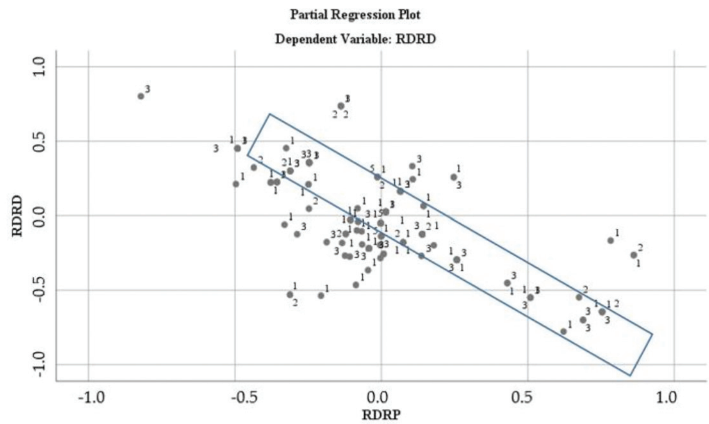

Figure 6. Regression analysis for RDRP.

This indicator, the promotion of the benefits and obligations of the association—RDBC, represents an intrinsic measure of the holding development. The β value of the non-standardized coefficient of the indicator is negative (−0.830) and indicates a strong indirect correlation in terms of promoting the benefits and obligations of the association in the case of rural development impact measures. Under these conditions, objective 2 of the research is achieved: ***O2:*** *Evaluating the efficiency of these elements by conceptualizing an econometric model of correlation regarding the holding efficiency and rural development.* It reflects a minimization of the efficiency function of the existing holding companies in the current socio-economic and legislative context, which demotivates rural development, an aspect also indicated by the negative value of the regression coefficient (see Figure 7).

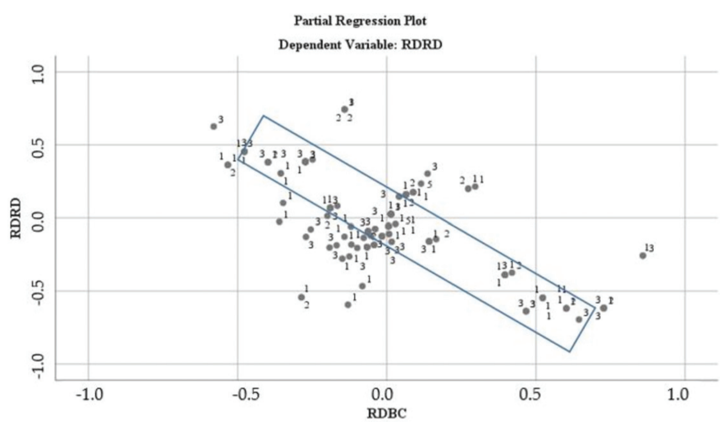

Figure 7. Regression analysis for RDBC.

The indicator concrete incentive measures, including financial—RDI, received a negative regression coefficient (−0.790) via modelling. This coefficient represents a strong indirect correlation based on the functioning of the associative forms as a way of vitalizing rural development in Romania and is motivated by considerations of inefficiency in the use of funds and poor efficiency of the management of holding companies subject to financing. The trend distribution is bipolar, the bipolarity manifesting itself on the productive and commercial sectors (1 and 3), which means that in sector 1, although a direct beneficiary of financing, the fructification of the financing activities does not represent a homogeneous feature of the system, but affects efficiency. This approach demonstrates objective 5 of the research: ***O5:*** *Identifying the role of financial support for the development of holding companies and rural development* (see Figure 8).

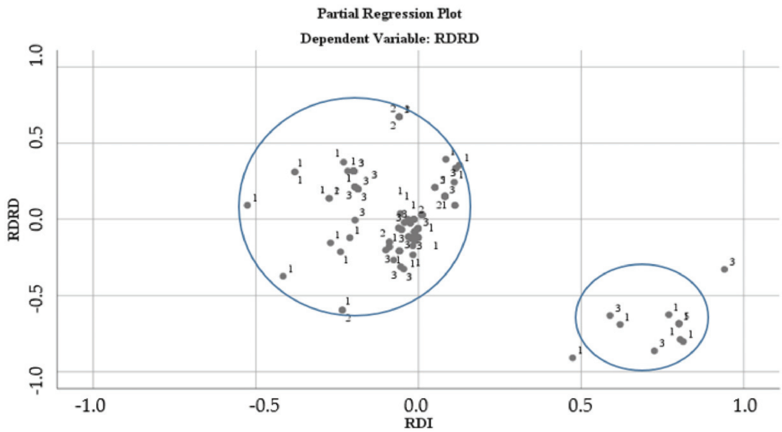

Figure 8. Regression analysis for RDI.

Another indicator which demonstrates the vulnerability of the associative forms in relation to the objective of maximizing rural economic development (Objective 3) is the opportunities to promote holding companies—OPAH. The level of the regression coefficient is minimal and negative (−0.034). It represents a weak indirect correlation regarding the opportunities to promote the holding companies as a measure of the rural development. The trend dynamics of the partial regression represents a bipolar distribution for the activities of production, processing and marketing of agricultural products (see Figure 9).

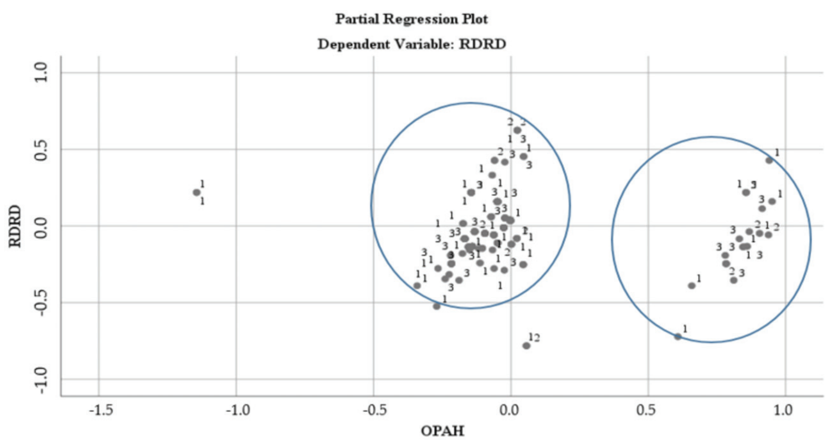

Figure 9. Regression analysis for OPAH.

An impact indicator is the awareness of the need for concrete measures of the economic stimulation—PICI, an indicator which, after modelling, has assimilated a positive regression coefficient of 0.568. This indicates a significant direct correlation regarding the concrete measures of economic stimulation as a unit of rural development. This measure is known by respondents and correctly assumed as a need for development. The bipolar trend indicator on the three activities (production, processing and marketing) answers to O4 of the research: *Quantification of the rural development measures that reduce the identified vulnerabilities and maximize the development function* (see Figure 10).

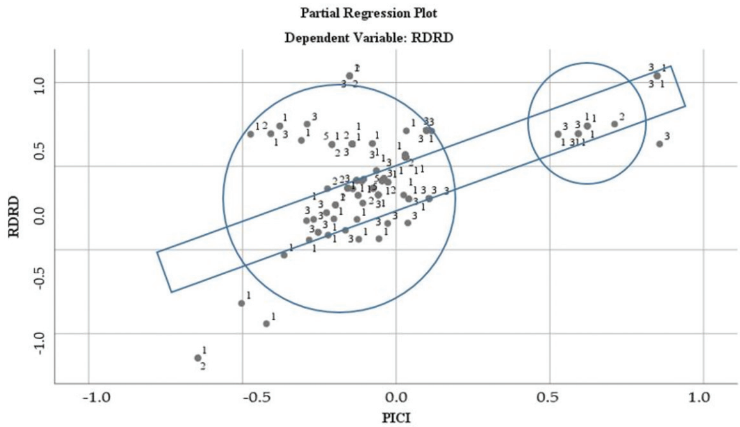

Figure 10. Regression analysis for PICI.

The vulnerability indicator discovered by modelling is the strategic cooperation with the authorities—RDSJ. The negative value of the regression coefficient (−0.704) reflects a strong indirect correlation regarding strategic cooperation with the authorities as a measure of rural development, due to a weak confidence in the public administrative capacity and the impossibility of starting viable projects with it. There is a homogenization of vulnerability, where there is a small group of producers and traders which appreciate strategic cooperation as a solution for economic development. The approach corresponds to objective 3 of quantifying vulnerability, and motivates *H1: The specific measures of rural development represent an effective way of state intervention in supporting local economic development if and only if they offer concrete measures of economic stimulation for at least 40% of the economic agents / associative forms in the region* (see Figure 11).

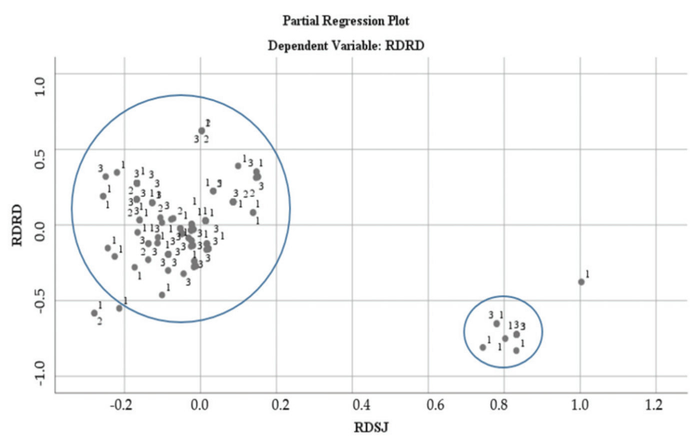

Figure 11. Regression analysis for RDSJ.

Promoting the transparency and traceability of the profession—PITT is one of the rural development measures that reduce the identified vulnerabilities and maximize the development function (O4). The positive value of the regression coefficient (0.516) indicates an average direct correlation regarding the promotion of the transparency and the traceability of the profession. It represents one of the viable options which the respondents from the administrative staff of the holding companies perceive regarding the effective development possibility for holding companies and rural development as a whole. The partial regression diagram shows an ascending trend with bipolar focus on the production and the marketing activities (see Figure 12).

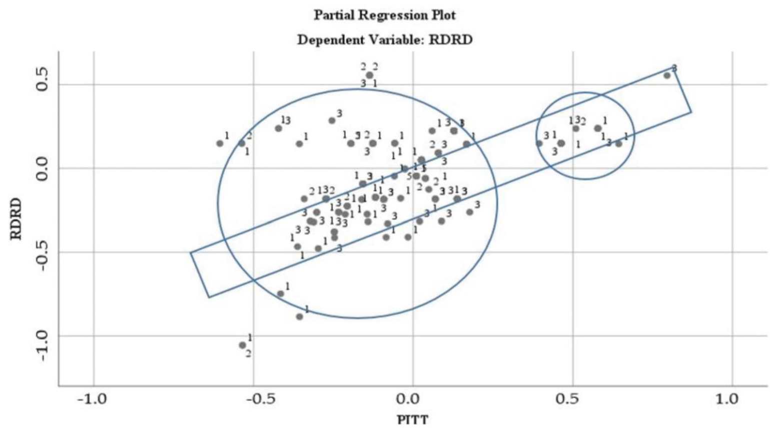

Figure 12. Regression analysis for PITT.

Strategic cooperation with other bodies than the authorities—PISP is part of the measures proposed in *O4* to reduce vulnerabilities and has a value of the non-standard regression coefficient β of 0.706. This reflects a strong direct correlation on the strategic cooperation with bodies, other than public authorities, seen by respondents as a viable alternative to rural development (see Figure 13).

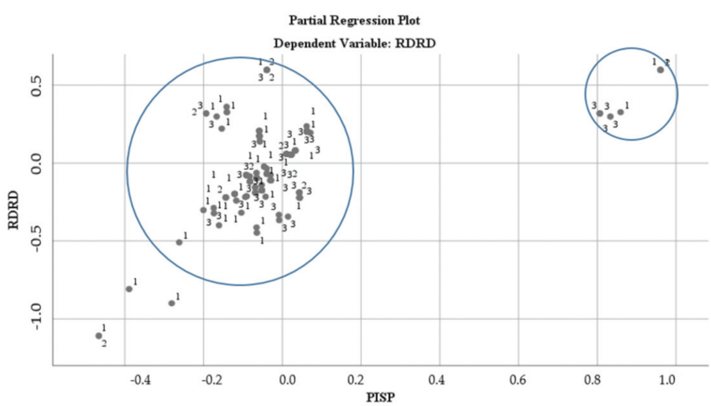

Figure 13. Regression analysis for PISP.

The implementation of viable regional development programs—PIRP is one of the impact measures which reduce the identified vulnerabilities and maximize the development function (*O4*). The value of the regression coefficient is positive (0.616), representing a significant direct correlation regarding the contribution of the viable regional development programs, as a contribution for the rural development. The coefficient is a discredited coefficient based on the experience of Romanian holding companies in accessing and carrying out development programs, regardless of whether they were financed from their budget or from European Funds. However, the trend is positive, which means that under good management this measure would be a viable alternative for rural development. The partial regression diagram has a bipolar distribution and upward trend (see Figure 14).

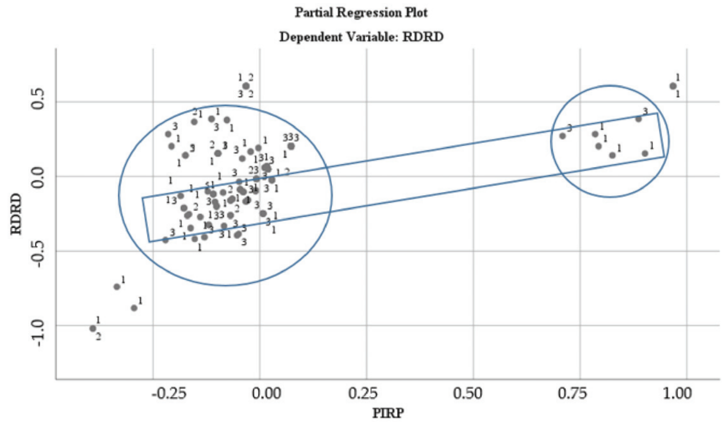

Figure 14. Regression analysis for PIRP.

Development of coherent agricultural policies—PIAP represents a viable solution (*O4*) under the conditions of a maximum correlation coefficient of 0.950. Thus, a strong/ maximizing direct correlation is estimated, which indicates that, in the opinion of the respondents, the development of coherent agricultural policies represents the most efficient measure of rural development for Romania. The trend is unitary on the cluster and presents a normalized punctual evolution around the median value of the dependent variable indicator (see Figure 15).

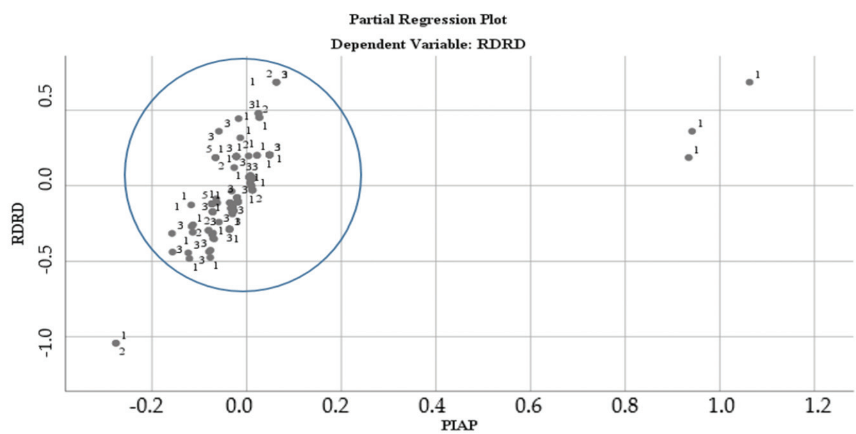

Figure 15. Regression analysis for PIAP.

Supply chain reduction—RDLC has a minimum negative correlation coefficient (−0.062), which indicates an insignificant indirect correlation that reflects that the reduction of the supply chain is not an alternative for rural development.

RDLC showed the market mechanisms succeeding to streamline operational and commercial chains for carrying out agricultural activities in Romania. The trend is unitary on the cluster and presents a normalized punctual evolution around the median value of the dependent variable indicator (see Figure 16).

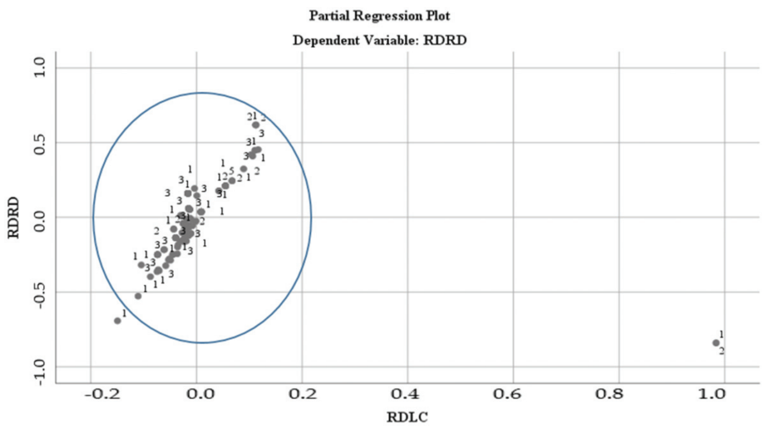

Figure 16. Regression analysis for RDLC.

5. Conclusions

Following research, we found that government financial support is a pivotal development tool for agricultural holding companies, provided that the support activity is focused on concrete measures that allow economic agents in the region to access and successfully implement the support measures.

The economic-financial framework becomes a tool for sustainability if it is periodically reviewed and improved and has an effect on the majority of holding companies in the region. Otherwise, it tends to become a disruptive factor that polarizes opportunities in favor of the regional leaders, discouraging free competition and reducing the region's sustainable agricultural dynamism.

According to the research, it resulted that, although associative forms represent an opportunity for rural development in Romania, they are not used efficiently, being identified during the research several vulnerabilities that affect the maximizing development function of holding companies. Among the elements of vulnerability, we identified the organizational aspects related to the holding companies, such as: promotion of the holding companies, dissemination of the benefits and obligations of the association, strategic cooperation with the authorities, involvement of the holding companies in regional cooperation programs and measures regarding the reduction of logistics chains.

On the other hand, the measures needed to strengthen the role of holding companies in rural development are: improving the legislative framework, adopting concrete measures of economic stimulation, economic fruition of support measures by transposing them into a sustainable economic growth of holding companies, improving strategic cooperation with other bodies than public authorities, promoting transparency and traceability of the profession, and intensifying the most viable measure, namely the development of coherent agricultural policies, which has, according to the developed model, a direct impact on rural development together with the development of viable programs at the regional level.

In this context, rural development becomes a pole of growth in terms of the good management of identified measures and in terms of reducing vulnerabilities through well-targeted policies and actions, with a stimulating effect for holding development and rural development. The limits of the study consist of the relatively limited number of the analyzed indicators. There may be other relevant indicators able to improve research findings. Moreover, the number of respondents to the questionnaire may be increased in a future approach.

The authors propose their extension to other significant aspects regarding rural development in future research. This future research will relate to the pandemic context and, by connecting to the sustainable dimension of agricultural holding development, including through the use of the IoT (Internet of Things), considering the study of [3] or Big Data.

The authors state that there is no conflict of interest regarding the data used in the research.

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What Drives the Choice of Local Seasonal Food? Analysis of the Importance of Different Key Motives

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Abstract: Local seasonal food choices are environmentally relevant behaviors and a promising opportunity for enhancing sustainable food consumption. Therefore, we need a more integrated understanding of motives driving consumers to opt for food that is produced locally and also in its natural growing season. The aim of this study is to (i) identify which motives for local food choices are also relevant for local seasonal food choices and (ii) investigate whether environmental motives become (more) relevant for these environmentally friendly choices. To assess consumer perceptions of socioeconomic, health, and environmental aspects, a survey in combination with a choice-based conjoint experiment to measure consumer preferences for seasonal (apples) and non-seasonal choices (tomatoes) was conducted. The data were collected by means of an online-panel survey (n = 499) and analyzed using two structural equation models. Results revealed that while the support of the local economy presents the most relevant driver, consumers' price sensibility is even more relevant as a barrier. What differs is the relevance of authenticity and local identity. While local seasonal food provides environmental benefits to consumers, these benefits have no implications for the relevance of environmental motives. Based on these findings, we derive evidence-based recommendations for policymakers and marketers and propositions for future research regarding additional drivers and barriers for local seasonal food consumption.

Keywords: seasonal food; local food; choice-based conjoint analysis; discrete choice experiment; consumer preference; sustainable consumption; structural equation modeling

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1. Introduction

Food choices are environmentally significant behaviors linked to the exploitation of resources such as land, water, raw materials, and the emission of greenhouse gases (GHG) [1–3]. Globally, food consumption accounts for 48% of household impacts on land resources and 70% of impacts on water resources [2]. GHG emissions of non-vegetal foodstuffs mostly result from non-fossil emissions, whereas the emissions of vegetable foodstuffs mainly stem from energy use in farming, transportation, and preparation of food [4]. The almost constant availability of different food products, regardless of seasonal conditions, resulting from the globalization in the food trade, for example, has led to a remarkable increase in the travel distance of food [5]. Consequentially, consumers demanding food according to its place of origin, production process, or producers plays an important role in the sustainability discourse [6,7]. As such, individuals choosing to eat locally harvested, seasonal, and/or organic food and follow a vegetarian diet have a lower per capita environmental impact than those relying on more customary diets [8]. The transition towards sustainable diets basing on organic, local, and seasonal foods, thus, presents an opportunity to advance commitments to sustainable development [9,10]. Vita et al. [11], for example, recommend policies to favor the synergies between local, seasonal, and organic agriculture, as these might lead to dynamic effects that can further improve sustainable food consumption. To promote and implement relevant policies, knowledge about the individual's motives driving the consumption of local, seasonal, and organic food products can be valuable. Such insights might assist policymakers and marketers in designing appropriate, target-group oriented communication strategies aiming at fostering sustainable food consumption [12,13]. Examples include public information campaigns and marketing cues aligned to underlying motives.

To provide relevant insights, researchers from different backgrounds investigated the role of different values, beliefs, and attitudes as drivers for sustainable food choices. Currently, the majority of studies focuses on either organic food [14–16], local food [5,17,18], or a combination of these two attributes [7,19–21]. In the case of local food, the review of Feldmann and Hamm [12] reveals that the consumer perceptions and preferences are manifold and relate to product quality (i.e., freshness, healthiness, and taste), the support of the local economy, and care for the environment. Seasonal variety was mentioned as a contextual factor related to local food [12]. Consumers, for example, in general perceive local food as healthier, more nutritious, and generally of higher quality [18,22,23]. Their preferences for local food are furthermore often positively related to consumer ethnocentrism [24], whereas consumers' price consciousness often poses a barrier for local food consumption [17]. While local and seasonal food is frequently associated with environmental benefits, resulting in the of use environmental concern as a common motive [1,7,25,26], respective findings regarding the relevance of environmental motives as drivers in the literature are often ambiguous [27].

Although the extant literature assesses the relevance of single motives or groups of related motives in parallel efforts, it falls short of integrating the variety of relevant motives to identify each motive's relative importance as a driver for sustainable food choices that combine local and seasonal attributes. Combining different motives can however potentially reveal trade-offs between them [13]. To our knowledge, studies evaluating the motives underlying the valuation of seasonality in combination with aspects related to origin are scarce. Most research focuses on specific and singular sustainability-related food options [28]. The few studies which combine different sustainability-related aspects (i.e., local and organic production) assessed consumer preferences for the different options by means of a choice-based conjoint (CBC) analysis [5,29]. While limited, the number of studies that investigate the choice of in-season food exclusively or in combination with organic or local food choices do demonstrate the relevance of considering this combination of attributes for a sustainable food choice [1,30,31]. As such, the study of Foster et al. [31] claims that a strong focus on seasonality exclusively is unlikely to deliver large environmental benefits.

Researchers such as Lazzarini et al. [32] and Aldaya et al. [33], among others, emphasize that a focus on local food alone is insufficient to reduce environmental impacts. Consequentially, to reduce environmental impacts regarding the primary energy use (PEU) [30] and water use [31], it is relevant to consider both locality and seasonality in the food choice [28,33]. With this study, we thus want to bridge this research gap and identify which motives are relevant to drive a consumer's preference for and choices of food that is local compared to food that is both local and in-season (and thus more environmentally sustainable). More specifically, we want to empirically investigate whether environmental motives, for example, compared to socioeconomic motives, become (more) relevant for local food options that offer additional environmental benefits by also being produced in season. Methodologically, in line with previous research on local organic food choices [5,29], we presented the different food options to consumers within a CBC experiment. We thereby aim to address divergent findings in the literature regarding the relevance of environmental motives to drive local food choices [17,34,35].

Thus, we first investigate (a) the concepts of seasonal and local food and (b) the relationships of motives and barriers and food choices in the context of local seasonal food and local non-seasonal food to develop testable hypotheses for the empirical study. We use a CBC analysis to measure an individual's preference for local seasonal food in combination with the assessment of five motives and one barrier for choosing these foods.

We then analyze the choices of individuals and the relative influence of the different motives. Accordingly, we analyze the relevant relationships by integrating the motives as independent variables and the choice of local seasonal food as a dependent variable in a structural equation model. Based on the insights gained on the relevance of different motives to drive consumer preferences for and choices of local and seasonal food options, we followingly aim to derive effective and evidence-based recommendations to assist policymakers and marketers in the communication and target-group-oriented promotion of sustainable food consumption.

2. Conceptual Model

2.1. Concept of Local and Seasonal Food

The definition of "local" in the context of food varies across studies, ranging from references to travel distances, political boundaries, and specific criteria to more holistic approaches related to, e.g., ethical dimensions such as personal relations [12]. Accordingly, there is no consensus on the definition of what is local [36]. The extant literature reveals that, in some cases, researchers avoid defining the term for consumers and instead instruct study participants to respond to questions according to their perception of what is local [36], or examine their perceptions by providing different definitions of local food, i.e., produced within a certain distance, within a state or a country [5,21]. In other cases, while acknowledging definitions of local food according to travel distances, researchers often use the domestic origin of food as a proxy for its locality [18,32,37], and domestic food as an example for local food [1,33]. This rather broad understanding of local as domestic presents an important driver for the demand for local food [37]. While consumers have a low country of origin accuracy across many product categories [38], they tend to use domestic origin cues as a heuristic to evaluate unprocessed food in terms of healthiness, quality, or environmental footprints [22,32]. This especially holds true for developed countries, where consumers tend to prefer domestic products [29]. Considering the domestic origin as a salient option for defining, demanding, and evaluating local food, we thus define, for this study, local food according to the political boundaries of a country and use domestic and local food synonymously.

With regards to seasonal food, there are different perceptions of what is seasonal, resulting in a production-oriented global definition, and a consumer-oriented local definition [27,31]. The global definition is production-oriented and views seasonal food as food that is outdoor-grown or produced during the natural growing period for the country where it is produced [27,31]. This definition applies to seasonal foods produced either domestically or overseas. In contrast, the local definition links a local production to local consumption, thus defining seasonal food as produced and consumed in the same climatic zone without high energy use for climate modification such as cold storage and heated glasshouses [27,31]. For our study, we rely on the consumer-oriented local definition of seasonal, as it considers the energy use for climate modification and thus encompasses a perspective that is more likely to deliver environmental benefits, according to Brooks et al. [27].

The overall environmental performance of local seasonal food depends upon the selection of indicators under research (i.e., PEU, footprints of water, land, material use, and carbon, as well as emission intensity) [5]. As such, the study of Canals et al. [30] found that, in the case of apples, there is little difference in the PEU of a seasonal imported apple and a non-seasonal domestic apple due to storage loss. Furthermore, Brooks et al. [27] highlight that low production standards of a product produced in season can result in higher environmental impacts compared to state-of-the-art non-seasonal production. This finding coincides with the claim that the emission intensity of production dominates the change in transportation emissions following a policy intervention related to food miles, e.g., in the context of vegetable oils [39]. Furthermore, the environmental costs must be assessed case-by-case [27] and require multi-product approaches to identify benefits available from a general shift to seasonal food [31]. Product-specific examples do often include apples and tomatoes. Apples were, as mentioned earlier, used as a case product to compare the PEU related to the transport of imported seasonal and storage of domestic non-seasonal food consumption [30]. They were further used as an exemplary product to analyze consumer preferences for organically and locally produced apples using a CBC analysis [21] and compare biases [22], as well as the perceived environmental impact [32] for domestic versus imported apples. Amongst others, tomatoes have been investigated with regard to their field production [40] as well as with regard to the import of Moroccan tomatoes compared to non-seasonal French tomatoes [41].

2.2. Consumer Preferences and Food Choice

There are numerous examples from the literature analyzing the influence of motives or perceptions underlying consumer preferences [17,20,26,36,42]. These studies are usually based on theoretical frameworks such as value theory [43], theory of reasoned action (TRA) [44] as well as theory of planned behavior (TPB) [45], and alphabet theory that combines the value-belief-norm (VBN) theory [46] and the attitude-behavior-context (ABC) theory [47]. In accordance with the underlying theoretical frameworks, beliefs, norms, and attitudes are often taken as a proxy for the perceptions of consumers. Attitudes towards local food are oftentimes used as a proxy for a consumer's preference [23,42]. Other studies use behavioral variables such as the intention and willingness to buy local foods [26] or self-reports of past behavior [17] as a proxy for an individual's food choice. The CBC analysis presents an alternative to these scale-based measures of preferences and has been recently used to estimate preferences in food choices that contain different product attributes, such as organic and country-origin cues [29] and locality labels [5].

2.3. Motives

International research shows that the motives underlying local and seasonal food choices are driven by values, beliefs, and attitudes related to socioeconomic, health, and environmental aspects. Numerous studies did for example reveal the belief of supporting the local economy and farmers by opting for local food [48–50] as relevant motive. Biases in the perception of the product quality, which can be explained by the domestic country bias [50], lionization [36], and halo effects of local food [51], further play a role for local food choices. Individuals can also choose seasonal and local food to preserve local heritage and tradition [52] or because they desire authenticity [18]. Regarding the role of environmental concerns, Tobler et al. [1], for example, concluded that numerous reasons are underlying ecological consumption behavior, of which not necessarily all have to focus on the environmental outcome of the behavior [1]. Correspondingly, Brooks et al. [27] found that reducing the personal environmental impact often plays a secondary, if not tertiary, role for the purchase. We followingly elaborate on the different motives in detail to develop our research hypotheses.

2.3.1. Consumer Ethnocentrism

Consumer ethnocentrism is defined as, "*beliefs held by consumers about the appropriateness, indeed morality, of purchasing foreign-made products*" [24]. The construct is based on the formation of "we-group" feelings, which define the in-group as the focal point, and all out-groups are judged in relation to it [53]. The construct aims to reflect normative beliefs concerning the appropriateness of buying domestic products compared to the inappropriateness of buying foreign products [54]. Accordingly, ethnocentric consumers are inclined to view the purchase of imported products as wrong, as according to them it affects the domestic economy and is not in congruency with in-group feelings of belongingness to the own society and patriotism [24]. A consumer's ethnocentrism gives the individual a sense of identity, a feeling of belongingness, and an understanding of what purchase behavior is unacceptable or acceptable in the in-group [24].

Consequentially, the construct presents a key factor influencing the preference of consumers for domestic over imported products [50]. The perception of supporting the local economy is one of the most common drivers investigated in the context of local and seasonal food consumption [23,29,42,49]. Empirical results show, for example, a positive relationship between consumer ethnocentrism and the attitude towards local food consumption [42]. Furthermore, Fernández-Ferrín et al. [49] found that ethnocentrism influences the valuation of local–traditional–regional food products. Studies investigating the role of ethnocentrism for the choice of not only domestic but also seasonal products are scarce, despite the conceptual relation of seasonal and local food. The predictive power of the concept for the choice of seasonal food is yet to be studied.

Based on the conceptual definitions and empirical evidence for the influence of ethnocentrism on the choice of domestic food, we assume that consumers' ethnocentrism also drives choices of a local seasonal food choice. Details on measurements are available in Section 3.3. Motive Measures and in Appendix A, Table A1.

Hypothesis 1 (H1). *Consumers' ethnocentrism positively influences consumers' preferences for and choice of food that is local and in season.*

2.3.2. Green Consumer Values

Green consumer values are defined as the "*tendency to express the value of environmental protection through one's purchases and consumption behaviors*" [55]. The concept is based on the motivated reasoning process that consumers with stronger green consumption values prefer environmentally friendly products. In the conceptual development of green consumer values, Haws et al. [55] refer to the Theory of Basic Values [43,56,57] and the Self-perception Theory [58]. Accordingly, individuals with green consumer values use them as guiding principles for the purchase of environmentally friendly compared to traditional products [55].

Concepts addressing the environmental concerns and consciousness of individuals (i.e., ethical sustainability) are often used in the context of local food consumption, as consumers associate local food with shorter transport distances and reduced GHG emissions [1,7,25,26]. In the context of seasonal food, Tobler et al. [1] found environmental motives underlying the participants' willingness to eat seasonal fruits and vegetables. These motives are partly covered by evidence from life-cycle analysis (LCA) on seasonal and local food reporting improvements in the performance of single environmental indicators [30,31,39,41]. A recent study further showed that from all consumer segments based on knowledge about sustainable food consumption, the segment focusing on origin attached the highest relevance to origin, transportation, and seasonality [59]. There are, however, also a number of studies that found no empirical evidence for the influence of environmentally driven motives in the choice of local products [17,27,34,35].

Consequently, studies reveal divergent results regarding the influence of environmental motives, such as green consumer value, on the choice of local products. We assume that adding seasonality as a product attribute to local food choices can add to the perceived environmental benefits of the food choice and enhance their green consumer value. Thus, we hypothesize that green consumer values will have a positive influence on the choice of local food that is also seasonal.

Hypothesis 2 (H2). *Green consumer values positively influence consumers' preferences for and choice of food that is local and in season.*

2.3.3. Local Identity

"*A local identity consists of mental representations in which consumers have faith in and respect for local traditions and customs, are interested in local events, and recognize the uniqueness of local communities; broadly, being local means identifying with people in one's local community*" [60]. The concept is based on the optimal distinctiveness theory, suggesting that the diagnosticity of a primed identity can be implicitly affected by whether people engage in integrative processing compared to differentiative processing [61]. In the context of product choices, Zhang and Khare [60] propose that a more accessible local identity influences their preferences for local products.

In line with this proposal, studies found that local identity predicts the valuation and purchase of local food products [62,63]. Local food is perceived as a way to preserve local heritage and traditions according to Seyfang [52]. Thus, we assume that based on the conceptual definition of identity, individuals who, for example, care for local traditions and customs are more likely to choose local food over imported food. This is due to the ambition of these individuals to integrate, e.g., their food choices with the local identity's characteristics [60].

Local identity and its effects on not only local but also seasonal food consumption has received scant research attention. As local food can address a consumer's local identity, we, however, assume that seasonal food can be specifically linked to the season the food is typically harvested (e.g., apples in autumn), as well as to regional and cultural history, e.g., Wachau apricots [64]. Based on the conceptual overlaps of local and seasonal food, we believe that the effect of local identity predicting the valuation and purchase of local food is even more pronounced for local seasonal food. Hence, we hypothesize the following effect:

Hypothesis 3 (H3). *Consumers' local identity positively influences consumers' preferences for and choice of food that is local and in season.*

2.3.4. Authenticity

Authenticity in the context of products can be conceptualized as perceived brand authenticity, defined as, "*the extent to which consumers perceive a brand to be faithful towards itself (continuity), true to its consumers (credibility), motivated by caring and responsibility (integrity), and able to support consumers in being true to themselves (symbolism)*" [65]. As seen in the conceptual definition, authenticity can relate to the self, e.g., by being true to one's self, or external entities, e.g., by projecting one's beliefs, expectations, and perspectives onto an entity [66]. In order to create a narrative sense of the self, consumers follow practices, such as authenticating acts or authoritative performance [67]. These practices include creating agency through purchases or creating and sustaining shared traditions [67]. Accordingly, consumers seek authenticity in consumption acts [67,68]. Hence, Morhart et al. [65] concluded that consumers will respond positively to brands that they perceived as authentic. Riefler [69] further found that the positive effect of authenticity can even mitigate the competitive disadvantages of global brands in localized markets. This indicates the relevance of authenticity as a key determinant for food choices.

In the context of local and seasonal food, consumers also pursue social and locational authenticity through consumption patterns [70,71]. Indeed, the study of Bryła [72] showed that the perceived authenticity of a product is strongly connected to its origin and sale in the region of origin. In the context of brands, localness was found to be an important brand attribute that helps to drive authenticity perceptions [73]. Furthermore, Ditlevsen et al. [18] found the desire for authenticity to be an important motivation for consumers of local foods.

Stemming from the conceptual nature of authenticity and the use of the concept in the local food context, we believe that authenticity can likewise be a motive for the choice of food combining local and seasonal attributes. This assumption is based on the connection of seasonal food to locational authenticity, as in certain harvesting seasons the consumption of certain seasonal food can be linked to traditions and local heritage. As the authenticity of a local and seasonal product is based not only on the product itself but on agricultural aspects, we propose that the perceived authenticity of local agriculture and local seasonal products influences food choice.

Hypothesis 4 (H4). *Consumers' perceived authenticity of the local agriculture and local food positively influences consumers' preferences for and choice of food that is local and in season.*

2.3.5. Healthiness Bias

The domestic country bias [50] includes the perception that local food is healthier, which is thus also referred to as healthiness bias [22] and more recently as lionization [74]. It can be defined as a "*systematic tendency to evaluate domestic products as healthier than equivalent foreign products*" [22] or as "*a belief that local foods possess superior taste and quality*" [36] within the food context. The construct, like ethnocentrism, is conceptually based on the formation of an in-group and an out-group being judged using the in-group as a reference [24,50]. The healthiness bias can be manifested in a consumer's perception and purchase intention of products [75]. It presents a self-beneficial motivation for the food choice [36]. As Balabanis and Diamantopoulos [50] found, the bias can be production/origin-specific.

So far, studies have mainly focused on origin-specific biases, which assess whether consumers perceive food products differently if they are domestic [18,22,23]. Research on the production-specific bias (for example, in the context of seasonal food) is rather limited and focuses on organic food. A review paper on that can be found in Aertsens et al. [76]. Regarding seasonal food, Tobler et al. [1] found their study participants to be convinced that seasonal fruits and vegetables taste better. Gineikiene et al. [22], among others, provided empirical evidence for the relation of the healthiness bias and the choice for domestic products. They further found that the positive effect of the healthiness bias on the choice of domestic products holds through different product categories such as apples, tomatoes, bread, and yogurt [22]. Furthermore, lionization as a part of the locavorism concept [74] predicts the attitude towards buying local food [36].

Hence, based on the conceptual nature of the healthiness bias or lionization and its relation to domestic food consumption, as well as the empirical evidence for the predictive quality of the belief on domestic food choice, we develop the following hypothesis, again considering the conceptual relation of seasonal and local food:

Hypothesis 5 (H5). *Consumers' perception of domestic and seasonal food as more natural, healthier, and tastier positively influences consumers' preferences for and choice of food that is local and in season.*

2.3.6. Price Consciousness

Price generally is one of the most important marketplace cues due to its presence in all purchase situations [77]. Price consciousness is defined as *"the degree to which the consumer focuses exclusively on paying a low price"* [77] and represents one of several price-related constructs. The construct stems from the marketing literature and is one of the constructs consistent with a perception of price in its "negative role" as an outlay of economic resources [77]. Consequentially, a high price can function as a barrier to the purchase of a product and thus presents an important food choice motive [78]. In a segmentation study, Scalvedi and Saba [7] found that non-local consumers were motivated in their food choice mainly by the brand and price. Accordingly, several studies associate price as a barrier to local food purchasing [17,26,34].

Based on the findings from substantive literature, we believe that the price of a food product can outweigh the utility of less present cues, such as origin and seasonality. Therefore, we assume, the price presents a barrier to the local seasonal food choice, leading to the following hypothesis:

Hypothesis 6 (H6). *Consumers' price consciousness negatively influences consumers' preferences for and choice of food that is local and in season.*

2.4. Conceptual Model

The conceptual model for this study, built upon the developed hypotheses following the literature review, is depicted in Figure 1. It assumes that the consumer preferences and choice of local and in-season food depend on a consumer's ethnocentrism, green consumer value, local identity, perceived authenticity of the local agriculture, healthiness bias and price consciousness. These motives are then also used in a conceptual model, which includes the preference of consumers for local but non-seasonal food as a dependent variable. The dependent variable of the conceptual model "Local and (non)local seasonal food choice" (LC) is measured by means of part-worth utilities; the latter are approximated by the CBC analysis (see Section 3.2).

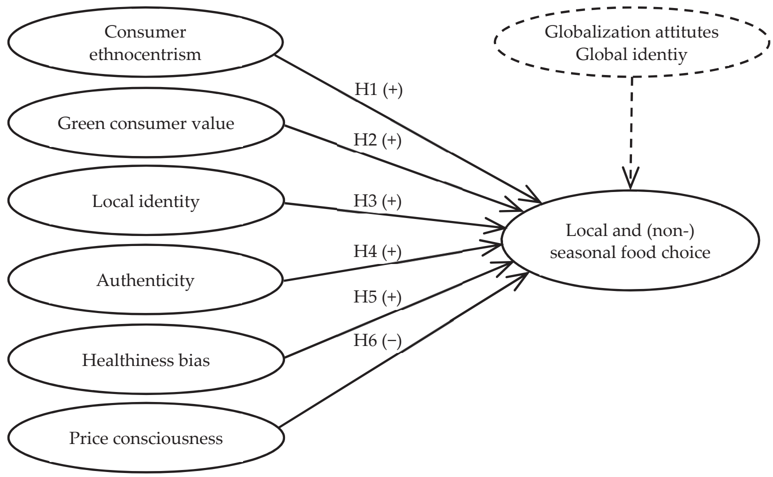

Figure 1. Conceptual research model.

In addition to the motives, for which we developed a hypothesis regarding their influence on local and (non)seasonal food choice, we included two control variables to balance the relation between motives driving and hampering the respective food choice. These are a consumer's globalization attitude, i.e., a positive evaluation of economic globalization [79], and global identity, i.e., a mental representation in which consumers see themselves as part of a global community [80]. These constructs were measured according to Spears et al. [79] (globalization attitude, three items) and Makri et al. [81] (global identity, four items) (see Appendix A).

3. Materials and Methods

3.1. Data Collection and Sample

The data to empirically investigate consumer motives and preferences were collected by an external panel provider in November 2019, using an online survey with an embedded discrete choice experiment with a representative sample of 499 Austrian households (quota sampling). Due to their harvesting season, we decided to conduct data collection in November to include a seasonal (apples) and a non-seasonal product (tomatoes) into our experimental design. Austria as an exemplary country imports apples and tomatoes from a number of countries, despite high self-sufficiency rates of these products [82]. To ensure representativeness and variance in the sociodemographic profile of respondents, quotas for age (range 18–65), gender, education, and residence were set accordingly. The sample was further screened for the (at least partial) responsibility of respondents for their household's grocery shopping and the consumption of the case product. Before the launch of the actual survey, about 10 individuals were asked to test the survey design and context for comprehensibility and functionality.

The survey consisted of (i) an assessment of the sociodemographic characteristics of the respondents and (ii) a discrete choice experiment, which is a common method for the analysis of consumer preferences for different product attributes [83,84]. The design and analysis of the CBC to assess consumers' preferences and the measurement of underlying motives are elaborated in detail in the following section. The final part (iii) of the questionnaire covered values, beliefs, and attitudes assumed to be underlying motives of choice responses using pre-developed scales from previous research. As a measure against the common method bias, the survey included a methodological separation of measurement in the study design (i.e., use of different scale formats to assess the independent variables (e.g., motives) and dependent variable (i.e., consumer preferences) [85,86].

3.2. Discrete Choice Experiment: Design and Analysis

Discrete choice experiments are based on the random utility theory [87–89]. Respondents are asked to choose out of a set of product options the most appropriate one (or none of them). The product options combine different product attributes sourced from a defined attribute set [90]. Based on the random utility theory it is assumed that the respondents will select the product option that represents the maximum utility perceived. Thus, the CBC analysis aims to reveal the weight of preferences consumers have towards single product attributes [91]. This method has the key advantage of further revealing apparent trade-offs made between the different product attributes and levels compared to an assessment of consumer preferences that uses hypothetical questions. These experiments are, thus, less influenced by response styles from scale use [92] and the social desirability bias [93]. Consequently, discrete choice experiments are a frequently used method within consumer research, with several application examples within the context of local food consumption [5,29].

Accordingly, this study also employed a discrete choice experiment, analyzing data by means of CBC analysis, to (1) realistically simulate choice sets (including a non-choice option) of grocery shopping, (2) estimate the importance of individual product attributes, and (3) estimate part-worth utilities of individual attribute values using Hierarchical Bayes estimation for each respondent. The first step included an assortment survey of apples (n = 79) and tomatoes (n = 80) conducted in October 2019 in Austria's retail sector within actual purchase settings. This survey included the assessment of product attributes such as origin, price, and packaging with relevant attribute levels (e.g., price range, indications country of origin, package weight) used for a realistic design of product options. The second step in the design process for the discrete choice experiment included the selection of relevant characteristics of apples, representing a seasonal fruit variety, and tomatoes, representing a non-seasonal vegetable variety, according to the assortment survey in step one. Both products have high market penetration and are available as regional and imported products. Furthermore, as mentioned earlier, apples and tomatoes are often used as case products in studies regarding consumer preferences and environmental impacts of different food choices [22,41]. The product options of the CBC analysis were combined from four product attributes, including their single attribute levels. This resulted in a total of 90 (3 countries of origin × 5 price points × 3 packaging weights × 2 types of production (organic/conventional)) product options for apples and tomatoes (see Table 1).

Table 1. Design of the choice sets.

Attribute	Levels	Apples (n = 250)	Tomatoes (n = 249)
Origin	Domestic Country 1 Country 2	Austria Italy Poland	Austria Spain Netherlands
Organic	no yes	conventional organic	conventional organic
Price	low high	EUR 1.29 EUR 1.79 EUR 2.39 EUR 2.89 EUR 3.49	EUR 1.49 EUR 1.99 EUR 2.49 EUR 2.99 EUR 3.59
Package size	small medium large	loose/singe Box of 6 pieces (750 g) 1.5 kg bag or net	loose 500 g 750 g

These product options were randomly selected and bundled into 10 choice sets designed following an online grocery store. A choice set provided the respondents with three product options and a fourth non-choice option, which allowed respondents to refuse the hypothetical purchase. Each respondent was randomly assigned to one of two choice experiments: one including seasonal food choices (apples) and one including non-seasonal food choices (tomatoes) by the time of the assessment in November 2019. The part-worth utility that respondents attributed to domestic (Austrian) apples and tomatoes functioned as an independent variable representing the choice of local seasonal food and local non-seasonal food. All steps in the process including random selection of choice sets, random assignment of respondents, and approximation of part-worth utilities were executed by means of the choice analytics survey software "Sawtooth Lighthouse Studio 9.7.2".

3.3. Motive Measures

The six motives functioning as independent variables were assessed using pre-developed scales selected based on previous research findings regarding their suitability and validity within the context of local and seasonal food choices.

As mentioned above, consumers' ethnocentrism was measured by four items of a short version [94] of the CETSCALE [24]. The environmental motive was assessed using the GREEN scale [55], which measures green consumer value with six items. As respondents are often prone to provide socially desirable answers regarding their environmental responsibility, we reversed the wording of two items and deleted the item "I would describe myself as environmentally responsible". The local identity of respondents was measured using four items as applied by Makri et al. [81] and previously developed by Tu et al. [80]. The perceived authenticity of the domestic agriculture and domestic and seasonal food was measured by four items adapted from Morhart et al.'s [65] brand authenticity scale. To measure the healthiness bias and domestic country bias, six items were used combined from the measures of Gineikiene et al. [22] and Aprile et al. [23]. To assess price consciousness as a possible barrier, two items were adapted from the measure of Koschate-Fischer et al. [95]. All motives were assessed on 7-point Likert scales ranging from 1 = strongly disagree to 7 = strongly agree (items shown in Table A1 in Appendix A).

3.4. Statistical Methods

The preference of consumers for domestic origin as a product attribute in both the seasonal and non-seasonal choice experiment was determined by the part-worth utility for this product attribute. This part-worth utility each individual attributed to Austria as the country of origin effect was assessed with the application of a Hierarchical Bayes estimation. A descriptive analysis of the motives and an analysis of their correlations were conducted using SPSS 26. The relationships between the motives and the choice preference for domestic and seasonal or non-seasonal products as specified in the conceptual model (Figure 1) were assessed using the Maximum Likelihood Estimation (MLE) with structural equation modeling in LISREL version 9.30. We chose a covariance-based SEM approach, as we primarily focused on the empirical confirmation of the respective relationships and their relative importance indicated by the relevant path coefficients, see [96–98].

4. Results

4.1. Profile of the Respondents

The sociodemographic characteristics of the representative sample of the study in November 2019 are described in Table 2. The sample was also grouped according to the case product to which the respondents were assigned in the CBC analysis. It is largely representative of the Austrian population, and deviations in view of age and gender were negligible. In view of the degree of urbanization, the rural population was underrepresented; concerning household size, one-person households were underrepresented as well, and the same was true for education in view of university degree. Overall, the sample consisted of 52.7% female and 47.3% male participants with an average age of 46.6 years. With regards to educational attainment, most participants absolved an apprenticeship (40.9%). Thirty-one percent of the sample completed high school or higher education. The residential areas of the respondents were evenly distributed between urban, suburban, and rural areas. Most of the respondents lived in two-person households (40.5%). Including these variables into the structural equation model (see Section 4.5) provided non-significant outcomes for age, gender, household size, etc. Accordingly, sociodemographic variables had no influence on the results of our causal model. Although there were some deviations in our sample in comparison to the total population, these deviations did not affect the reliability of our results.

Table 2. Sociodemographic characteristics.

		Apples (Seasonal)		Tomatoes (Non-Seasonal)		Total		Austria *
Variable	**Sample Size**	**250**		**249**		**499**		
	Description	**Frequency**	**Percentage**	**Frequency**	**Percentage**	**Frequency**	**Percentage**	**Percentage**
Gender	Female	129	51.6%	134	53.8%	263	52.7%	50.8%
	Male	121	48.4%	115	46.2%	236	47.3%	49.2%
Age (in years)	15–29	47	18.8%	46	18.5%	93	18.6%	15.3%
	30–44	64	25.6%	65	26.1%	129	25.9%	28.6%
	45–59	82	32.8%	81	32.5%	163	32.7%	32.4%
	60–75	57	22.8%	57	22.9%	114	22.8%	23.8%
Highest degree of education	Compulsory school	12	4.8%	19	7.6%	31	6.2%	17.6%
	Apprenticeship	106	42.4%	98	39.4%	204	40.9%	33.4%
	Vocational School	51	20.4%	58	23.3%	109	21.8%	14.4%
	Secondary school	49	19.6%	43	17.3%	92	18.4%	16.0%
	University degree	32	12.8%	31	12.4%	63	12.6%	18.6%
Degree of urbanization	Cities	87	34.8%	88	35.3%	175	35.1%	32.2%
	Suburbs	92	36.8%	82	32.9%	174	34.9%	27.7%
	Rural area	71	28.4%	79	31.7%	150	30.1%	40.1%
Household size	1	42	16.8%	52	20.9%	94	18.8%	37.8%
	2	108	43.2%	94	37.8%	202	40.5%	30.4%
	3	56	22.4%	51	20.5%	107	21.4%	14.6%
	4	29	11.6%	38	15.3%	67	13.4%	11.3%
	>5	15	6.0%	14	5.6%	29	5.8%	6.0%

* Source: Statistics Austria, https://www.statistik.at/web_en/statistics/index.html (accessed on 5 October 2021).

4.2. Results of the CBC Analysis

Hierarchical Bayes estimation was used to approximate the individual preferences of respondents regarding four product attributes: country of origin, production type, price, and package size. The part-worth utilities were estimated for each product attribute and the relevant attribute levels (see Table 3). The results show that origin had the highest part-worth utility in both choice experiments (48% for apples, 39% for tomatoes), followed by the price, packaging weight, and type of production. The part-worth utilities for all four product attributes sum up to 1. The lowest part-worth utility was set to zero within each attribute. Consequently, as seen in Table 3, respondents credited less utility to imported apples and tomatoes that are conventionally produced, have a high price and medium packaging weight. Accordingly, the higher the resulting part-worth utility is, the greater the benefit the consumer perceived for him or herself provided through the specific product attribute. Consequentially, these greater benefits result in a greater likelihood that the consumer will purchase a product with the relevant characteristics (attribute level) he or she perceives as beneficial [99]. Mean, standard deviation, minimum, and maximum can be taken from Table 3; it shows the wide range of values based on Hierarchical Bayes estimation. According to Hypotheses 1–6, we assume that the importance of the attribute "Local" (i.e., domestic origin of the product) is influenced by the motivational structure of respondents (research model in Figure 1).

Table 3. Estimated part-worth utilities (aggregated).

Attributes and Levels	**Apples (Seasonal)**				**Tomatoes (Non-Seasonal)**			
	Mean	**Std. Dev.**	**Min**	**Max**	**Mean**	**Std. Dev.**	**Min**	**Max**
Origin	0.474	0.211	0.032	0.864	0.393	0.203	0.012	0.790
Local	0.471	0.215	0.000	0.864	0.386	0.213	0.000	0.790
Country 1	0.157	0.073	0.000	0.381	0.029	0.040	0.000	0.242
Country 2	0.001	0.008	0.000	0.069	0.025	0.048	0.000	0.363
Price	0.235	0.158	0.021	0.728	0.326	0.181	0.026	0.818
low	0.235	0.158	0.021	0.728	0.326	0.181	0.026	0.818
medium-low	0.210	0.143	0.014	0.610	0.265	0.128	0.022	0.572
medium	0.142	0.102	0.005	0.505	0.202	0.088	0.016	0.414
medium-high	0.120	0.082	0.004	0.383	0.155	0.088	0.006	0.393
high	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Package size	0.210	0.112	0.016	0.660	0.187	0.108	0.004	0.571
loose	0.177	0.111	0.000	0.660	0.173	0.115	0.000	0.571
small	0.018	0.059	0.000	0.462	0.012	0.057	0.000	0.502
large	0.152	0.107	0.000	0.452	0.103	0.062	0.000	0.380
Organic	0.080	0.085	0.000	0.597	0.094	0.088	0.001	0.545
no	0.007	0.027	0.000	0.234	0.013	0.032	0.000	0.275
yes	0.073	0.087	0.000	0.597	0.082	0.094	0.000	0.545

A detailed analysis of the single choices revealed that 67% of the chosen apples and 63% of the chosen tomatoes were of Austrian, thus local, origin. If a choice set did not offer any domestic choice options, respondents refused the hypothetical choice in 43% of the cases in both discrete choice experiments.

4.3. Descriptive Analysis of Motives

Table 4 lists the results obtained from the descriptive analysis of the motives assessed (sample size $n = 499$). The mean value of all six latent variables ranged from 4.15 to 5.49, and the standard deviation ranged from 1.08 to 1.43 on a 7-point Likert scale. The mean values of all the variables were above the midpoint of 3.50. Authenticity scored the highest with a mean of 5.49, compared to price consciousness that scored the lowest with a mean of 4.15. The dispersion values, reported through the standard deviation, were the highest for price consciousness and the lowest for green consumer value.

Table 4. Description of focal motive constructs.

Construct	No. of Items	Apples (Seasonal)		Tomatoes (Non-Seasonal)	
		Mean	Std. Deviation	Mean	Std. Deviation
Consumer ethnocentrism	4	5.208	1.236	5.137	1.272
Green consumer value	5	5.183	1.125	5.060	1.153
Local identity	4	5.156	1.138	4.912	1.148
Authenticity	4	5.493	1.114	5.342	1.069
Healthiness bias	6	5.259	1.085	5.173	1.038
Price consciousness	2	4.152	1.427	4.257	1.512

4.4. Assessment of the Measurement Model

Validity and reliability were determined as part of the measurement model assessment [100]. This includes an assessment of the constructs' convergent and discriminant validity by computing composite reliabilities (CR) and average variance extracted [101]. All CR scores exceeded the recommended threshold of 0.7, suggesting that the constructs had good internal consistency in both samples (Table 5). The AVE values, except for the construct of green consumer value, were all above the threshold of 0.5. AVE values below 0.5 indicate that the measurement error accounts for a greater amount of the variance occurring in the indicators than the variance in the latent variable account for [100]. In the case of the green consumer value construct, the AVE score below 0.5 was related to the low magnitude of the loading λ of the items env3 and env5. After removing these items from the measurement, the AVE of green consumer value exceeded the critical threshold of 0.5 (AVE_{apples} = 0.635, $AVE_{tomatoes}$ = 0.641). Thus, both measurement models indicated a reasonable convergent validity.

Table 5. Measurement parameters, construct reliability, and AVE scores.

Construct	Item	Apples (Seasonal)			Tomatoes (Non-Seasonal)		
		λ	CR	AVE	λ	CR	AVE
Consumer ethnocentrism	cet1	0.817	0.872	0.631	0.846	0.882	0.652
	cet2	0.754			0.767		
	cet3	0.830			0.854		
	cet4	0.774			0.759		
Green consumer value	gcv1	0.862	0.838	0.635	0.815	0.842	0.641
	gcv2	0.811			0.839		
	gcv4	0.709			0.745		
Local identity	lid1	0.771	0.861	0.608	0.813	0.846	0.580
	lid2	0.770			0.712		
	lid3	0.822			0.773		
	lid4	0.755			0.744		
Authenticity	auth1	0.800	0.915	0.730	0.851	0.905	0.705
	auth2	0.884			0.850		
	auth3	0.874			0.884		
	auth4	0.857			0.770		
Healthiness bias	hb1	0.864	0.914	0.703	0.738	0.896	0.633
	hb2	0.895			0.786		
	hb3	0.705			0.690		
	hb4	0.839			0.795		
	hb5	0.791			0.821		
	hb6	0.687			0.776		
Price Consciousness	pri1	0.669	0.813	0.692	0.761	0.797	0.663
	pri2	0.968			0.884		

Note: λ = factor loading, CR = Composite Reliability, AVE = Average Variance Extracted.

Table 6 shows the results of the discriminant validity assessment following the Fornell and Larcker [101] criterion of comparing the correlation between constructs and the square root of the AVE (along the diagonal) of that construct. The square root of the AVE for each construct was greater than the correlations, indicating that each construct had discriminant validity in both samples [101].

Table 6. Discriminant validity of the measurement model.

	Apples (Seasonal)						Tomatoes (Non-Seasonal)					
	1	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**
1 CET	0.794						0.808					
2 GCV	0.521	0.797					0.652	0.801				
3 LID	0.642	0.420	0.780				0.526	0.417	0.761			
4 AUTH	0.687	0.523	0.743	0.854			0.654	0.592	0.653	0.840		
5 HB	0.670	0.517	0.506	0.669	0.838		0.655	0.527	0.590	0.738	0.796	
6 PRI	−0.128	−0.164	0.025	−0.039	−0.035	0.832	−0.228	−0.256	0.124	−0.069	−0.016	0.814

Diagonals represent the square root of AVE for each construct, and off-diagonals represent the correlations among constructs. The diagonal elements should be larger than the off-diagonal elements to establish discriminant validity. Note: CET = consumer ethnocentrism, GCV = green consumer, LID = local identity, AUTH = authenticity, HB = healthiness bias, PRI = price consciousness.

The model fit indices of the measurement models were tested (Apple sample: chi-square = 774.544, 399 df; CMIN/df = 1.94; TFI = 0.904; RMSEA = 0.061; CFI = 0.917; Tomato sample: chi-square = 749.906, 399 df; CMIN/df = 1.88; TFI = 0.909; RMSEA = 0.059; CFI = 0.922), yielding in an acceptable fit considering commonly used thresholds [102].

4.5. Estimation of the Structural Model

After the assessment of the measurement model, the structural models for both seasonal and non-seasonal food choices were estimated, using summated scores (factor scores) of the six independent variables and fixing error variance at a level appropriate to its coefficient alpha reliability, i.e., $1 - \alpha$ [103]. We obtained the factor scores by performing an exploratory factor analysis (EFA) in SPSS 26, extracting the data based on the principal axis factoring method [104] with varimax rotation and Kaiser normalization (KMO = 0.905; df = 435; p = 0.001) [105] (see Supplementary Material S1 for factor loadings). The total variance explained was 63.79%, indicating a well-explained factor structure. Given that there was no single factor, and the first factor did not represent the majority of the variance, we can assume that the relationship between the variables was not inflated by the common method bias (CMB) [86,106,107]. According to Hypotheses 1–6, we assume that the dependent variable LC of the model (i.e., the part-worth utility for the attribute "Domestic") should be influenced by the motives and the price barrier. We, therefore, analyzed the hypothesized directions and strength of relationships captured by the standardized coefficients γ (gamma). Table 7 summarizes the results of the structural model analysis for the hypothesis testing. The data show that consumer ethnocentrism and the healthiness bias were significantly and positively related to the preference for and choice of both seasonal and non-seasonal domestic food. Followingly, Hypotheses H1 and H5 are supported. When comparing the strength of the relationships captured by the standard coefficient γ, Table 7 indicates that the influence of consumers' ethnocentrism was positive and stronger for non-seasonal food choices ($\gamma_{tomatoes}$ = 0.383) compared to seasonal food choices (γ_{apples} = 0.268), while the influence of the healthiness bias was stronger for seasonal food choices (γ_{apples} = 0.193 vs. $\gamma_{tomatoes}$ = 0.182). The results further show that the preference for and choice of seasonal food was slightly influenced by the perceived authenticity of the local agriculture (γ_{apples} = 0.130), but not by the local identity. In contrast, the local identity had a low, positive, and significant influence on the preference for and choice of non-seasonal food ($\gamma_{tomatoes}$ = 0.165). Thus, in this case, H3 is supported for the model including local seasonal food choice as the dependent variable, and H4 is supported for the model including local non-seasonal food choice as the dependent variable. The influence of price consciousness as a barrier on choice was supported for both seasonal (γ_{apples} = −0.306) and non-seasonal food ($\gamma_{tomatoes}$ = −0.429). Accordingly, the negative impact of price seemed to be even stronger for non-seasonal food compared to seasonal food. This finding confirms H6, as the influence is significant and negative between the constructs.

However, the explanatory power of these models was low, in particular for seasonal food choice where the motives and barrier explained only 25.8% of the variance in seasonal food choice. In addition, for non-seasonal food choice, the explanatory power of the model was rather low (45.8% of the variance). The control variables globalization attitude and global identity had no influence of both types of food consumption; γ was not significant. These variables were eliminated from the model. As mentioned above, the same can be said for the sociodemographic variables. These, too, did not influence LC.

Table 7. Structural model parameter estimates for the seasonal consumption model and for the non-seasonal consumption model (H1–H6).

		Apples (Seasonal)			Tomatoes (Non-Seasonal)		
Hypothesis	**Relationship**	γ	***t*-Value**	**Result**	γ	***t*-Value**	**Result**
H1	CET → LC	0.268 ***	4.193	supported	0.383 ***	6.666	supported
H2	GCV → LC	0.058	0.898	not supported	0.094	1.547	not supported
H3	AUTH → LC	0.130 **	2.068	supported	0.049	0.882	not supported
H4	LID → LC	0.015	0.225	not supported	0.165 **	2.871	supported
H5	HB → LC	0.193 **	3.122	supported	0.182 ***	3.236	supported
H6	PRI → LC	−0.306 ***	−4.533	supported	−0.429 ***	−6.952	supported
control var.	GAT → LC	−0.092	−1.353	no influence	0.005	0.084	no influence
control var.	GID → LC	0.095	1.452	no influence	−0.040	−0.707	no influence

** $p < 0.05$, *** $p < 0.001$, Note: LC = Local and (non)local seasonal food choice, CET = consumer ethnocentrism, GCV = green consumer, LID = local identity, AUTH = authenticity, HB = healthiness bias, PRI = price consciousness, GAT = globalization attitude, GID = global identity.

5. Discussion

The present study aimed to identify the relative importance of different motives underlying local and seasonal food choices compared to non-seasonal food choices. It aims to derive effective and evidence-based recommendations for promoting environmentally friendly food choices. We assessed the motives using established scales from the literature and derived the consumer preferences for local and seasonal food (i.e., apples) as well as local but non-seasonal food (i.e., tomatoes) from the part-worth utility attributed to these choice options approximated by means of a CBC analysis (including Hierarchical Bayes estimation of individual part-worth utilities). The relationships between motives and preferences were then analyzed using structural equation modeling (see Figure 2a,b). The focal objective was to identify whether environmental motives drive choices of food that delivers potential environmental benefits, as the literature currently provides divergent findings regarding the relevance of such motives. By adding the seasonality aspect in the local food discourse, this study further addresses calls from studies emphasizing that local food choices alone are insufficient to ensure low environmental impacts of the consumption, as local food is only environmentally friendly when harvested in season and derived from sustainable production systems [32].

Our findings showed that, despite respondents having a strong tendency to express values of environmental protection through their purchase, these green consumer values did not influence their choice of local and seasonal (Figure 2a) nor local and non-seasonal foods (Figure 2b). This is in line with Tobler et al. [1], who found that environmental motives for the consumption of seasonal food did not have a significant influence on the transition from considering changing to actually adopting such consumption patterns. We believe that a reason for the lack of relevance of environmental motives could lie in the complexity of understanding which and how environmental benefits result from a seasonal food choice. As Tukker et al. [8] conclude, the assessment of the environmental impact gets more complicated when comparing local fruits and vegetables produced in energy-intensive greenhouses with the "food miles" that are accrued by alternatives grown on the field in distant locations. As a consequence, one has to consider not only the carbon but also the land, material, and water footprint for a holistic evaluation of possible impact reductions related to seasonality. The complexity of this evaluation could hamper the consideration of the seasonality aspect in general. Literature findings show that consumers perceive the consumption of seasonal fruits and vegetables as less relevant to the environment than, for example, excessive packaging and more relevant than the purchase of organic food, which is in contrast to LCA results [1,108]. This might be related to an underestimation of the environmental impacts of out-of-season production [32]. Consumers seemingly attribute more relevance to the environmental impacts resulting from food transport and regard local food as more environmentally friendly due to short transportation distances [25].

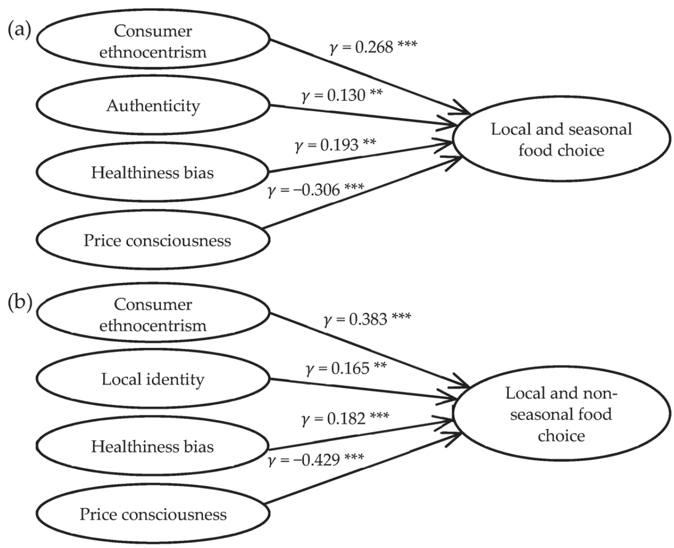

Figure 2. Evaluated research model including significant relationships between three motives and one barrier on (**a**) local and seasonal food choice and (**b**) local and non-seasonal food choice; ** $p < 0.05$, *** $p < 0.001$.

While our results showed that environmental motives influence neither the choice of seasonal or non-seasonal local food, they indicate that authenticity plays a more relevant role when choosing seasonal local food, while local identity is more relevant when choosing non-seasonal local food. We believe that this difference stems from the conceptual nature of both motives. Authenticity is a broad concept that is linked to not only the geographical origin of a product but also to traditions related to its production and marketing [63]. This layer of the authenticity motive, capturing aspects in addition to those regarding the origin of a product, could be the reason for the relevance of this motive for a seasonal food choice. The origin might not be the main aspect for the choice of food that is also seasonal, as some consumers might understand the local origin as a precondition for seasonality, according to the consumer definition of the concept [27,31]. The opposite might be true for non-seasonal local food, for which consumers then attribute even higher importance to the fact that the food is not seasonal but of a local origin, which they can relate to as part of their local identity.

In addition to revealing the relevance of authenticity and local identity as motives for seasonal and non-seasonal, local food choice, our study further confirmed the healthiness bias as the second most relevant motive in the context of local food choices. The descriptive results (see Table 4) correspond to previous findings, which indicate that local food is also perceived as healthier, better in taste, and more natural and nutritious [18,22,23,50,74]. By integrating this motive in a structural equation model to estimate its influence on consumer preferences, we confirmed the relevance of this bias not only for local food [22] but also for seasonal food.

Both structural equation models revealed that consumer ethnocentrism is a key driver for a local food choice. This is in line with previous research [23,29,42,49]. Our results show that, especially, those consumers who want to support local farmers and agriculture reach for both seasonal and non-seasonal local products. A comparison of both models showed that consumer ethnocentrism is even more relevant for food choices that are non-seasonal but of local origin. This indicates that consumers might consider it more important where a product is produced compared to how it is produced, as the support of the local economy as a key driver is more dependent upon the location than on the type of production (i.e., indoor- or outdoor-grown). The relevance attributed to origin is also seen in the results of the CBC analysis, which accordingly revealed origin as the most relevant product feature, with Austria as the domestic country having the highest part-worth utility. The part-worth utility of origin was slightly higher for apples as a seasonal product than for tomatoes as a non-seasonal product. Consumers are probably more flexible regarding the country of origin when the product is non-seasonal. An additional analysis of the choice sets, however, revealed that consumers went for the non-choice option in 43% of the cases that offered no local option. The identification of motives that underlie the non-choice of consumers when confronted with non-local food options thereby opens an avenue for future research. In this context, certain biases towards countries of origin play a relevant role and should be considered in further studies. As such, future research should also consider these biases when addressing the reasons underlying the reduced importance attributed to a local origin of non-seasonal products and the increased flexibility regarding the country of origin.

The main barrier to buying local and seasonal or non-seasonal food is price consciousness, which was more relevant than any other motive. The models of both samples showed that consumers who want to, or have to, buy cheap tend to purchase fewer local foods, which corresponds to findings from the literature [17,26,34]. A comparison of the models showed that the price consciousness is lower for seasonal (Figure 2a) compared to non-seasonal, local food (Figure 2b). This might indicate that consumers, in the case that food is both local and seasonal, attribute less importance to the price as an attribute, whereas the opposite is true for local but non-seasonal products. The results from the CBC analysis indeed show that the price as an attribute is less relevant for seasonal apples than for non-seasonal tomatoes. Both samples attributed the highest part-worth utility to a low-price level, whereas this was repeatedly less important for seasonal products.

The above discussion of the key motives and barriers shows the demand for future research to investigate further drivers of food choices that combine locality and seasonality. According to the variance explained by our model, there are further influencing factors to be considered. As such, future research could consider the relevance of environmental knowledge [109] for the choice of seasonal and local food, as our research showed that environmental values, such as green consumer values [55], are not linked to a respective environmentally friendly food choice. As a consequence, researchers could investigate whether a certain level of environmental knowledge is positively related to the preference for and choice of food that is not only local but also seasonal. As the assessment of the environmental impact of food choice gets increasingly complicated [8], and the impact of an out-of-season production might be underestimated [32], a high level of environmental knowledge could facilitate this understanding and followingly drive consumers to opt for an environmentally friendly option. As a further avenue, future research could assess amongst others to what degree a consumer's connectedness to nature [110], environmental identity [111], or ecological identity [112] influences his or her preference for and choice of seasonal products. As according to a consumer-oriented local definition seasonal food is outdoor-grown or produced during the natural growing period [27,31], consumers that feel connected to nature, or as a part of nature, could be more aware of the seasonality of different foods, which might be a motive to also opt for seasonal food. These environmental motives should, again, be integrated into analyses that include additional motives specifically related to seasonal food choices, such as the importance attributed to the foods' taste and freshness [1]. When engaging research on seasonal food consumption, it is further relevant to not only consider motives for the commission of seasonal food choices but the omission of non-seasonal food choices. From an environmental perspective, benefits can also stem from reducing food choices with a potentially negative environmental impact. An interesting driver in this context could be a consumer's past environmentally motivated consumption reduction [113]. Altogether, the inclusion of some of these variables could help to increase the explanatory power of our research model significantly, which is rather low in particular for seasonal food choice.

6. Conclusions

With this study, we aimed at contributing to a holistic concept of local food that encompasses seasonality. To reach this goal, we used a methodological mix of CBC analysis and SEM. This approach allowed us to obtain valid and reliable results leading to the following evidence-based recommendations. We conclude that policymakers and marketers should link the consumption of local and seasonal food to the contribution to the domestic economy and support of local farmers. Regarding the role of price as a barrier, the main challenge for marketing local and seasonal origin as a product attribute particularly lies in strengthening the willingness to pay more as a result. The branding and labeling of food should reflect the intrinsic qualities that consumers are seeking [17]; thus, we recommend marketers to consider the perceptions and expectations consumers hold towards local and seasonal food. In the communication, marketers should thus emphasize aspects related to product quality and the authenticity of seasonal food.

As our study could not identify the relevance of motives related to environmental sustainability but to economic sustainability (expressed by the support of local farmers through local and seasonal food consumption), we recommend policymakers to adopt a holistic concept of local food. Embracing a "local seasonal food" concept can, according to Vargas et al. [28], force methodological approaches that address additional layers of sustainability, further allowing more concrete results to foster sustainable consumption.

Despite the contributions, this study must be considered under the following limitations. First, seasonality is dependent on the product and season; thus, this study was limited to the choice of specific case products. To decrease certain biases towards products, we would recommend increasing the varieties of in-season and out-of-season products and further replicate this study in a different season, as different products will be seasonal. Second, in the case of this study, the primary objective for the experiment was a realistic simulation of the currently available offer in the retail stores in Austria; therefore, we did not focus on biases towards the chosen countries of origin. However, these possible biases towards the selected countries of origin could influence the respondent's choice. Third, regarding the motives, it would be interesting to assess the role of not only environmental values but also environmental knowledge regarding the actual environmental impacts of specific food choices. And forth, the data were collected in one specific, highly developed food market (Austria). Other markets that are not comparable to the Austrian market could deliver different results. This could be an interesting field of future research. Hence, we recommend future research to further investigate consumers' understanding of seasonal food and its environmental impact and to conduct these studies in other food markets. More specifically, researchers could elaborate on which conditions in retail stores facilitate and foster the choice of seasonal food. Furthermore, the joint effect of seasonality and origin cues on consumer perceptions could be further investigated, as it is currently often practiced with organic and local attributes [29]. The lack of influence of environmental motives for the choice of seasonal products could be investigated by including further barriers in the model that might explain the gap between present environmental values and the limited consideration of those when choosing products.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/foods10112715/s1, Supplementary Material S1: Factor loadings, Supplementary Material S2: SEM.

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Appendix A

Table A1. Measurement items to assess constructs.

Items of Constructs	Measurement Items	
Consumer ethnocentrism [94]	cet1	One should not buy imported food because it hurts Austrian farmers
	cet2	It is not right to purchase imported food because it causes the loss of jobs in Austria.
	cet3	One should only buy local food.
	cet4	I always prefer Austrian food over imported products.
Green consumer value [55]	gcv1	It is important to me that the products I use do not harm the environment
	gcv2	I consider the potential environmental impact of my actions when making many of my decisions.
	gcv3	My purchase habits are not affected by my concern for our environment
	gcv4	I am concerned about wasting the resources of our planet
	gcv5	I am not willing to be inconvenienced in order to take actions that are more environmentally friendly.
Local identity [81]	lid1	My heart belongs to my local community.
	lid2	I respect my local traditions.
	lid3	I see myself as a local citizen.
	lid4	I care about knowing local events.
Authenticity [65]	auth1	Local agriculture produces food that is original.
	auth2	Local agriculture puts authentic food on your plate.
	auth3	With local agriculture I know what I get
	auth4	Austrian food gives me a feeling of home.

Table A1. *Cont.*

Items of Constructs	Measurement Items	
Healthiness bias [95]	hb1	Local foods are more nutritious
	hb2	Local foods are healthier
	hb3	Local foods are more environmentally friendly
	hb4	Local food is tastes better
	hb5	Local foods have higher standards
	hb6	Local foods are more strictly controlled
Price consciousness [95]	pri1	I buy groceries mainly when they are on sale.
	pri2	Price is the most important factor for me when choosing food
Globalization attitude [79]	gat1	In my opinion, increased economic globalization encourages a maximum of personal freedom and choice.
	gat2	In my opinion, increased economic globalization leads to quality and technical advances
	gat3	In my opinion, increased economic globalization provides consumers the goods and services they want
Global identity [81]	gid1	My heart belongs to the whole world
	gid2	I believe people should be made more aware of how connected we are to the rest of the world.
	gid3	I see myself as a global citizen.
	gid4	I care about knowing global events.

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sustainability

Concept Paper

Sustainable Agrifood Value Chain—Transformation in Developing Countries

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Abstract: To service high-value international markets, many agrifood value chains in developing countries are required to transform to meet the strict quality and safety standards. This transformation process has become further complicated by increased sustainability expectations. The key players in these countries, typically smallholders, are struggling to meet this new sustainability value focus. Economic drivers pervade in this context, whilst the lack of integration often decouples producers from the end market. To address these challenges, this paper develops a framework to enable sustainable agrifood value chain transformation in developing countries. A narrative review was used to analyse the major enablers and barriers in sustainable agrifood value chain transformation specifically in developing countries. The framework novelty lies in the synthesis and prioritisation of transformations actions, by integrating three central dimensions: sustainability, governance, and value addition. The incorporation of sustainability drivers into value chain governance provides a holistic approach that balances profit maximization with social and environmental impacts, thus enabling smallholders in developing countries to access higher value markets. The framework can assist these value chain actors in identifying their transformation trajectory and guide policymakers, along with the public sector, in prioritising their intervention to overcome barriers.

Keywords: value chain transformation; sustainability; smallholders; agrifood; developing countries

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1. Introduction

To increase income, many agrifood actors in developing countries are attempting to transform their value chains to access higher value markets [1,2]. Many of these actors are smallholder farmers, who are required to interact with multiple actors when transforming their practices to join complex high-value markets, including the global market [3,4]. These smallholders have been compelled to increase their income by shifting their focus towards the value drivers of the final market. Downstream global players are progressively targeting supply sources from developing countries in the high value food industry [5,6]. However, regardless of the profit opportunity, advancing smallholder practices into a high-value market is an area that requires further exploration.

High-value markets place increased expectations on food quality and safety, which contribute to the growing relevance of sustainability as a new component of 'value' [7,8]. To service higher value markets, smallholder's goals are expanded from a singular profit agenda to include socially acceptable practices that also have minimal environmental impact. Transformation requires all value chain players to work towards an acceptable mutual outcome from production to consumption [9]. Global consumers' preference have shifted into higher value, increasingly processed foods [10] that include additional attributes to price [11,12]. Wider stakeholder pressures from society, including the World Health Organization require value chain actors to embrace sustainable production and consumption as a vital component of food security [13]. Therefore, the growing demand for sustainability practice further affects the transformation process to improve not only product quality and efficiency but also social–environmental considerations that enable the business environment [14].

Smallholders face several challenges when attempting to develop sustainable value chain practices. Prior studies have concluded that smallholder farmers in developing countries are often the weakest link during transformation, as they are typically trapped in a traditional system [1–15]. They have limited resources that constrain them from achieving high-value market requirements such as low productivity, inconsistent quality, limited education, and restricted access to market information [16–18]. Many of these barriers impede value chain participation in terms of governance and value addition [1]. For these reasons, smallholder farmers have limited power, dependent relationships, and are marginalized from more profitable markets [15].

Developing countries often undertake value chain transformation as part of a poverty alleviation strategy for smallholders [5–20]. Asia (i.e., Southeast Asia and South Asia) and Africa contain the highest concentration of developing countries with a significant proportion of smallholders in the agrifood value chains [6–21]. A poverty alleviation strategy often prioritises economic growth at the expense of social and environmental concerns [22]. In fact, smallholders, who generally have traditional practices, often lack the capacity to be fully engaged with the ideals of sustainability in high-value markets [8]. Enhanced value-adding activities by smallholders carry the potential to damage the environment and degrade social life. The agro–industrial revolution (through the development of tools, fertilizers, and planting technology) resulted in a substantial increase in land use and productivity [23]. Many of these activities have negative consequences such as overexploitation of natural resources, deforestation, and harmful waste [13].

Many studies have advanced the discussion on smallholder sustainability practice improvement in the high-value markets regarding global value chains [24,25]. Governance enhancement [15–26], higher value market linkage [27,28], and certifications [29] have been proposed as approaches to advance sustainable practice in developing countries in Asia and Africa. Most of these approaches list enablers without a clear structure, and often, they use a top–down lens to enable transformation, where lead firms design and dictate practices throughout the chain. As a consequence, many global players source from developing countries producers by controlling the value-adding activities [1–30]. This prevalent practice clearly demonstrates a marginal discrepancy in sustainable value chains, which minimizes smallholders' participation in enhancement initiatives. Moreover, most of these approaches view wider stakeholders (such as the government) as external, additional functions and overlook them as critical components. Conversely, it is widely acknowledged that stakeholders strongly influence the business environment and frequently enable smallholders' practice improvement [5–31]. While sustainable agrifood value chain transformation approaches have been insufficiently researched, the underlying enabling mechanisms remain unclear, and transformation trajectories have only been partially explored.

To address the aforementioned research gap, this paper aims to develop a framework for enabling sustainable agrifood value chain transformation in developing countries. The framework will assist actors to assess sustainability initiatives quantitatively and qualitatively [32]. The conceptual framework development in this paper uses a narrative review method. By using this method, a broad body of literature can be synthesised under an umbrella idea [33] and thus be able to support assumptions, identify research gaps, and establish integrated frameworks. A literature review, according to Snyder [34], provides the foundation for developing a new conceptual model/theory, and it can be useful to map the evolution of a particular research subject over time. Despite the fact that the narrative method heavily relies on the researcher's interpretation, the narrative structuring generally generates a perceptible pattern [35]. This type of review can be conducted through integrative review by discussing and summarizing the current state of knowledge, noting areas of agreement and disagreement [36]. The literature discussion starts with the fundamentals of agrifood value chain transformation in developing countries. The following section investigates how to incorporate sustainability drivers in value chain thinking. Thereafter, the key elements that enable the transformation process (to balance the profit maximization and social environmental aspects) are synthesized into a holistic framework to operationalize the change process.

Sustainable value chain transformation in developing countries has sparked great interest in the agrifood sector recently. This paper contributes to a deeper understanding of the enabling mechanism in several ways. While previous studies focused on postulating various enablers for sustainable value chain transformation, this paper will advance literature via the prioritisation of actions depend on value chain maturity. This study provides a structured process to assess and advance the sustainability of agrifood value chains. Further, the framework provides practitioners with information on how to enable sustainability, manage the risks of transformation, and therefore gain access to high-value markets. Finally, this study will assist policymakers to provide tailored support by prioritizing interventions to address context specific barriers.

2. Agrifood Value Chain Transformation in Developing Countries

While agrifood value chain transformation has various definitions, a classical definition by Reardon [37] describes it as the process of reforming the agrifood sector through the procurement of modernized systems. The transformation of the agrifood sector has been triggered by various modernization factors such as globalization industrial structures, technology, and consumerism [12–38]. Miller and Jones [39] elaborated further, stating that the agrifood value chain progresses towards a modern system that delivers higher market value via increased processing and stringent quality and safety standards.

Previous studies have identified a range of value chain characteristics to evaluate agrifood transformation. Boehlje [40] proposed six codependent dimensions: process flow, product flow, financial flow, information flow, incentive, and governance. Subsequently, many scholars have focused on the central role of governance, as it drives the rest of chain's activity and determines a firm's interactions throughout the chain [17–41]. Governance describes market dynamics in arranging and organizing the chain's operational rules. It generally involves vertical and horizontal integration [19–37] and information exchange [19–27]. Governance may also include incentives and assistance such as loans, warranty, recognition programs, and financial assistance through contracts and agreements [42,43]. Going further, Hidayati et al. [1] argue governance activities also have a significant impact on the actual value added activities. Value addition underscores the sequential product transformation, including physical form, space, and time, with each stage potentially contributing value to the market offering [12–45].

Value chain transformation in developing countries generally starts from a traditional value chain state and progresses towards a modern domestic or modern global value chain [2–10]. Defining transformation states and vectors provides each value chain stage with clear boundaries and future orientations. Simultaneously, it indicates how agrifood value chains can progressively become market-oriented [46]. However, market orientation may not adequately describe many immature value chain transformation processes. This is because a significant gap remains in many developing countries' value chain practices, regardless of the market requirements. According to Gereffi [47], there have been variations of governance practice used by value chain actors, despite the development of global markets. Thus, to facilitate a better understanding of agrifood value chain transformation, Hidayati et al. [1] proposed three practice maturity levels by integrating governance and value addition attributes (shown in Table 1).

Table 1. Agrifood Value Chain Transformation in Developing Countries.

Dimension	Value Chain Transformation		
	Traditional	Managed	Best Practice
Governance	Limited Integrated	Formal Integration	Collaborative Integration
System	Informal, transactional	Structured, controlled	Orchestrated, aligned
Market	Local	Modern domestic	Modern global
Value Addition	Commodity based	More processing based	Branded and certified
Value	Raw	Processed	High
Quality and safety	Inconsistent	Standardised	Superior

Source: adapted from Hidayati et al. [1].

Maturity level evaluation facilitates an evolutionary assessment in terms of experience and practice quality [48]. Table 1 provides a means to assess the maturity of practice regarding governance and value addition. Once current status is determined, transformation routes can be identified to advance value chains to service high value global markets. Practice in developing countries necessitates the adoption of an integrative structure as the bases for directing the transformation process, as integration is a fundamental factor to determine the success of value chain operations [49]. The classification of integration structure to detect transformation direction aligns with Collins [12], who highlighted that value chain managerial takes progress through three key stages: traditional chain, managed chain, and best practice management.

Transforming value chains from traditional systems in developing countries is not a straightforward task that will undoubtably face numerous challenges. To addresses this, barriers need to be identified prior to transformation and potentially be exploited to create opportunities [24]. While the discussion in this area is continuously evolving, most of the studies highlight the major barriers of value chain transformation in developing countries relate to smallholders' practice. Smallholders typically operate in a traditional mode, disjointed from advanced value chain systems [1–15]. The main barriers to advancing smallholders' practice are associated with their characteristics, which include low productivity, inconsistent quality, high transaction costs, limited skills, and limited access to market, best practice, and financial information [5–50]. These factors hinder the value chain integration via the disconnection of practices in terms of goal setting, planning, working cultures, and synchronization [51]. In addition to these barriers, several enablers have also been identified in the developing countries context. Table 2 synthesises the most pertinent barriers and enablers for agrifood value chain transformation in developing countries.

Table 2. Agrifood Value Chain Transformation Enablers and Barriers in Developing Countries.

Level (Stage)	Enablers and Barriers	Description	Sources
Niche (Farmers)	Collective action (i.e., farmer groups or cooperatives)	Collective action improves members' position and facilitates economies of scales (i.e., production, product aggregation, communication)	[5,20,27,52,53]
Meso (Buyers) and Potentially Macro (Government/NGO)	Off-farm business support	Smallholders often rely on support from alternative sources of income	[54]
	Access to service	Service access improves the opportunity to capture higher-value products (i.e., input, finance, technical expert, information sharing, production improvement)	[5,52,53,55]
	Access to market development	Many smallholders can be reached through the facilitation of market projects (establish contract terms, negotiation capacity, collaboration, standard arrangement)	[1,50,56,57]

Table 2. *Cont.*

Level (Stage)	Enablers and Barriers	Description	Sources
Meso (Buyers) and Potentially Macro (Government/NGO)	Capacity enhancement (i.e., financial, technical, human resources)	The capacity enhancement offers technological transfer activities to deal with smallholders' technical constraints	[15,20,37,52]
	Incentive (i.e., input, price, risk on buying warranty)	Incentives encourage smallholder participation in higher-value markets	[27,37,43,58]
Macro (Government)	Regulation within facilitation	Government policies and assistance to support smallholders (i.e., producer organization development, service, and market support)	[5,45,58,59]
	Infrastructure	Infrastructure impacts quality of high-value food, transaction costs, and information (i.e., transportation, telecommunication, etc.)	[2,43]
Macro (NGO)	Assistance from public sector	The public sector represents community responses and often provide assistance to meet their requirements (i.e., Networking, Capacity Building, Monitoring)	[21,59]

In transformational actions, setting the boundary is fundamental to clarify the enabling tasks. The key enablers and barriers of value chain transformation in developing countries are categorised into niche, meso, and macro levels in Table 2. By knowing which part drives the value chain transformation, the process can be managed appropriately based on the governance and facilitation requirements [5]. Therefore, transformation studies in the agrifood context increasingly require a Multilevel Perspective (MLP) to analyse transitions [60–62]. Within the MLP approach, value chain transformation in developing countries focuses on smallholder's perspective as the niche level, a value chain perspective at the meso level, and stakeholder's perspective as the macro level. Despite the differences in perspectives, these levels are not opposed to each other. Rather, these perspectives complement one another in terms of providing a consistent focus to enable transformation.

As stated earlier, the first critical investigation regarding value chain transformation is the smallholders' perspectives. The information pertains to smallholders' characteristics along with their intention to participate in the transformation process [28] and their capacity to scale up operations through horizontal coordination [52–63]. The attention then turns to the value chain stage perspective. Through a vertical coordination lens, the value chain perspective explores the relationship between smallholders and buyers. Due to the need to obtain consistent supply, buyers frequently combine buying processes with facilitation approaches to motivate smallholders to participate in the chain [58]. Finally, the last stage is to consider stakeholders' views in order to enable agrifood value chain transformation in a broader context.

Many stakeholders (such as government and NGOs) perceive agrifood value chain transformation as a strategy for reducing poverty in developing countries, which benefits global supply [5]. For this reason, transformation is often seen as the agenda of stakeholders, which often involves capacity enhancement and incentives [21–63]. While most assistances from stakeholders are advantageous, many of these have been associated as transient interventions and project-based operations [27–58]. Hence, despite stakeholders' interventions aimed at improving smallholders' practices [24–31], they are often considered as an additional, somewhat external player.

3. Agrifood Value Chain Sustainability

The most pressing challenge in the high-value food industry is sustainable practice. Value chain actors are required to refocus on 'value' from the multifunctionality elements of sustainability [7]. In general, Choudhury [64] introduced the sustainability concept as a global system that focuses on environmental, social, and economic elements, which fulfils the needs of current generations' whilst considering future generations' ability to meets their needs. To respond to the urgency of sustainability in the agrifood sector, many scholars stress sustainability as a foundation for long term food security [55,65]. The World Health Organization (WHO) defines food security as economic and physical access of agrifood activities that adhere to sustainable production and consumption principles [13]. Aligned to this food security definition, sustainable value chains are defined in accordance with FAO [19] (p. 6):

> *'The full range of farms and firms and their successive coordinated value-adding activities that produce particular raw agricultural materials and transform them into particular food products that are sold to final consumers and disposed of after use, in a manner that is profitable throughout, has broad-based benefits for society, and does not permanently deplete natural resources'.*

Within the scope of food security, sustainability is not simply a set of indicators. Rather, sustainability is an integrated system of dimensions [54]. A value chain is perceived as an economic-based activity that accesses both social and environmental dimensions. The value chain combines resources such as natural capital, knowledge, and skills within the social structures to deliver products or services [66] in which the products also end up in the environment [67]. Based on this, the dimensions of sustainable agrifood value chains are seen as a layered system. For instance, according to Gidding et al. [67], the economic dimension exploits society and environment dimensions, and Raworth [68], who identified the social foundation and ecological ceiling as an embedded dimension, expressed as much through a doughnut economy approach. A layered or nested system, on the other hand, has a tendency to prioritise certain dimensions above others. Meanwhile, strong sustainability practice necessitates a more balanced interaction of practice. In other words, economy, ecology, and social dimensions are to be accounted for at each value chain stage [69].

A value chain is deemed economically sustainable if each stage's activities generate value that leads to profit [19–54]. Being sustainable in the social dimension refers to a value chain that is both culturally and socially acceptable. However, assessing this social dimension continues to be a daunting task [70]. Higher levels of comprehensiveness and stringency in the social dimension can only be achieved by addressing foundations on standards within scope [71]; therefore, the social dimension direction should not be limited to social acceptability. Being socially engaged would strengthen connectedness and shared meanings with the community [72]. The third dimension, illustrated in Figure 1, is the environment that refers to the actor's ability to minimize any negative environmental impacts from the value-adding activities and, if possible, have a positive impact [19–54]. To represent this practice, some scholars recommend the term 'environmentally friendly' [73,74]. However, an environmentally respectful practice better depicts the act of practicing in a responsible way by respecting the environment [54–75].

A fully sustainable value chain is only possible if all three dimensions are aligned. In a developing country's context, this will be the compelling goal, yet the most difficult task. Enabling synergic incorporation of sustainability into a value chain is an area under intense research but has been incompletely explored in developing countries' literature. In contrast, many sustainability studies have been broadly explored in developed countries [32–77]. The approach for sustainable agrifood value chain transformation has been extensively viewed from various perspectives such as the individual (farm or household), local, global (sector-specific), and plot (ex-post and ex-ante). Despite this, some fundamental principles from developed countries may serve as the foundation for this context. For instance, incorporating sustainability into agrifood value chains begins with emphasizing farm practices [74–78]. This stage plays a significant role that determines the subsequent stages' performance. Farm practices are highly reliant on environmental sources [9], the production of perishable goods [45], and supplying the basic attributes of consumer's value [12].

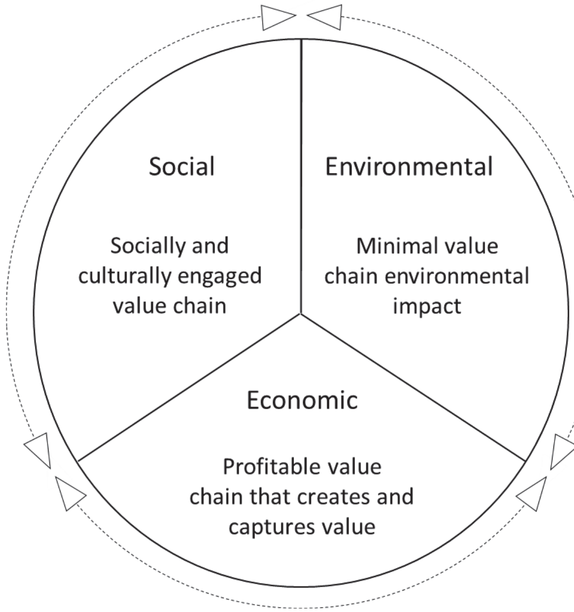

Figure 1. Sustainable Value Chain Dimensions.

The economy dimension is prioritised in developing countries [54–73]. Although the Economic for Common Good (ECG) perspective has also seen the rationale of using economic gain to tailor the other aspects [68], economic growth that jeopardizes nature and human life is no longer deemed acceptable. Nature is an asset priced beyond market value, and human life ultimately depends on the natural environment [79]. The interactions between the three dimensions can be considered as synergies, complementary, competitive, or in conflict [54–80]. To assess transformation directions, the two most contradictory routes can be consolidated as positive and negative. While the competition and conflict relationships can lead to a negative transformation, synergy and complementary relationships can help to achieve a positive transformation.

A positive economic transformation represents an improvement of profit, which can be achieved by enhanced activities such as new processes, products, or functions [75]; elimination of inefficient activities [81]; an increase of productivity [82]; and an expansion of market opportunities [69]. A positive and meaningful social transformation benefits both value chain actors and the wider society [81,83]. Value chains in the agrifood sector in developing countries are characterized by the presence of a multitude of individual smallholder farmers. Individual (or within-group) levels are determined by factors such as education, working conditions [84], farming skills, and experience [54]. However, more accurate social dimension indicators are obtained by observing social components of specific farming systems [71]. Meanwhile, a wider society level is often determined by employment, acceptable cultural practices, and the safety and quality of products and processes [84–86]. A positive environmental transformation results when natural resources are utilized in line with domestic and international regulations [83], waste handling [69], and ecosystem protection and restoration [64].

Negative transformation is the opposite of positive transformation, and value can be added or lost at each stage [19]. Value-adding often puts pressure on natural resources, resulting in environmental degradation and the eroding of social traditional norms [9]. In the same way, social conditions through the interaction of people and nature also influence ecological sustainability [87]. As a consequence, conflict can arise due to natural deterioration caused by a chain's activities [13–55]. Long-term consequences affect not only the environment but also the economic foundations, as the food industry is highly reliant on nature for the supply of raw materials [50]. Table 3 incorporates sustainability into the agrifood value chain by identifying the major enablers and barriers.

Table 3. Key Enablers and Barriers to Incorporate Sustainability into Agrifood Value Chains.

Element	Positive (Enablers)	Scheme	Negative (Barriers)	Source
Plan	The plan leads to sustainability practice in terms of long-term survival within changing contexts (i.e., input, price, productivity, regulation, market demand).	[74,84]	No available plan or orientation will make farmers (and other VC actors) difficult to recognize and adjust any sustainability requirement.	[74,84]
Information Quality	Well-defined value addition and sharing (such as products' specification, logistics, and price) would encourage farmers to capture more sustainable value.	[70,88,89]	Poor information quality will leave farmers unaware of sustainability specification (either product or practices).	[1,88–90]
Effective communication	Effective communication information (in delivery, collecting, accessing, and digital tool use) between farmers and buyers would improve sustainability practice.	[26,40,54,73,91,92]	An ineffective communication method (asymmetrical sharing) results in poor and delayed decisions.	[26,91,92]
Incentives	Incentives (i.e., financial, subsidies, tools, and price) stimulate farmers to adopt and create sustainable value.	[73,91,93,94]	Lack of incentives hinders farmers' motivation to practice sustainability.	[23,50,95]
Sustainable market	Access to the sustainable market would encourage VC actors (especially smallholders) to practice sustainability.	[93,96]	Lack of access to sustainable markets hinder smallholder farmers' sustainable practice.	[93,95,96]
Behaviour	The socio demography (i.e., farm structure, behaviour, self-identity, and motivation) motivates farmers to adopt an ecological practice.	[73,74]	The socio demography (i.e., poor in farm structure, behaviour, self-identity, and motivation) affects farmers to adopt an ecological practice.	[73,74]
Government role	Regulation may provide fundamental tasks and pressure on sustainability adoption.	[13,19,27,58,91]	Indifferent regulation hinders the sustainability implementation by smallholder farmer.	[13,19,27,58,91]
Facilitation	Facilitation from the private or public sector will escalate sustainability concerns and practice.	[24,66,97–99]	Less facilitation will hinder the sustainability implementation by smallholder farmers.	[9,97,99,100]
Certification	Certification (i.e., GAP) helps to satisfy sustainable market requirements, create transparency, and guide smallholders to integrate into a high-value market.	[19,29,44,101]	Lack of certification degrades trust and evidence of sustainable practices, which hinders high-value market expansion.	[19,29,44,101]

Amidst the variation and complexities of enablers/barriers for a sustainable practice transformation shown in Table 3, more exploration of enabling mechanisms is urgently needed. The underlying method to transform value chain practice in line with sustainability is still far from clear. Many of the enablers may work in tandem or different ways and be applied by various actors without a clear structure. A discussion on a systematic structure to leverage the sustainability enablers has been overlooked to date. Structuring the activities will help provide a clearer view of the mechanisms and synergize between players [1]. It is critical to shed light on prioritizing each stage activity in order to portray the precedence of goals while simultaneously eliminating irrelevant activities to avoid negative transformations.

Preventing detrimental transformation is the most challenging task; numerous studies have suggested the employment of sustainable value sharing as a key governance activity. Value sharing enables sustainable value inclusion into a value chain [100,102], which ultimately contributes to sustainable production and consumption [103]. The merit of sustainable value results from synergizing value chain actors (i.e., farmers and firms) in sharing their sustainability vision and willingness through a common sustainable strategy in order to avoid conflicts [70–103]. Value sharing requires further exploration to accurately capture the needs of developing countries' practice. Value sharing that exclusively focuses on value chain actors may limit the sustainability scope and overlook the critical role of wider stakeholders. Sharing activities in developing countries should address not only internal value chain actors but also external actors [69]. In the meantime, the use of the term 'external actor' for the government tends to disconnect its important function in affecting the business environments [104]. Government and/or NGOs play critical roles in determining value chain guidelines as part of the governance dimension [53]. Sustainable value creation is an ideal target, where all three sustainability dimensions are considered concurrently resulting in a commitment to delivering ecological, societal, and economical value addition [69].

4. Sustainability and Agrifood Value Chain Transformation in Developing Countries

Enabling sustainable agrifood value chain transformation is a burgeoning research area that is relatively underexplored in a developing countries context. Various approaches are often used to address the increased focus on sustainability in agrifood value chain transformation via a combination of variables as enablers. However, the persistent challenge in this area primarily lies in the enabling mechanism. In particular, how to manifest in a myriad of specific practices for smallholder actors of developing countries and convert their orientation towards sustainability requires addressing. Therefore, to advance the current state of knowledge, this paper synthesizes approaches of agrifood value chain transformation and sustainability. An organised and aligned structure of actions is indispensable to transform a value chain in developing countries [1]. The solution offered herein synthesizes three key constructs: sustainability, governance, and value addition, as shown in Figure 2. Incorporating sustainability orientation into value chain governance leads to an enhancement of value addition activities, resulting in a sustainable value chain.

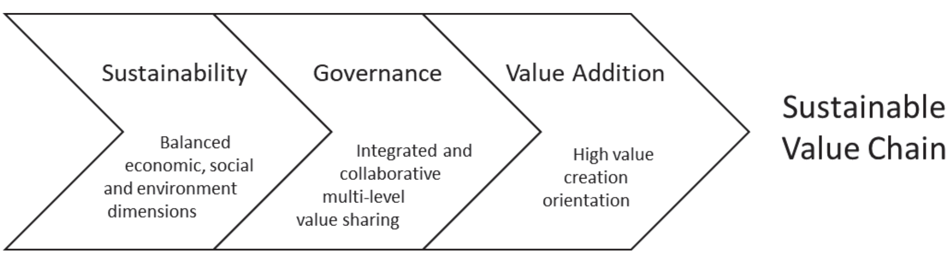

Figure 2. Sustainable Agrifood Value Chain Transformation Drivers.

The sustainability element draws attention to prior literature that highlights economic priorities in developing countries. This issue raises concern to balance the economic profit orientation with more social and environmental aspects to achieve sustainable practice. Being economically profitable is the first and primary orientation of smallholders in developing countries. Literature highlights that in order to create a profit, the enhancement activities contain a productivity increase, cost efficiency, premium pricing, and/or market opportunity [69–81].

Being socially engaged is the next important orientation to be embedded in developing countries. This dimension first considers the link between work and life quality [71]. After making a profit from farm work, smallholders would generally enhance their individual well-being via education/knowledge, skill, lifestyle, and working conditions. Meanwhile, simultaneously, literature also suggests smallholders consider activities that have an impact on a wider society [84–86]. Smallholders' consideration for broader societal requirements is primarily concerned with product safety and quality, employment issues, and acceptable cultural practices.

Operating environmentally respectful practices is the last critical and most important orientation that completes the overall sustainability in developing countries. The most fundamental aspect of environmental orientation relates to natural resource management, waste handling, and preservation. It is also important to mention that the key actors in the production of raw commodity are farmers, who thus ultimately determine environmental sustainability [80]. Hence, transformation must focus on the needs of developing technologies and practices that have minimal adverse environmental effects, which are accessible and effective for farmers while also improving productivity [90]. Galdeano-Gómez et al. [80] further state that reducing pressures on natural resources link positively to economic and social elements. Another way to see this is that a long-term economic condition can be achieved at the cost of not only social considerations but also environmental pressures [54].

The governance dimension refers to the degree of multilevel value sharing in order to capture a comprehensive sustainable perspective that suits the developing countries' context. Value sharing starts at the smallholder stage (as a niche level) to establish the scope of the practices and motivation to transform. This level represents smallholders' typology in producing the basic value at the farm stage. Smallholders generally have a heterogeneous typology [29]. Therefore, farmers' demography (within farm characteristics) frequently influences their decision to join higher value markets [28]. Next, smallholders also need to scale up operations in order to transform into a higher value market. To do so, they can develop horizontal coordination by collectively acting as producer organizations (PO) [20–52]. Collective action not only strengthens the members' positions as smallholders but also opens up new opportunities to capture more of the value from high-value markets and improves access to both markets and services [27–63].

In order to further advance activities, value sharing progresses to the wider value chain domain (as meso level). This level highlights the activities between smallholders with key buyers in the chain who play a significant role in sourcing from smallholders [1]. The relationships between farmers and buyers generally comprise transaction terms, negotiation, collaboration, and standard arrangements [1–12]. This type of vertical coordination also often includes a sourcing strategy applied by buyers to enable smallholder farmers to produce commodities that are compatible with high-value-adding chains [27].

In line with the preceding literature review, sustainable value chains in the developing countries' context need to advance the value sharing activities by incorporating stakeholders as key governance actors. Value sharing is complete once stakeholders are included (as macro level). Stakeholders enable value sharing expansion to broader actors, who can become business influencers. For ease of interpretation, stakeholders are commonly classified according to their motivations. Most governmental actions are identified as being relevant to policy setting within program implementation [27–58]. Meanwhile, the public sector is often viewed to be concerned with nonprofit activities conducted by NGOs and aid organisations [5]. Despite the difference in motivation, many of these institutions undertake similar actions to facilitate the advancement of smallholders' activities. Typically capacity enhancement programs are most relevant to harvesting techniques, storage facilities, and financial skills [50]. Meanwhile, incentives are commonly interpreted as input-, price-, and risk-related elements [37].

The value addition dimension in developing countries has generally denoted orientation to create potential value that includes: commodity-based orientation, which indicates smallholder's focus to produce and sell raw material products with minimal treatment; processed-based orientation that indicates an expansion in value-adding by smallholders via post-harvesting treatments; and branded/certified orientation, which indicates smallholders' orientation in optimizing value creation through branded and certified products.

In addition to ensuring the clarity of enabling mechanism, the direction of the dimensions should be aligned. The alignment of direction will be necessarily constructed progressiveness towards each dimension's goals. A more progressive direction in each dimension increases the possibility to achieve a sustainable value chain status [92] and vice versa. Thus, progression and regression can represent the alignment of sustainable value chain transformation.

The last alignment includes enablers and barriers, which are synthesized in Table 4. The integration of both approaches has generated four key enablers/barriers for sustainable value chain transformation. The literature contains many similarities between approaches, such as the demography within the typology of practices, information sharing, access of market and service, and facilitation. Meantime, there are horizontal coordination and certification elements, which symbolize the uniqueness of each approach. Agrifood value chain transformation approach emphasises the fundamental role of collective action, as smallholder actors are the major stumbling block [28,52], whereas certification is the ultimate goal that verifies sustainability practices [29,101].

Table 4. Sustainable Agrifood Value Chain Transformation Enablers/Barriers in Developing Countries.

Agrifood Value Chain Transformation	Enablers/Barriers	Sustainability
Characteristics	1. Demographic Typology	Behaviour
Collective Action	2. Horizontal Coordination	
	3. Vertical Coordination	
Information Sharing	a. Information sharing (information quality)	Information quality Effective communication
Access to market development Access to market service	b. Access (market and service)	Sustainable market
	4. Facilitation	
Incentives	a. Incentives	Incentives
Capacity Enhancement		Capacity Enhancement
Regulation within Facilitation	b. Advancement Practice Assistance	Government Role
Assistance from Public Sector		Facilitation (public/private)
	c. Certification	Certifications

Once the enablers/barriers are identified, the next stage is to identify who is best placed to drive the transformation. To do so, connecting enablers/barriers with the governance dimension clarifies the enabling mechanism in the sustainable value chain transformation. As illustrated in Figure 3, this starts with the smallholders, progresses into the value chain level, and concludes with stakeholder facilitation. The smallholder level covers the enabling tasks in regards to demography within the typology of farm stage practices. As smallholders' conditions are generally heterogeneous, they may necessitate group-specific support [29]. Meanwhile, the typology of practice encompasses their behaviour and initiatives to better participate and effectively distribute the value to subsequent stages. In addition to this, their initiative in connecting and obtaining resources with other smallholders is vital to scale up operations. Next, the value chain level focuses on vertical integration, which orchestrates information sharing along the chain and provides access and services to end markets. At this level, buyers' involvement is critical to enhancing smallholders' capacity for meeting the sourcing requirements. Finally, stakeholders facilitate the smallholders' transformation via incentives, practice advancement support, and certification.

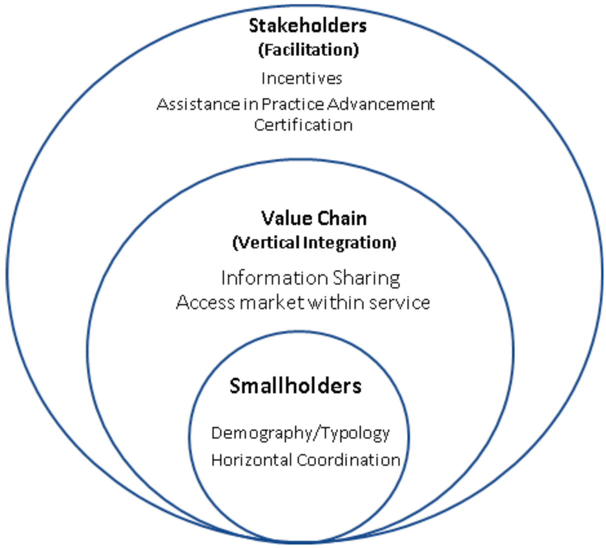

Figure 3. Sustainable Value Chain Transformation Governance.

5. Sustainable Agrifood Value Chain Transformation Operationalisation

Agrifood value chains in developing countries are aspiring to higher value markets and urgently need assistance to transform value chain practices sustainably. Smallholders are the 'transformation agent' in developing countries because they hold the majority role as produce suppliers and are responsible for the base value for any subsequent value chain stages. However, smallholders are the weakest actor in the value chain and are primary focuses on economic gains. Consequently, value chain transformation carries a high risk, as smallholder practices may conflict with social and environmental sustainability. A narrow short-term economic focus degrades the basic value produced at the farm stage, which further hinders full participation in the higher value markets [22–99]. Many social and environmental issues are under the care of government and NGOs as key agrifood value chain stakeholders [5–31]. Therefore, sustainability value has pressured the expansion of the transformational approach from 'the business as usual' in the value chain operation towards a holistic agenda.

The central contribution of this paper is the development of a framework to enable sustainable value chain transformation in the developing countries context. While previous research have focused on unearthing various enablers and barriers, e.g., [77–93], this paper focuses on the enabling mechanism of these factors in order to gain greater clarity on how to find effective transformation trajectories. Building on the preceding synthesis of literature, the development of the mechanism constitutes the structuring of the transformation process based around three major dimensions (sustainability, governance, and value addition) and transformation direction (progression or regression). Figure 4 integrates the three dimensions transformation states.

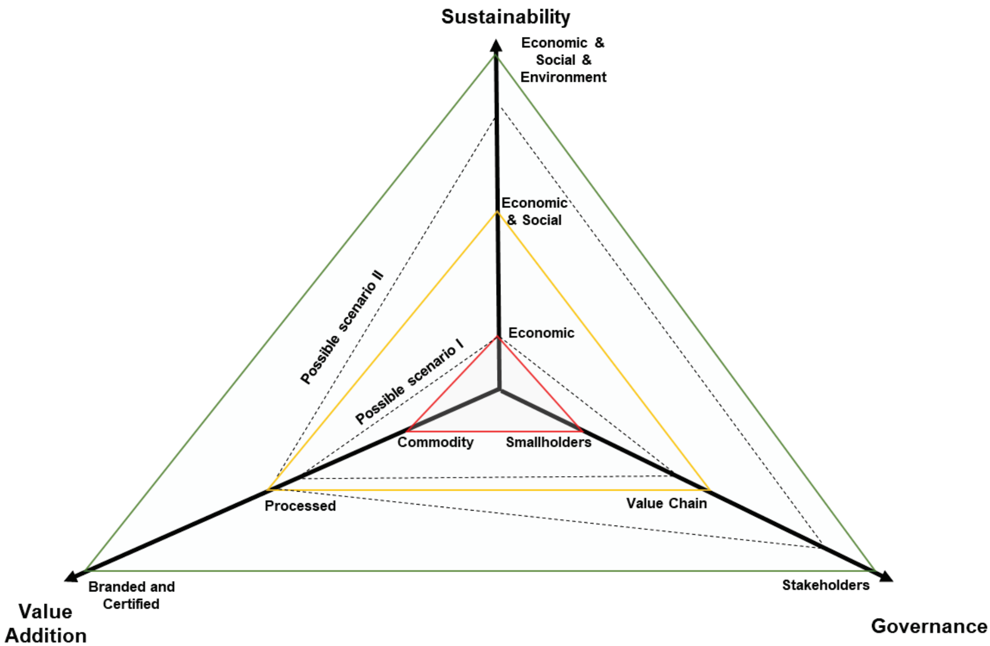

Figure 4. Sustainable Value Chain Transformation Framework for Developing Countries.

The trajectories reflect the sequential practice (in terms of sustainability, governance, and value addition) to transform into a sustainable value chain in the developing countries context. Generally, the current state of sustainable value chain practice in developing countries is assumed as smallholder-centric, with a restricted focus on pursuing their individual profitability resulting in being trapped as a commodity seller, as illustrated in the central red zone in Figure 4. Red is used to indicate this inner zone as a warning, with the lowest level of value chain sustainability. This traditional value chain state should be first transitioned into the yellow zone. Thereafter, to develop a sustainable value chain, the activities need to be shifted gradually into the green zone of Figure 4.

There is a high probability that transformation will not follow a linear stepwise path. Smallholders, for example, may have shifted their practice orientation towards a value chain perspective due to the influence of buyers, by performing more processing (shown in Figure 4 as possible scenario I). However, it is more than likely that they may continue to be driven by economic profit, putting social and environmental aspects at risk. In possible scenario II, smallholders, supported from buyers at the value chain stage and the government/NGO at the stakeholders' stage, expand their consideration towards social and environmental aspects. They might also move into more processing activities; if they are not interested in pursuing the branded and certified products, they will lose out on potential higher value markets.

To help pave the transformation path, sustainability orientation is incorporating into governance, which leads to value-adding activities required in a high-value market. Incorporating sustainability dimension into the value chain practice is fundamental by advancing the economic profit orientation towards a more socially engaged and environmentally respectful practice. To accomplish this, the sustainability dimension should be embedded via the governance dimension, with the smallholder level serving as the key initial stage in the value chain. Smallholders should progress their orientation from the farm stage towards the value chain stage and ultimately level up their orientation towards wider stakeholders. The use of a multiperspective approach is critical to appreciate the dynamics of the agrifood chain at the different scales in regards to power and the interplay of relationships [105]. By doing so, smallholders are expected to progress their value-adding activities from purely commodity-based to processed-based and to eventually achieve the branded high-value certification. In short, progressive advancement of smallholders' practice in each dimension acts as a gateway in transforming the value chain into enhanced sustainability. As a practical guide, we can position the axis of any future transformation direction by using the detail indicators in Table 5.

Table 5. Operationalisation of Sustainable Agrifood Value Chain Transformation in Developing Countries. Bold is required to emphasis and distinguish between the key elements and the derivations aspects.

Dimension	**Transformation**		
Sustainability	**Economically Profitable** 1. **Enhanced product and process** 2. **Efficient costs** 3. **Price increase** 4. **Market expansion**	**Socially Engaged** 1. **Individual wellbeing:** improvement of education, experience/skill, lifestyle, and working condition 2. **Wide society:** increase of employment, engaged with cultural practice, safe product, and process	**Environmentally Respectful** 1. **Input management** 2. **Waste handling** 3. **Preservation**
Governance	**Smallholders (Niche Level)** 1. **Demography and typology of practice** a. **Demography:** gender, age, family member, education, experience, farm size, plants, production b. **Typology:** input arrangement, farm cultivation, harvesting and labour using 2. **Horizontal Coordination:** farmer group membership, activities in farmer group (service for input, subsidy, credit, marketing, information)	**Value Chain (Meso Level)** 1. **Information communication** a. **Information quality:** products specification, logistic, and price b. **Effective methods:** digital tool and reliable informant 2. **Access and service to market development:** transaction term, negotiation, collaboration, standard arrangement)	**Stakeholders (Macro Level)** **Facilitation:** a. **Capacity enhancement:** training b. **Incentives/Support:** input and tool subsidy, credit, financial support, market connection, and expert sharing c. **Certification**
Value Addition	**Commodity-Based** Raw material withminimal treatment	**Increased Processing** Post-harvest treatments	**Brand Certified** Branded and certified product

Providing a practical assessment will benefit both individual players and industries to independently evaluate their position and prioritise their transformation. Using the indicators in Table 5, each player can perform a detailed evaluation of their enablers and barriers. Once value chain players are aware of their enablers and barriers [31], they can develop their unique plan and find the most effective transformation route. This will assist value chain actors to respond and engage with the high-value market requirements. On a larger scale, industries could examine the common issues in their value chains and collectively rectify unsatisfactory and substandard practices. Overall, the development of enabling mechanisms constitutes a powerful framework to guide developing countries' players in attaining sustainability practice, managing the transformation risks, and building strong connection with the high-value market.

Policymakers can also use the framework to evaluate specific agrifood sectors and prioritise tailored assistance activities. Facilitation to smallholders is generally offered in various forms, such as capacity enhancement (in the form of training) and incentives (i.e., input subsidy, tool, financial support) and could be further prioritised based on the urgency of each transformation case. Stakeholders need to stringently 'hit the right button' to intervene in smallholders' actions in order to provide efficacious assistance. For this reason, facilitation should ultimately lead to certification. Although certification might seem to be a long-term goal in many developing countries [29–52], certification can create a tremendous difference on practice. Certification is very empowering for smallholders to securely participate in higher value markets. Subsequently, stakeholders can take control through policies or regulations to make positive changes [19].

The framework in this paper complements and advances the existing value chains frameworks. For instance, the DFID framework [9] aims to integrate the poor (including smallholders and traditional practices) into value chains using three tools: a general tool (value chain analysis and mapping value chain), a qualitative tool (governance, linkages–relationship–trusts, and upgrading demand), and a quantitative tool (margin, income, and employment distribution). While each tool provides detailed, practical, and informative analysis, it falls short in delivering a holistic and interconnected value chain view. Furthermore, the sustainability agenda is not explicitly expressed in these three tools.

In 2014, FAO [19] developed a sustainable value chain framework using vertical coordination (governance), broad commodities scope importance, and value added along with sustainability. In 2016, FAO [50] places more emphasis on developing countries and focuses on three main strategies: equity aspects, smallholders' linkage, and policy along with public investment foundation. The framework developed herein advances the FAO approach by operationalising the actions required to advance and via the provision of transformation pathways.

To sum up, the framework represents transformational trajectories that involve a complex interaction between three primary sustainable value chain dimensions. Prioritization on one dimension at the neglect of the other two will detract from the overall achievement of sustainable value chain transformation. This framework represents the enabling mechanism, where the value given to the society takes wider environmental impacts into account [19].

6. Conclusions

This paper highlights the adversity developing countries' value chains face when transforming to service higher value markets, given additional sustainability imperatives. The sustainable value chain transformation framework developed in this paper goes beyond previous works by synthesising governance, value addition and sustainability. The framework goes one step further by stressing the need for a distinctive approach to overcoming the major problems in developing countries' transformations: the dominance of powerless actors (smallholders) and their economic orientation.

Theoretical and technical contributions are provided by the synthesised framework. Theoretically, the enabling mechanism for a sustainable value chain transformation approach is structured regarding three dimensions along with transformation trajectories. A systematic transformation approach allows developing countries' value chains to optimally arrange actions and create effective routes for a positive transformation. Technically, the development of a practical guide in this paper assists both practitioners and policymakers to investigate transformation status and improvement trajectories. The guidelines enable practitioners to assess and self-determine their transformation path to fully align with higher value market requirements. Correspondingly, the guidelines assist policymakers in terms of delivering efficacious support for the transformation process by prioritizing and placing their interventions to address specific barriers.

To verify the framework and progress the investigation, empirical tests are proposed in the agrifood sector of developing countries. The empirical testing set for this framework will necessarily focus on high-value food produced mainly by smallholders and traded on the global market. This setting would help to depict the inevitable sustainable value chain transformation, which is currently the concern of the global agrifood industry. This paper focuses on the transformation mechanism that emphasizes the positive and negative directions. These vectors and orientations require broader investigation, as trade-offs between activities on each dimension are empirically explored. Trade-offs sometimes are needed between the degree and rate for the sustainability achievement through vis-a-vis objectives [87]. For instance, it would be crucial to specifically distinguish the relationship between complementary, synergy, competition, and conflicts [54,55]. Thus, future exploration on each element's impacts between dimensions would be beneficial to verify sustainable value chain transformation mechanisms.

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Article

Financial Support Program for Small Farmers, and Its Impact on Local Food Security. Evidence from Indonesia

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Abstract: This paper addresses the implementation of the *Kawasan Mandiri Pangan* (KMP) program, a microfinance program for farmer groups, assessing whether the program affects farmers' decisions concerning production, marketing, and consumption or not, and its impacts on household food security along three dimensions: food availability, food access, and food utilization. Based on a qualitative and theory of change mixed-methods analysis, which uses interviews and focus group discussions (FGDs), this research sheds light on the program's success among two groups of farmers. Both groups experienced improved productivity and increased food availability, but only one group sustained the program. The results indicate that the program has not affected the commercialization of any particular crop, where the crop's best selling price, relationships, and commitments are factors that affect the farmers' marketing decisions. Other findings show how food access at the household level increased when the crop's selling price was reasonable, while food utilization was influenced predominantly by local wisdom. Taken together, the research findings highlight the importance of the capability of the management, the commitment of the members, and the supervision of the agricultural extension agents. There is a need for a locally owned enterprise to absorb agricultural products and maintain the selling price of crops, which is the primary driver of food accessibility and utilization at the household level.

Keywords: financial access; small family farms; food security; Indonesia

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1. Introduction

The agricultural sector in Indonesia plays a crucial role in the economy by employing 40% of its population and contributing to more than 15% of GDP [1]. More than 27 million families run family farms, with the total number of family members close to 100 million [2]. Of this total, 93% were small family farms, with one in five of them trapped in poverty [3]. Despite being economically active, these poor families experience poverty and food insecurity. One of the strategies implemented to improve food security in the rural community or for small farmers is through a microfinance program. A number of studies have carefully measured the impact of microfinance programs on household food security, such as Hidayat and Nugraha (2011) [4] on the fulfillment of household food needs in Indonesia, Baihaqi (2013) [5] on the food shortages experienced by low-income families in Indonesia, Darwis et al. (2014) [6] on the cases of staple food shortages in Indonesia, Bidisha et al. (2017) [7] on household incomes and dietary diversity in Bangladesh, Meador and Fritz (2017) [8] on the empowerment of women and household food security in Uganda, and Adnan Shahid and Bohara (2020) [9] on household food consumption measures in Nepal.

The Sekayam subdistrict, located in the Sanggau Regency, Indonesia, was selected as an illustrative case study. It is an inter-country border area between Indonesia and Malaysia with an area of 841.01 km^2 and a total population amounting to 35,141 people [2]. The community in the border area faces some challenging conditions in terms of attaining food security. Food prices in Indonesia were recorded to be higher than in neighboring countries [10], especially in the border areas between countries. This scenario is exacerbated by a common problem that occurs in border areas, which is a lack of access to infrastructure that further limits food distribution. As a consequence, the price of food commodities has escalated.

As a result, the Indonesian Ministry of Agriculture issued a set of regulations in 2014 (number: 06/Permentan/OT.140/1/2014), which included the *Desa Mandiri Pangan* (DMP) guidelines. The scope of DMP activities included KMP—a target of the program is inter-country border area communities. The general objective of the KMP program is to empower poor/food insecure people, helping them to become self-reliant. It also includes the following outputs: the distribution of social assistance funds, and the provision of training/assistance for affinity groups. The social assistance funds are channeled to farmer groups and distributed to their members in the form of loan. The expected outcomes are an increase in income, higher purchasing power among the people, and better access to food, all of which would contribute towards improving food security within the community.

This paper is aimed at addressing the following research question: what is the impact of the KMP program on local food security, and, in particular, how has it affected food availability, food access, and food utilization for households within the community? The primary aims are: (1) to explore the implementation of the KMP program in the Sekayam subdistrict, (2) to determine the impact of the KMP program on farmers' decisions as they concern production, marketing, and consumption, and (3) to evaluate the impacts of the program through an analysis of household food security among family farmers who have participated in the KMP program based on their experience in three areas, namely, food availability, food accessibility, and food utilization.

2. Literature Review

Microfinance (MFI) is defined by Robinson (2002) [11] as small-scale financial services, especially savings and loans provided to small farmers, fishers, and pastoralists or those who run small businesses that produce, recycle, repair, and sell goods, provide minor services, work on a commission basis, or earn an income from renting agricultural machinery at the local level, both in rural and urban settings.

According to Morris and Barnes (2015) [12], providers of MFI should consider the feasibility of providing individual loan products to participants who were diligent in repaying their group loans. These individuals seek to "graduate" to larger loans with collateral to secure the loan. This program is not a microfinance program, however, where the term 'microfinance' denotes the entire range of financial services (e.g., savings, money transfer, insurance, production and investment credit, and housing finance), the upgrade of skills, and entrepreneurial development, which are vital to escape poverty [13]. Rather, the scope of the program is narrower, and it simply provides microcredit for farmers, offering small loans for short durations with repayments beginning as quickly and as frequently as possible [14].

A study by the Consultative Group to Assist the Poor (CGAP) (see Mahajan, 2005) [14] revealed that only about 100 out of 10,000 MFI programs across the globe were financially self-sufficient. Thus, the dual promise that microcredit can serve the very poor in a financially sustainable manner is not borne out in practice. Experience reveals that either one of these two mutually contradictory goals can be achieved, but not both together [14].

A key issue is whether the provision of MFI to small farmers influences their decisions regarding production and marketing or crop commercialization. Most decisions related to farm production are influenced by the characteristics of the farmers in their community and the commodity's selling price at any given moment. Finnis (2006) [15] asserted that constant market demand is one of the reasons that make some crops good crops to cultivate during times of environmental uncertainty, due to their good selling price and the certainty of income from the crop. The same was reported by Baker (1995) [16] for crop decisions and cassava cultivation in Gambia (see Rigg, 1987) [17].

Crop commercialization cannot be understood solely in terms of external pressures, such as government policies [18–20]. Instead, it is necessary for researchers to consider local-level agricultural decision making [21], including the experiences and perspectives highlighted by Attwood [22] (p. 16), who referred to small farmers as "enterprising peasant families". Crop commercialization and intensification can be the result of conscious decisions based on individual and household aspirations [15]. Changes in local-level farming and crop commercialization are referred to as an "indigenous intensification of cultivation", a process that "takes place without specific external development impetus", such as government practices, NGO projects, as well as new international trade policies and rulings [15,18,23].

3. Materials and Methods

The qualitative data gathered in this study were analyzed using inductive and descriptive analyses to obtain in-depth and accurate results [24]. A non-probability sampling technique was employed, with the purposive sampling of a total of 34 informants, who comprised six key informants (one food security officer, three agricultural extension workers, and two coordinators of farmer groups), 15 participant farmers, four non-participant farmers, and nine informants for three forum group discussions (FGDs) (which consisted of farmers and other key informants). We collected primary data through FGDs and in-depth interviews, and we assessed a range of documents to obtain the secondary data. Data collection was conducted between April and August of 2019. This present study measured food security by assessing food availability, food access, and food utilization. We used several indicators to assess both food availability and food accessibility at the household level, and we used modified household dietary diversity score (HDDS) indicators and several additional questions to explore household food utilization. The indicators that were used during the interview and FGD sessions (Table 1) facilitated an exploration of the implementation of the KMP program, while concurrently helping us look into food availability, food accessibility, and food utilization within the community, with the informants telling us about their experience in their own words.

The HDDS indicators were used, which were modified from those used in the Food and Nutrition Technical Assistance (FANTA) project, which determined if a household consumed food from the seven food groups (see Swindale and Bilinsky, 2006) [25]. (FANTA was a cooperative agreement funded by USAID. The project was managed by FHI 360, a nonprofit human development organization dedicated to improving lives in lasting ways by advancing integrated, locally driven solutions.) Data for the HDDS indicators were gathered through the use of qualitative interview questions regarding the food items used in the participant's household, the relative amount used in a month, and where they obtained their food items. We asked participants to determine their household consumption over a one-month period, which we found to be more reliable than asking them to select a specific day. In deciding if a food item was often consumed in the household, a 14-day standard was used: if the item was consumed at least once a day on less than 14 days of the month, this signified that its use was uncommon (0), while more than 14 days of food consumption indicated common household consumption (1). The HDDS thresholds used in this study were <4.5 = low dietary diversity, 4.5–6 = medium dietary diversity, and 6+ = high (good) dietary diversity. Table 2 lists the HDDS thresholds proposed by the International Food Policy Research Institute (IFPRI) that were used in this study.

Table 1. Indicators used during interviews and FGD sessions.

Indicators			
No.	**Farmer**		
1.	Information related to the respondent and the household	10.	Experiences of difficulty accessing food (no money to buy food) and strategies on how to deal with such situation
2.	Duration of stay in the community/place	11.	Method and fuels used in preparing food for consumption
3.	Land for farming, plant types, and amount of annual harvest for each crop	12.	Involvement in the KMP program
4.	Crops consumed, sold, and used for agricultural inputs	13.	Use of aid/loan
5.	Current family income per month	14.	Loan application requirements and obligations of borrower
6.	Monthly income five years ago	15.	Obstacles faced in running the agriculture (program)
7.	Money spent on food and agricultural inputs	16.	The differences before and after the program, in terms of food access and food utilization
8.	Water sources for consumption and agriculture	17.	Improvements needed for this program or a similar agricultural program
9.	Determining factors for choosing food to consume and special moments for food		
No.	**Agricultural Extension Worker and Chief of Farmer Group**		
1.	Activities and outcomes of the KMP program	4.	Impact of the KMP program on farmers
2.	Procedures and obligation of the participants	5.	Other program(s) participated in by farmers
3.	Obstacles and problems in implementing the KMP program	6.	Suggestion(s) for improving the program

Table 2. HDDS thresholds proposed by IFPRI.

HDDS	Profile
<4.5	Low dietary diversity
4.5–6	Medium dietary diversity
6+	High (good) dietary diversity

The stages of data analysis in this study adhered to that prescribed by Neuman, as illustrated below (Figure 1).

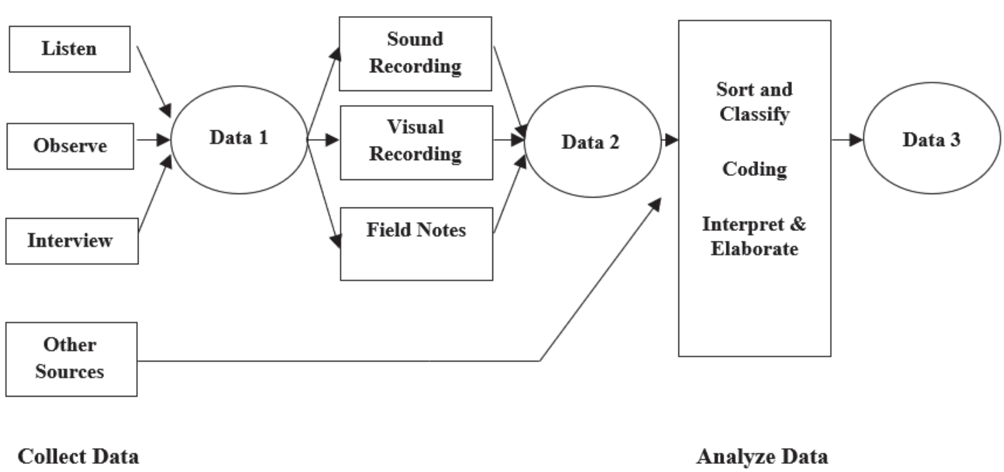

Figure 1. Data analysis process (modified from [24]).

The theory of change was also employed in this paper as a tool to creatively and productively blend our analysis with other evaluation methods, meaning that it could be applied at various levels to help us yield deeper insights [26]. In particular, these mixed methods generate the most impactful, "most significant change" stories [27]. The term "theory of change" comes from the field of program assessment. It is the process of creating a model that depicts the underlying logic, assumptions, influences, causal relationships, and projected consequences of a development project. This model may be validated by comparing it to the actual process and outcomes of the intervention [28–30]. The theory of change can be used in conjunction with other data collection and analysis methods. In this way, it is a flexible instrument that encourages analytical rigor, learning, and cost effectiveness. The theory of change allows us to question programs at all levels, including as they regard specific investments, and at community, family, and individual levels. For example, to challenge an impact investing program, we should ask: how much do impact investments help the poor and the marginalized? [26]. The theory of change is an appropriate strategy for this study since it serves the objectives of monitoring and evaluating [31]. As a theoretical framework, the theory of change has been used by Adekunle and Fatunbi [32], Mayne and Johnson [33], de Silva et al. [34], Schierhout et al. [35], and Fullan [36] in the fields of agriculture, medicine and healthcare, as well as education.

There are three communities involved in the KMP program in the research area (the Sekayam subdistrict), namely, the Ruis hamlet, the Kenaman hamlet, and the Berungkat hamlet (Table 3). These farmers planted any commodity with good selling prices that would sustain their income. They varied their crops to deal with the price volatility that could affect their income. On average, they managed 2.68 ha of farm field per household (data were obtained from all farmers, who participated in the study as informants). They mostly relied on family labor, extended family, and the community for farming activities.

Table 3. Population and farmers in the Ruis, Kenaman, and Berungkat hamlets.

Hamlet	Population	Tribe	Farmer Group	Farmer (Members)
Ruis	410	Malay	3	78
Kenaman	1370	Dayak, Malay, Javanese	7	166
Berungkat	1018	Dayak	6	153
Total	2798		16	397

4. Results and Discussion

4.1. The Implementation of the KMP Program

The KMP program in the study area was carried out in five stages (5 years), which began in 2013. The program covered the preparation, growth, and development stages, and also dealt with farmers' independence and exit strategies. The first year of implementing the program failed due to floods that struck the agricultural areas for 5 days in December 2013, which was followed by a prolonged drought for 4 months in early 2014. The social assistance fund ended with the issuance of statements of non-repayment of loans by borrowers due to natural disasters. In the next year, there were two groups participating in the program, the Karir group and Sumber Rejeki group. In the Karir group, the aid was distributed 31 times to farmers in 2015 (see Table 4), whose poor yield was evident by the state of their fields. They failed to return the loans, however, and so the roll was discontinued for other members. Meanwhile, the farmers in Sumber Rejeki group succeeded in managing the aid in accordance with the plan. Since the members repaid the loan, the roll was continued to the other members. A total 24 members of the group applied for a loan from 2015 to 2018 (Tables 5–7), and most of them re-applied for a loan (see the timeline in the Figure 2 below).

Table 4. Loan distribution among the Karir group 2015–2016 (2015 rates USD 1 = IDR 13,795 and EUR 1 = IDR 15,070).

No.	Participants	Amount of Loan (IDR/USD/EUR)	Activity
1	Farmer 1	15,000,000/1087.3/995.4	Goat livestock
2	Farmer 2	14,000,000/1014.9/929	Banana flour processing
3	Farmer 3	5,000,000/362.5/331.8	Oil palm plantation
4	Farmer 4	5,000,000/362.5/331.8	Oil palm plantation
5	Farmer 5	5,000,000/362.5/331.8	Banana plantation
6	Farmer 6	5,000,000/362.5/331.8	Oil palm plantation
7	Farmer 7	7,000,000/507.4/464.5	Pepper plantation
8	Farmer 8	8,000,000/579.9/530.9	Pepper plantation
9	Farmer 9	5,000,000/362.5/331.8	Pepper plantation
10	Farmer 10	5,000,000/362.5/331.8	Pepper plantation
11	Farmer 11	5,000,000/362.5/331.8	Motorbike
12	Farmer 12	5,000,000/362.5/331.8	Oil palm plantation
13	Farmer 13	8,000,000/579.9/530.9	Oil palm plantation
14	Farmer 14	5,200,000/376.9/345.1	Oil palm plantation
15	Farmer 15	5,000,000/362.5/331.8	Oil palm plantation
16	Farmer 16	5,200,000/376.9/345.1	Horticultural vegetable farming
17	Farmer 17	5,260,000/381.3/349.0	Chicken livestock
18	Farmer 18	3,400,000/246.5/225.6	Horticultural vegetable farming
19	Farmer 19	5,000,000/362.5/331.8	Pepper plantation
20	Farmer 20	5,000,000/362.5/331.8	Horticultural vegetable farming
21	Farmer 21	3,000,000/217.5/199.1	Horticultural vegetable farming
22	Farmer 22	3,400,000/246.5/225.6	Rice farming
23	Farmer 23	3,400,000/246.5/225.6	Rice farming
24	Farmer 24	1,800,000/130.5/119.4	Horticultural vegetable farming
25	Farmer 25	5,710,000/413.9/378.9	Horticultural vegetable/rice farming
26	Farmer 26	3,350,000/242.8/222.3	Rice farming
27	Farmer 27	6,000,000/434.9/398.1	Goat livestock
28	Farmer 28	4,200,000/304.5/278.7	Rice farming
29	Farmer 29	6,000,000/434.9/398.1	Pepper plantation
30	Women Group	12,280,000/890.2/814.9	Duck livestock
31	Karir group	25,000,000/1812.3/1658.9	Cattle activities
	Total	200,000,000/14,498/13,271.4	

Table 5. Loan distribution among the Sumber Rejeki group 2014–2015 (2014 rates USD 1 = IDR 12,440 and EUR 1 = IDR 15,746).

No.	Participants	Amount of Loan (IDR/USD/EUR)	Activity
1	Farmer 1	5,000,000/401.9/317.5	Rice farming
2	Farmer 2	5,000,000/401.9/317.5	Rice farming
3	Farmer 3	5,000,000/401.9/317.5	Rice farming
4	Farmer 4	5,000,000/401.9/317.5	Rice farming
5	Farmer 5	5,000,000/401.9/317.5	Maintaining vehicle
6	Farmer 6	5,000,000/401.9/317.5	Pepper plantation
7	Farmer 7	5,000,000/401.9/317.5	Pepper plantation
8	Farmer 8	5,000,000/401.9/317.5	Pepper plantation
9	Farmer 9	5,000,000/401.9/317.5	Pepper plantation
10	Farmer 10	5,000,000/401.9/317.5	Pepper plantation
	Total	50,000,000/4019.3/3175.4	

Table 6. Loan distribution among the Sumber Rejeki group 2016–2017 (2016 rates USD 1 = IDR 13,436 and EUR 1 = IDR 14,722).

No.	Participants	Amount of Loan (IDR/USD/EUR)	Activity
1	Farmer 7	5,000,000/372.1/339.6	Pepper plantation
2	Farmer 9	5,000,000/372.1/339.6	Pepper plantation
3	Farmer 1	5,000,000/372.1/339.6	Pepper plantation
4	Farmer 11	5,000,000/372.1/339.6	Pepper plantation
5	Farmer 12	5,000,000/372.1/339.6	Pepper plantation
6	Farmer 13	5,000,000/372.1/339.6	Pepper plantation
7	Farmer 14	5,000,000/372.1/339.6	To make a home kitchen
8	Farmer 15	5,000,000/372.1/339.6	Pepper plantation
9	Farmer 5	5,000,000/372.1/339.6	Rice farming
10	Farmer 16	4,500,000/334.9/305.7	Rice farming
11	Farmer 8	5,000,000/372.1/339.6	Rice farming
12	Farmer 17	5,000,000/372.1/339.6	Rice farming
13	Farmer 18	5,000,000/372.1/339.6	Rice farming
14	Farmer 11	5,000,000/372.1/339.6	Rice farming
Total		69,500,000/5172.7/4720.8	

Table 7. Loan distribution among the Sumber Rejeki group 2018 (2018 rates USD 1 = IDR 14,481 and EUR 1 = IDR 16,560).

No.	Participants	Amount of Loan (IDR/USD/EUR)	Activity
1	Farmer 7	5,000,000/345.3/301.9	Pepper plantation
2	Farmer 9	5,000,000/345.3/301.9	Pepper plantation
3	Farmer 1	5,000,000/345.3/301.9	Pepper plantation
4	Farmer 11	5,000,000/345.3/301.9	Pepper plantation
5	Farmer 12	5,000,000/345.3/301.9	Pepper plantation
6	Farmer 13	5,000,000/345.3/301.9	Pepper plantation
7	Farmer 14	5,000,000/345.3/301.9	Health treatment
8	Farmer 15	5,000,000/345.3/301.9	Pepper plantation
9	Farmer 19	5,000,000/345.3/301.9	Pepper plantation
10	Farmer 20	5,000,000/345.3/301.9	Pepper plantation
11	Farmer 5	5,000,000/345.3/301.9	Rice farming
12	Farmer 16	5,000,000/345.3/301.9	Rice farming
13	Farmer 8	5,000,000/345.3/301.9	Rice farming
14	Farmer 17	5,000,000/345.3/301.9	Rice farming
15	Farmer 18	5,000,000/345.3/301.9	Rice farming
16	Farmer 11	5,000,000/345.3/301.9	Rice farming
17	Farmer 21	5,000,000/345.3/301.9	Rice farming
18	Farmer 22	5,000,000/345.3/301.9	Rice farming
19	Farmer 23	5,000,000/345.3/301.9	Rice farming
20	Farmer 24	5,000,000/345.3/301.9	Rice farming
Total		100,000,000/6905.6/6038.6	

4.1.1. Was the Program Theory Valid, Appropriate, Relevant, and Accurate? Did Change Actually Occur in the Ways the Government Had Expected?

One of the key points in the KMP's theory of change was the distribution of social assistance funds, which were distributed in the form of loans to farmers, instead of involving MFI organizations, such as banks and credit unions. The loan acquisition process was easy as the farmers only had to submit some documents to the LKK, such as a copy of the family card and identity card. The farmers were able to acquire a loan worth below IDR 5 million without collateral, and above IDR 5 million with collateral and after repayment of the initial loan. Morris and Barnes (2015) [12] argue that MFI organizations should explore offering individual loans to individuals who paid back their group loans on time, helping them "graduate" to bigger loans with collateral.

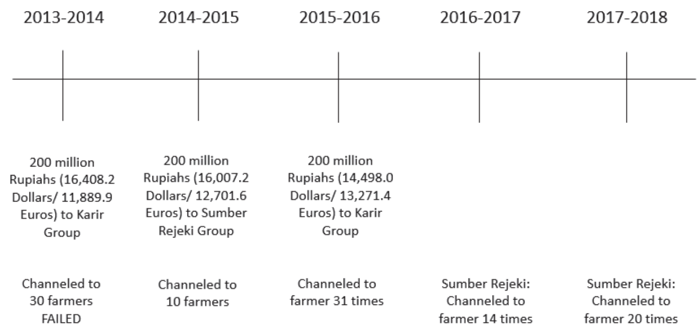

Figure 2. KMP program implementation timeline.

In the KMP program, farmers were expected to use the loan for farming activities or for farming-related business. Accordingly, most farmers spent the loan from the program on their farms, purchasing farming tools, fertilizers, pesticides, and seeds, as well as spending money on clearing land. Some farmers used the loan for other needs, such as maintaining the vehicles that they used for harvesting crops, health needs, building houses, and buying a motorcycle for non-farm income purpose (see Tables 4–7). Some points gathered from the FGD session in Berungkat are as follows: farmers had better access to food with better income, bought some necessities, and saved some money.

Based on the explanation given above, a change in the communities was caused by the KMP program, with the establishment of MFI for farmers and easy access to loans, as expected. The flexibility of loan use and its dynamic impact on households exceeded the program's theory of change (see Figure 3). Despite only being intended to increase access to food and farmers' purchasing power to enhance their food security, the microloan had helped farmers meet multiple needs, such as paying for the education of their children and their healthcare, contributing to family savings, and improving their assets. Clearly, change dynamics were noted due to deployment of the program (see Figure 3).

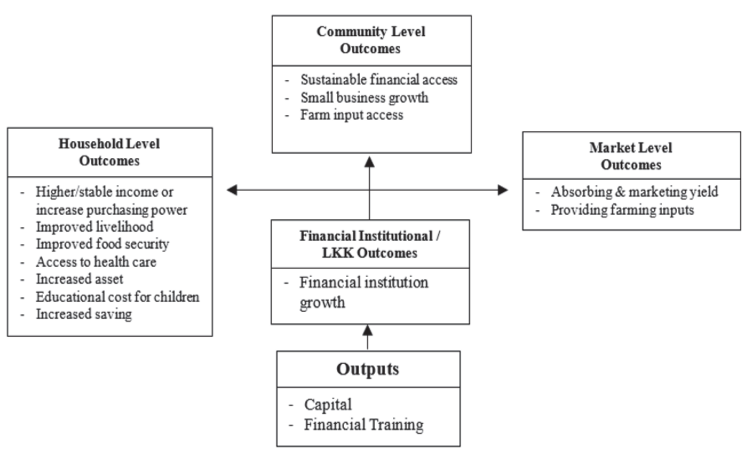

Figure 3. Change dynamics caused by the KMP program.

In the Karir group, the borrowers for each last loan did not return the money, and the management did not make any effort to collect the loans due to the location of the recipients of the aid, who were in three villages in distant hamlets. In the Sumber Rejeki group, however, the fund was repaid in full, as the program managers had expected. They also provided farming inputs, such as fertilizer, to their members annually from 2015 to 2018 and planned to absorb/market crops on behalf of farmers in the future. Thus, the change dynamic of the program portrayed in Figure 3 suited the Sumber Rejeki group, due to the KMP program's impact at the household, community, and market levels. In this group, the capability and the commitment of the group members were assessed before sanctioning the loan to make sure that they were able to repay the loan. This led to the following question: "how can the very poor access this microcredit if they lack the capability to repay the loan?" As Mahajan [14] mentioned, the dual promise that microcredit may benefit the very poor while also being financially viable is not fulfilled in practice. These two seemingly opposing objectives can be attained separately, but not simultaneously [14].

4.1.2. Are There Unforeseen Actors and Factors That Promote or Impede Change?

Some particular conditions prevented some actors from performing exceptionally, and they are as follows. Firstly, extension workers lacked control when deploying the program because they were rotated four times over the program's duration. Secondly, there was a lack of training prior to the distribution of the fund. Both of these obstacles caused the program to not run as expected. Thirdly, there was a lack of trust among the members, because the Karir group consisted of three subgroups of farmers, with two groups in the Ruis hamlet and a group in Kenaman hamlet. Finally, the geographic distribution of these groups across the hamlets influenced the management to provide extra time and money to help them control their members. This, however, did not occur in the LKK in Sumber Rejeki as there was only a single group in the Berungkat hamlet.

Other factors that impeded the expected change are as follows. First, climate conditions harmed farming activities, with a flood in the monsoon season at the end of 2013 and a subsequently long drought season in early 2014. Second, instability in the selling price of cash crops after 2017 decreased the income of the farmers. This impacted their ability to access farming inputs, which translated into decreased farm productivity and reduced their income from farming. Hence, the financial aid did have an impact on their family, but it was only temporarily due to low selling prices. Figure 4 shows changes in the income of farmers from 2014 to 2019 due to the selling price volatility of agricultural crops.

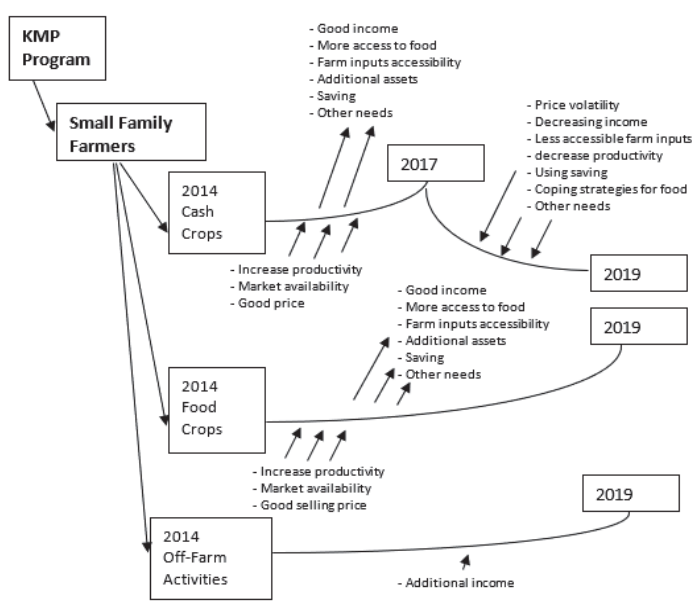

Figure 4. Changes in the income of farmers from 2014 to 2019.

4.2. Did the Microloan Affect Farmers' Production, Marketing, and Consumption Decisions?

In the Berungkat hamlet, most of the farmers cultivated cash crops, such as rubber, pepper, and oil palm, along with rice and vegetable for self-provision. At the start of this program in this hamlet, the price of rubber was low. Thus, the farmers used the loan to grow pepper plants and/or oil palm. Then, as claimed by a farmer in Kenaman, where most farmers in this hamlet grew food crops, such as rice and vegetable, "I managed vegetable farming and planned to focus only on vegetable farming, in 2015, I borrowed 3 million rupiah [IDR 3 million] to support vegetable farming activities. We used all the money to buy agricultural inputs, such as seeds and fertilizers" (Farmer 6, Kenaman). This is in keeping with what Finnis [15], Baker [16], and Rigg [17] discovered, i.e., that most farm production decisions were impacted by the characteristics of farmers and current commodity prices.

The instances above also reveal the absence of intervention by the program in the commercialization of specific crops. The farmers were free to choose any kind of crop to cultivate using the loan from this program. External pressures, such as government policies, cannot fully explain crop commercialization [18–20]. Instead, agricultural commercialization and intensification can be deliberate decisions driven by personal and family goals [15]. The indigenous intensification of agricultural products is a process that occurs "without explicit external development impetus" [15,18,23]. The price was the main factor that affected the farmers' marketing decisions, along with relationships and other commitments. A farmer informed us that if they could reach the border line between the two countries to gain a better price, they would do it. In the 2000s, when the border door between Indonesia and Malaysia was still open and free, selling pepper and cocoa between the countries was free, too. Therefore, farmers used to sell these goods directly at the border gate to gain a better price. Now this is no longer possible, and farmers sell pepper to middlemen. The last time that they sold directly at the border was 2013, when the price of pepper was still reasonable. Approximately 30% of the farmers who participated in this study stated that they sold their crops wholesale in other villages to obtain a better price. Another farmer added that he always sold his rubber to one person due to the close interaction between them. "We always sell our rubber to a middleman in this hamlet, he is our relative and we always borrow goods from him as he manages a small grocery" (Farmer 11, Ruis).

The other factors include a wide range of connections with people to whom they could sell their products and the availability of a traditional market, where farmers can market their crops, especially vegetable farmers. As one farmer said, "Rice is sold directly to consumers, relatives, and colleagues. Mustard greens, kangkong, and spinach are sold to traditional markets in Balai Karangan. We have 15 customers who sell the products to their consumers. Every time we harvest, we immediately deliver the produce to the retailers" (Farmer 6, Kenaman). As many as 27% of the total respondents stated the same thing—they, too, sell rice directly to consumers, relatives, or colleagues. Based on the depiction above, there is no strong evidence that closely ties the KMP program to the marketing decisions made by the farmers.

Consumption decisions were very much influenced by local wisdom, such as not changing food consumption too much even after gaining extra money, but instead saving the money for future needs. "Actually, the opportunity to access better food was very wide open, but people in this community are not accustomed to changing their simple eating patterns; neither excessive nor deficient. Many other needs must be met, such as education cost, agricultural inputs, loan, and other daily costs (gas, electricity, gasoline, etc.). They need to save money for different needs in the future and to survive when the selling price of agricultural commodities is lower" (a participant in the FGD in Ruis). The habit of these farmers who do not spend much on food even with a good income is reasonable. They are the type of farmers who see opportunities, and who are not focused on one commodity. With such a farming model, it is clear that there are times when their income is good and times when it is otherwise. This is similar to the observations of Mahajan (2005) [17], who stated that "savings are particularly important, as these act as self-insurance in case of smaller contingencies; meet sudden demands of cash due to illness, for instance; act as margin money or 'equity' for borrowing; and finally, to some extent, act as a collateral for repayment of loans".

On the other hand, other factors that influenced food consumption decisions, but which were indirectly related to the KMP program, were the availability of extra income, the willingness or desire to eat a specific food, curiosity, and specific moments in time, such as religious and cultural celebrations. Good selling prices led to additional earnings, which were influenced by the program. The extra income enabled them to access more food, although the level of food access may differ from one household to another, or from one community to another, as noted in this study. Hence, we can say that the program did not influence farmers' household consumption, except when the selling price of crops was better, as discuss in the next section.

4.3. The Impact of the Program on Food Security Levels among Small Family Farmers

4.3.1. Food Availability

All of the communities increased their farm production volume in some commodities. Some were for consumption, and some were sold directly to middleman to obtain the benefit of the sale. Three crops were both consumed and sold: rice, banana, and vegetables. Meanwhile, pepper and oil palm fruits were sold to gain income.

As depicted in Table 8 below, the Ruis hamlet produced 8 tons of bananas annually, of which they consumed only 5%. The farmers increased their rice grain production to 1.5 tons and consumed 90% of the yield. As for the 80 tons of oil palm fruits and 1.6 tons of pepper, they were sold. As such, they had access to more bananas and rice for consumption. Other food items were accessed using the money obtained from selling oil palm fruits and pepper, as well as the remaining unconsumed bananas and rice. In the Kenaman hamlet, the farmers harvested more than 7 tons of vegetables (of which 2% was consumed) and 12 tons of rice grain (of which 90% was consumed) annually. The main non-consumable crop was pepper, of which around 200 kg was harvested annually. In this case, the farmers had better access to rice and vegetables, and other food items were purchased using the money that they gained from selling pepper. In the Berungkat hamlet, the farmers grew more than 10 tons of rice grain (of which 80% was consumed) annually. Rice, being their staple food, was more available and accessible to them. At the same time, they sold 2.2 tons of pepper and 131.5 tons of oil palm fruit annually to meet their financial needs, helping them purchase additional food items for family needs.

Table 8. Estimation of additional farming productivity (ton/year) after the implementation of the KMP program.

No.	Community	Additional Farming Productivity (Ton/Year) after KMP				
		Rice	Vegetables	Bananas	Oil Palm Fruit	Pepper
1	Ruis	1.5	-	8	80	1.6
	Consumed	90%	-	5%	-	-
2	Kenaman	12	7	-	-	0.2
	Consumed	90%	2%	-	-	-
3	Berungkat	10	-	-	131.5	2.2
	Consumed	80%	-	-	-	-
Total		23.5	7	8	211.5	4
Consumed		86.66%	2%	5%	0%	0%

4.3.2. Food Access

The KMP program helped the farmers to increase their income, although food access was not always directly in line with the increase in income. When discussing the impact of this income rise on food access, one farmer said, "the income increased when the selling price of agricultural commodities was still reasonable. At least, it was better twice than now. As for food access, it is not directly in line with rise in income. This is because; many needs must be fulfilled, and saving needs in the context of preparation if at any time the selling price of crops declines" (a participant in the FGD in Ruis).

Food access increased when two conditions were present: increased productivity and the reasonable selling price of crops. For instance, when the selling price of their products was reasonable in Ruis between 2015 and 2017, the participating family farmers gained up to 35% additional access to food. This ratio was around 50% for farmers in Kenaman and approximately 65% for farmers in Berungkat. Hence, the KMP program did affect their productivity as they gained more income from selling crops, which led to greater access to food and fulfilled other needs. However, in 2018 and 2019, the drop in the price of pepper badly affected their income. Approximately 71% of the total respondents confirmed the decrease of the selling price of their crops. On top of that, the prices of necessities had been rising, along with the costs of other needs, such as the costs of supporting children in tertiary level education, where a few years ago they had still lived with their parents. Instead of saving money, they were spending the savings that they had accumulated from several years ago when the prices of latex, palm, and pepper were still reasonable. In particular, from 2015 to 2017, the farmers enjoyed good incomes as the prices of goods were still low and their financial condition was better. Table 9 below shows the changes in the selling prices of cash crops.

Table 9. Selling prices of cash crops.

Crops	Volume	Selling Prices 2015–2017 (IDR)	Selling Prices 2018–2019 (IDR)
Palm oil fruits	1 kg	1200–1400	700–800
Rubber	1 kg	18,000–20,000	6000–7000
Pepper	1 kg	100,000–120,000	23,000–25,000

In contrast, the farmers in the Kenaman hamlet were experiencing an increase in their income even at the time of this study. Since this community focused more on vegetable crops, they earned a more stable income than farmers from other communities. This is because vegetable crops had more stable selling prices than other agricultural commodities in the area.

One noted impact from the KMP program was better food access due to better farming productivity for both sales and self-consumption of rice, vegetables, and bananas. As observed from the field data, the enhanced farming productivity among the farmer groups reflected the positive impact of the loans used by farmers for their farming activities. They gained better access to food crops and received extra income from selling cash crops. The three crops that were both consumed and sold were rice, banana, and vegetables. All of the pepper and oil palm fruits were sold to gain income.

4.3.3. Food Utilization

To measure dietary diversity within the communities, the household monthly consumption of seven food groups was assessed based on the standard 14-day measurement explained above. In the Ruis hamlet, the eating patterns at the household level did not change much over five years, except for the quantity. They saved excess money for other needs, especially for their children's school or college needs, rather than for supplementing food. The community maintained the same standard of food. Their consumption was neither excessive nor deficient, but merely sufficient. Therefore, the condition of eating at home, regardless of income level, remained the same. The HDDS before the program in 2015–2016 (when crops had a reasonable selling price) and at the time of this study was 4 (low dietary diversity (DD)) (see Table 10). The HDDS of a non-participant family farmer was also measured and it resulted in a score of 3 (low DD).

Table 10. Current HDDS of the community in the Ruis hamlet.

Food Groups	Food Groups Used	Staple Food Ingredients (First List of All Food Items)	Proportion of Monthly Food Consumption (Days/Month)	Weight for HDDS	HDDS (Consumed More Than 14 Days)
1. Cereals, roots, and tubers	Cereal and grain	1. Rice 2. Cassava	1. 45 kg 2. 5.2 kg	0/1	1
2. Pulses and legumes	Legumes/nuts	1. Long beans 2. Tempeh and tofu	1. 2 days 2. 5 days	0/1	0
3. Vegetables	Orange vegetables (rich in vitamin A) Green leafy vegetables Other vegetables	1. Cassava leaves 2. Bamboo shoots 3. Ferns 4. Kangkong 5. Banana blossom 6. Mustard green 7. Spinach 8. Aubergine 9. Pumpkins leaves 10. Cucumber leaves	30 days	0/1	1
4. Fruits	Orange fruits (rich in vitamin A) Other fruits	1. Banana 2. Orange 3. Longan	1. 4 days 2. 2 days 3. 1 day	0/1	0
5. Meats, fish and seafood, and eggs	Meat Liver, kidney, heart and other organ meats Fish/shellfish Eggs	1. Meat 2. Fish 3. Eggs	1. 5 days 2. 6 days 3. 23 days	0/1	1
6. Dairy products	Milk and other dairy products	Milk	0.7 kg	0/1	0
7. Oils and fats	Oil/fat/butter	Cooking oil	2.8 kg	0/1	1
		Total HDDS			4

In the Berungkat hamlet, the farmers there were also affected by the low selling prices of farm commodities. The crops included pepper, oil palm, rubber plant, and rice. The good selling price period in 2015–2017 helped them gain better access to food and to consume a more diverse range of food. At that time, they consumed more fruits than the other communities, meaning their HDDS was 5 (medium DD). The two non-participant family farmers in this community scored 6 and 5 (medium DD) for their HDDS due to their better family condition and farming activities than the participant family farmers in this hamlet. Table 11 below shows the current HDDS of the community in the Berungkat hamlet.

The last community is the Kenaman hamlet. In this hamlet, the dietary diversity was better because they consumed more legumes and nuts. Their dietary diversity was better after the program due to two factors: first, most of them were not native people (they came to this place looking for a better opportunity for their life), and second, they cultivated rice and vegetable crops, which had a more stable price at that time. As for dietary diversity, they had a better score compared to other communities because they consumed more legumes and nuts. The current HDDS in this community is 5 (medium DD) (see Table 12 below), while the HDDS before the program was 4 (low DD). Meanwhile, a non-participant family farmer in this community scored 4 (low DD).

Table 11. Current HDDS of the community in the Berungkat hamlet.

Food Groups	Food Groups Used	Staple Food Ingredients (First List of All Food Items)	Proportion of Monthly Food Consumption (Days/Month)	Weight for HDDS	HDDS (Consumed More Than 14 Days)
1. Cereals, roots, and tubers	Cereal and grain	1. Rice 2. Cassava 3. Sweat potatoes	1. 31.5 kg 2. 6 kg 3. 2 kg	0/1	1
2. Pulses and legumes	Legumes/nuts	1. Long beans	1 day	0/1	0
3. Vegetables	Orange vegetables (rich in vitamin A) Green leafy vegetables Other vegetables	1. Cassava leaves 2. Bamboo shoots 3. Ferns 4. Cucumber leaves 5. Pumpkins 6. Pumpkins leave 7. Katuk 8. Kangkong	Every day, always consume vegetables with different types of vegetables	0/1	1
4. Fruits	Orange fruits (rich in vitamin A) Other fruits	1. Banana 2. Orange 3. Watermelon 4. Pineapple	1. 5 days 2. 2 days 3. 2 days 4. 2 days	0/1	0
5. Meats, fish and seafood, and eggs	Meat Liver, kidney, heart and other organ meats Fish/shellfish Eggs	1. Meat 2. Fish 3. Eggs	1. 6 days 2. 7 days 3. 22 days	0/1	1
6. Dairy products	Milk and other dairy products	1. Milk	0.2 kg daily only for toddlers	0/1	0
7. Oils and fats	Oil/fat/butter	Cooking oil	3.5 kg	0/1	1
		Total HDDS			4

Table 12. Current HDDS of the community in the Kenaman hamlet.

Food Groups	Food Groups Used	Staple Food Ingredients (First List of All Food Items)	Proportion of Monthly Food Consumption (Days/Month)	Weight for HDDS	HDDS (Consumed More Than 14 Days)
1. Cereals, roots, and tubers	Cereal and grain	1. Rice 2. Cassava	1. 37.5 kg 2. 3.8 kg	0/1	1
2. Pulses and legumes	Legumes/nuts	1. Tempeh and tofu 2. Long beans 3. Soybean	1. 10 days 2. 5 days 3. 1 day	0/1	1
3. Vegetables	Orange vegetables (rich in vitamin A) Green leafy vegetables Other vegetables	1. Cassava leaves 2. Bamboo shoots 3. Ferns 4. Mustard green 5. Spinach 6. Cabbage 7. Kangkong	25 days	0/1	1

Table 12. *Cont.*

Food Groups	Food Groups Used	Staple Food Ingredients (First List of All Food Items)	Proportion of Monthly Food Consumption (Days/Month)	Weight for HDDS	HDDS (Consumed More Than 14 Days)
4. Fruits	Orange fruits (rich in vitamin A) Other fruits	1. Banana 2. Papaya 3. Guava 4. Orange 5. Zalacca 6. Watermelon	1. 4 days 2. 2 days 3. 3 days 4. 2 days 5. 0.2 day 6. 0.2 day	0/1	0
5. Meats, fish and seafood, and eggs	Meat Liver, kidney, heart and other organ meats Fish/shellfish Eggs	1. Meat 2. Fish 3. Eggs	1. 3 days 2. 3 days 3. 12 days	0/1	1
6. Dairy products	Milk and other dairy products	Milk	- 0.7 kg - Milk for baby	0/1	0
7. Oils and fats	Oil/fat/butter	Cooking oil	3.1 kg	0/1	1
		Total HDDS			5

Table 13 below lists the HDDS of each hamlet before the program, during the program when the crops' selling prices were reasonable (2015–2017), and after 2017 when government support ended.

Table 13. Household dietary diversity score before and after KMP program.

No.	Community	HDDS			Note
		Before	2015–2017	After 2017	
1	Ruis	4	4	4 (non: 3)	<4.5 = Low dietary diversity
2	Berungkat	4	5	4 (non: 5)	4.5–6.0 = Medium dietary diversity
3	Kenaman	4	5	5 (non: 4)	>6.0 = High/good dietary diversity

5. Conclusions

The regulations issued for this program stipulated that DMP is meant for one community in a regular region, while KMP is dedicated to several communities in a region. It was found that the KMP model did not succeed, as discovered with the Karir group. Some obstacles were identified, including the distance between hamlets, a lack of control, a lack of trust among groups, low management capability, and low commitment. The DMP model with the Sumber Rejeki group was very successful because it targeted only one group in one community. They knew and trusted each other. Other factors included the good capability of the management and the good commitment of the members. Moreover, the microloan program in this group was used not only to help farmers increase their farming production, but also to meet many needs, such as education costs for children, helping with healthcare, contributing to family savings, and improving assets. Thus, this program should be continued in future within the DMP model, where one LKK (local financial institution) is only for one community.

One solution for the LKKs in Karir is where the loan is collected by each subgroup. In this way, each subgroup can roll out the loan only among their members in the future, while they (the sub-management) can regularly send reports of their activities to the management. This stands in contrast to the LKK in Sumber Rejeki, where the management assessed the commitment and capability of their members to repay the loan. This policy would undeniably have a good impact on program sustainability, but it would exclude the very poor. Therefore, it is crucial to provide a specific service to the very poor, and support not only the program members, but also any other person from their community.

The rise in income did not lead farmers to purchase more nutritious food for consumption. Rather, the increased income motivated farmers to fulfil many needs, such as education costs for their children, farm inputs, healthcare, and asset improvement. However, the farmers in this study constantly faced difficulties due to climate conditions and volatility in the selling price of crops, which then motivated the farmers to save their money to prepare for uncertain times. Thus, ensuring sufficient food security for their family was not a priority for them. Hence, the government should use the food security measurement to assess food security at the household level among the participant farmers as they exit the program.

As revealed in this study, the income of the farmers decreased when the price of crops dropped despite increases in yields due to the financial access that they gained from the program. This prevented them from accessing farming inputs, thus harming their farms' productivity. Therefore, in order to prevent price volatility with agricultural commodities, the government could install a locally owned enterprise that would buy their agricultural products. This may be a viable solution to provide a market for small family farmers. At the same time, this enterprise must provide and sell everything that farmers need, such as fertilizers, herbicides, pesticides, as well as agricultural, fishery, and livestock-related equipment. With the provision of a good monitoring system, appropriate trainees, adequate financial support to buy goods, conduct supervision, and transparent audits, the proposed enterprise may be able to maintain or even increase the income of the farmers.

6. Study Limitation

First, this study lacks a discussion on the sociological aspects of MFI, such as social action, culture, motives, and values (religion and ethics), which could influence one's behavior. This also includes a lack of supportive institutions and grassroots participation. Research to evaluate the KMP program, inclusive of sociological dimensions, is integral to gain a more comprehensive understanding and to help develop a better formulated and more innovative financial aid program for the local small family farms and the local community. Second, this study did not explore the role of local government agencies and agricultural extension workers in the Sekayam subdistrict, who act as supervisors in deploying the programs. A study that assesses the importance of the implementation of cross-sector coordination, synchronization, and integration for rural infrastructure development across local government agencies and agricultural extension workers, who support the programs by administering technical and managerial training, supervision, additional budget support (if any), infrastructure support, or other types of support outlined in the expected outcomes of the KMP program, could be substantial. A study on the multi-level governance that is required when implementing the program for small family farms could also be interesting. More work should look into the role of each level of the government to explain the smooth implementation of the program, and then formulate a better investment program framework that fits all government levels to provide better support to small family farms for achieving better local food security.

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Finger Millet Production in Ethiopia: Opportunities, Problem Diagnosis, Key Challenges and Recommendations for Breeding

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Abstract: Finger millet (*Eleusine coracana* (L.) Gaertn) is a highly nutritious crop, predominantly grown in the semi-arid tropics of the world. Finger millet has a niche market opportunity due to its human health benefits and being rich in calcium, iron and dietary fiber and gluten-free. Ethiopia is the center of the genetic diversity of the crop. However, the productivity of finger millet in the country is low (<2.4 tons ha^{-1}) compared with its potential yield (6 tons ha^{-1}). The yield gap in Ethiopia is due to a range of biotic and abiotic stresses and socio-economic constraints that are yet to be systemically documented and prioritized to guide future production and improved variety development and release. The objective of this study was to document finger millet production opportunities, constraints and farmer-preferred traits in Ethiopia as a guide to variety design in improvement programs. A participatory rural appraisal (PRA) study was undertaken in six selected districts of the Southern Nation Nationalities People Region (SNNPR) and Oromia Region in Ethiopia. Data were collected from 240 and 180 participant farmers through a semi-structured questionnaire and focus group discussion, respectively. Finger millet was the most important crop in the study areas grown mainly for a combination of uses, including for food, feed and cash (reported by 38.8% of respondent farmers), food and feed (14.5%), food and cash (13.7%), food (11.5%) and food, cash, feed and construction material (9.7%). Hand weeding was used by 59.2% of the respondent farmers, followed by hand weeding and chemical herbicides (40.8%). Finger millet was mainly planted as a sole crop (reported by 97.0% respondents), mixed (1.7%) and sole and mixed (1.3%). About 75.6% of respondent farmers only practiced finger millet rotation with other crops. Respondent farmers indicated their source of fresh seed was from the Bureau of Agriculture (49.1%), farmer-to-farmer seed exchange (22.1%), own saved seed (7.5%), local producers (7.5%), research institutions (5.8%), unknown sources (4.1%), local market (3.5%) and cooperatives (0.42%). The total cost of finger millet production per hectare was calculated at 1249 USD with a total income of 2139 USD/ha, making a benefit to cost ratio of 1.71:1.00 and indicating the relatively low yield gains using the currently grown varieties. The main constraints to finger millet production in the study areas were drought stress (reported by 41.3% respondents), lack of improved varieties (12.9%), lack of financial resources (11.3%), small land holdings (10.8%), limited access to seed (10.0%), a shortage of fertilizers (5.4%), poor soil fertility (4.6%), shortage of draught power (1.3%), labour shortages (1.3%) and high labour costs (1.3%). The most important farmer-preferred traits in a finger millet variety were high grain yield, compact head shape, 'enjera'-making quality, high marketability and early maturity, resolved through principal component analysis. The above-mentioned production constraints and farmer-preferred traits are strategic drivers to enhance finger millet productivity and need to be incorporated into Ethiopia's finger millet breeding and technology development.

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1. Introduction

Finger millet (*Eleusine coracana* (L.) Gaertn) is an important cereal crop in the semi-arid and tropical regions of the world. The name finger millet is derived from the appearance of spikes or fingers, which are arranged and appear like human fingers. Compared with other major cereals such as rice, wheat and barley, it is relatively drought-tolerant due to its C4 photosynthesis system and adaption to grow under harsh and marginal agro-ecologies. Agriculture is an important economic sector in Africa, including Ethiopia. The sector accounts for 25% of Africa's GDP, 21% of exports, and 65–70% of the workforce supporting the livelihoods of 90% of population [1–3]. In Ethiopia, agriculture contributes to 44% of GDP, 70% of export earnings and 80% of employment opportunity [4]. Finger millet is grown mainly for its grain, which is utilized to make traditional food and drinks, while the stalks are used for livestock feed, construction and fuel. Finger millet has various human health benefits such as reducing diabetes [5], obesity [6], osteoporosis [7,8], anemia [6], malaria [9,10] and diarrhea [9,10]. The health values of finger millet are linked to its high calcium, iron and dietary fiber content and being gluten-free. These health benefits will render finger millet as a crop of niche market opportunity in the future. Finger millet is cultivated in more than 25 countries in Africa and Asia [11]. Ethiopia is the second largest producer of finger millet in the world after India [12,13]. In Ethiopia, the grain is processed to make unleavened bread (locally referred to as enjera) and for malting to prepare local drinks such as a distilled spirit 'Areki' or local beers such as 'tella' and non-alcoholic drinks such as 'karibu' and 'shamita', while the straw is vital as a livestock feed and for thatching of houses [14,15].

The global production area and total production for finger millet are unknown since both statistics are merged and reported with other millets. An estimated total production area of 32,554,127 ha is devoted to millets production worldwide [12]. It is estimated that the share of the global finger millet production area is about 12.5% of the millet. Ethiopia's total finger millet production area is 455,581 ha [16], making an 11.2% global share [12,16]. A total of 3,834,021 tons of finger millet grain is produced per annum globally [12], while Ethiopia's output is estimated at 1,125,958 tons [16], equivalent to 29.4% of global production. Finger millet is the sixth most important cereal crop in Ethiopia in total area and production after tef (*Eragrostis tef* (Zucc.)Trotter), maize (*Zea mays* (L.)), sorghum (*Sorghum bicolor* (L.) Moench), wheat (*Triticum aestivum* (L.)) and barley (*Hordeum vulgare* (L.)) [16]. It accounts for 5% of the total area allotted to cereal production in Ethiopia [17]. Finger millet is grown in more than 1.8 million households on more than 455,000 hectares of land in the northern, north-western, western, the Central Great Rift Valley and West Hararghe zones of Ethiopia [16]. In 2017 the total grain production was 1,017,059 tons, increasing by 87% in the preceding 20 years [17].

Despite the importance of finger millet for food security and livelihoods, its productivity is relatively low (2.47 t/ha) [16] in Ethiopia compared with the potential yield of the crop (6 t/ha) achieved under experimental conditions [18]. The low productivity of the crop in the country is attributable to a range of biotic and abiotic stresses and socio-economic constraints prevalent in the smallholder production systems in Ethiopia. Finger millet blast caused by *Magnaporthe grisea* (Barr) (teleomorph) is the most damaging disease, causing yield losses in the range of 7.32–54.07%, depending on climatic conditions and cultivar susceptibility [19]. Notable insect pests of the crop include grasshoppers (Caelifera) and shoot fly (*Atherigona soccata* (Rondani)) [15], pink stem borer (*Sesamia inferens* (Walker)), finger millet root aphid (*Tetraneura nigriabdominalis* (Sasaki)) and aphids (aphidoidea) [20,21]. Yield losses have been reported due to several insect pests such as termites (isopteran) (with a loss of 23%) [22], aphids (35.1%) [20] and pink stem borer (56%) [21]. Weeds cause severe yield loss during the early growth stages of finger millet. In Ethiopia, yield losses of up to 73.5% have been reported due to weeds [23]. The most problematic weed species of finger millet in Ethiopia include *Digitaria ternata* (A. Rich.) Stapf, *Guizotia scabra* (Vis.) Chiov, *Cyperus rotundus* L. [23] and *Striga hermonthica* (Delile) Benth [24].

Recurrent drought stress associated with climate change is the leading constraint affecting finger millet production and other main crops in Ethiopia. The impact of drought stress on finger millet production depends on cultivar susceptibility, the onset date, the intensity and duration of the drought stress and the associated prevailing environmental conditions. Although finger millet is relatively drought-tolerant, 100% yield losses can be incurred due to intense and early onset of drought stress [25]. Supplementary irrigation, early planting and moisture conservation techniques such as mulching, zero tillage and tie ridging are often used to mitigate drought stress [26]. However, most smallholder farmers do not have access to irrigation and other resources to manage drought stress. Drought stress also significantly affects grain quality and yield components [27]. Hence, drought-tolerant varieties could be the most economical and environmentally friendly approach to controlling drought under smallholder production systems.

In Ethiopia, formal research on finger millet improvement started in the early 1980s [28]. In the last four decades, finger millet improvement activities in Ethiopia have focused on characterization and evaluation of locally collected and introduced germplasm for pure line selection. As a result, some 23 finger millet varieties have been registered and released for production [29]. Two varieties, Tadesse (KNE#1098) and Tessema (ACC#229469), were released with the beneficial traits of wide adaptability, high grain yield potential, good biomass and compact head shape. However, these varieties are late maturing, susceptible to insect pests and diseases, have relatively low human nutrition value and a seed shattering problem. The mean grain yield of improved finger millet varieties in Ethiopia is low at 2.7 t/ha [30], compared with 4.74 and 4.79 t/ha reported for Kenya [31] and India [32], respectively. Ethiopia is the primary centre of origin and diversity for finger millet [33]. The finger millet landraces grown by farmers are essential genetic resources that are known to hold useful genetic variation for desirable traits. Therefore, these landraces can be evaluated and selected for their desirable characteristics for new variety development, genetic analysis and gene discovery, leading to high yielding varieties that have all the essential farmer-preferred traits [34]. The finger millet production opportunities, farming systems, production constraints and preferred traits of the end-users are essential components for variety design and breeding strategies. Incorporating the needs and preferences of farmers would increase the adoption of new varieties of finger millet.

Farmers have a wealth of knowledge about their crops, farming systems and the constraints [35] that can be harnessed through a participatory rural appraisal (PRA). A PRA is a research tool used to gather useful information on farmers and their production systems for designing intervention strategies [36]. The PRA approach provides a platform for farmers and breeders to engage in information sharing actively. Plant breeders must understand farmers' situations and choices to design appropriate varieties to meet their needs. Several studies have used the PRA approach to gain insight into farmer production systems and varietal choices to prioritize breeding objectives, including in tef [37], sorghum [38], wheat [39]), pearl millet (*Pennisetum glaucum* (L.) R. Br) [40] and finger millet [41]. For example, drought is the major production constraint of finger millet in Eastern Uganda, according to Owere et al. [24], and in sorghum production in Ethiopia [42,43]. Similarly, a lack of access to improved seeds of groundnut [44] and sesame [34], a lack of improved varieties of sorghum [43] and a shortage of arable land and poor soil fertility in sorghum [42] were also identified as production limiting factors in Ethiopia. Likewise, a lack of improved finger millet and sorghum varieties in Uganda [24,38] and limited access to fertilizers in pearl millet production in Burkina Faso [40] have also been documented as production constraints. However, no recent study has documented farmers' perceptions of production constraints and trait preferences in finger millet in Ethiopia. Therefore, the objective of this study was to document finger millet production opportunities, constraints and farmer-preferred traits in Ethiopia to set breeding goals and guide variety design in a finger millet improvement program.

2. Materials and Methods

2.1. Description of the Study Areas

The study was conducted in 2021 in the following two finger millet growing regions in Ethiopia: the Southern Nation Nationalities People Region (SNNPR) and Oromia (Figure 1). In the SNNPR, two districts, namely, Atote Ulo and Wera, were selected, while four districts (Shala, Siraro, Habro and Daro Lebu) were identified in the Oromia region for the study (Figure 1; Table 1). The geographical and climatic information for the study areas is presented in Table 1 [45]. The study areas fell within the mid to high altitude range between 1200 and 2400 m above sea level. The temperatures (°C) ranged between 12.5 and 29.1 °C with moderate to high mean annual rainfall of between 781.8 and 1103.6 mm year^{-1}.

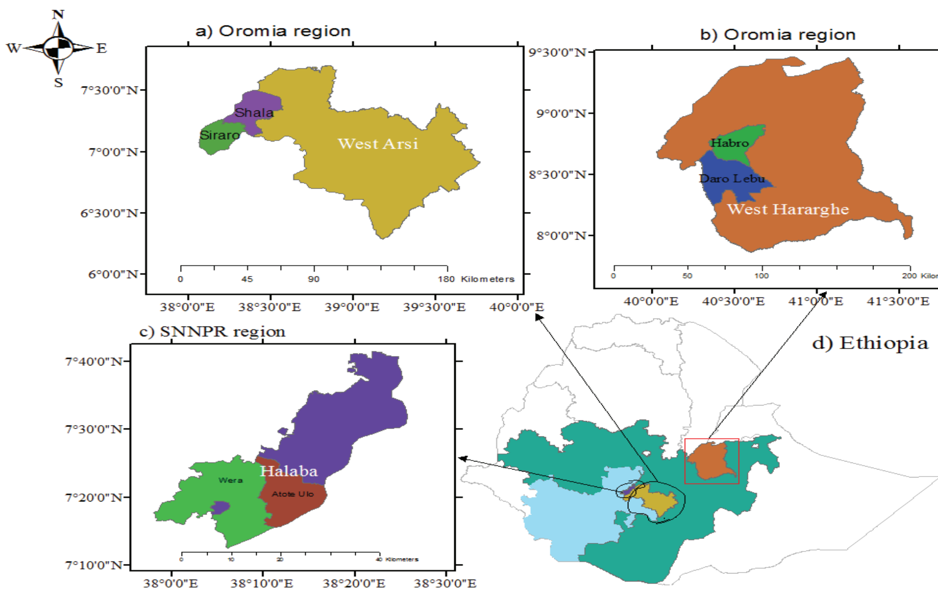

Figure 1. Geographical location of the study areas showing the regions, districts and zones.

Table 1. Descriptions of the study areas and number of sampled farmers for interviews and focused group discussion.

Regions	Zones	Districts	Peasant Association	Altitudinal Ranges (m.a.s.l.)	Daily Mean Temperature Ranges (°C)	Annual Rainfall (mm year^{-1})	No. of Interviewees			No. of Focused Group Discussants		
							Male	Female	Total	Male	Female	Total
Oromia	West Arsi	Shala	Awara Gema	1500–1900	12.9–26.7	781.8	10	10	20	08	07	15
			Fendi Ejersa				15	05	20	11	04	15
		Siraro	Boye Awarakasa	1500–2075	12.5–27.2	783.0	19	01	20	14	01	15
			Damini Leman				18	02	20	13	02	15
	West Hararghe	Habro	Gadisa	1500–2400	13.4–28.3	1103.6	19	01	20	14	01	15
			Kufa Kas				16	04	20	12	03	15
		Daro Lebu	Gelma Jeju	1200–2000	14.1–29.1	1076.8	16	04	20	12	03	15
			Oda Leku				20	01	20	14	01	15
SNNPR	Halaba	Atote Ulo	1st Ansha	1800–1950	13.1–27.2	787.3	16	04	20	10	05	15
			Girura Bucho				15	05	20	11	04	15
		Wera	Gedeba	1700–2300	13.7–27.3	840.8	17	03	20	12	03	15
			Kufe				19	01	20	13	02	15
			Total				199	41	240	144	36	180

Note: m.a.s.l. = meters above sea level; SNNPR = Southern Nation Nationality and Peoples Region.

2.2. Sampling Procedures

A multi-stage sampling procedure was used to ensure a good representation of finger millet growers and the diverse agro-ecological zones in Ethiopia. Hence, a purposive sampling procedure was used to capture representative finger millet producing areas, major production opportunities and constraints and different socio-economic challenges. For the study two finger millet growing regions, SNNPR and Oromia, were selected. In the SNNPR region, the study was conducted in the Halaba Zone from which two districts were selected, namely, Atote Ulo and Wera. From each district, two peasant associations (PAs) were selected. A peasant association is locally referred to as 'Kebele', which is the smallest unit of administration in Ethiopia. This sampling provided a total of four PAs, including 1st Ansha and Girura Bucho (from Atote Ulo district) and Gedeba and Kufe (Wera district). The study was conducted in two zones in the Oromia region, including West Arsi Zone and West Hararghe Zone. From each zone two districts were selected (Siraro and Shala from West Arsi Zone and Habro and Daro Lebu from West Hararghe Zone). From Shala district, two PAs were selected (Awara Gema and Fendi Ejersa), two PAs from Siraro district (Boye Awarakasa and Damini Leman), two PAs from Habro district (Gadisa and Kufa Kas) and two PAs from Daro Lebu district (Gelma Jeju and Oda Leku). Participant farmers were randomly selected to represent the various wealth, gender and age group in the finger millet production community. Therefore, in each PA, 20 and 15 farmers were selected for face-to-face interview and focused group discussion (FGD), respectively, making a total of 240 and 180 participant farmers (Table 1).

2.3. Data Collection

Before data collection, enumerators were trained to ensure effective and efficient interviews and focus group discussions. The questionnaire was prepared in English and administered after translation to the local languages through trained enumerators. In the Oromia region, the local languages, namely, Afaan Oromo and Amharic, were used interchangeably to improve communication among researchers, enumerators and respondents, whereas in SNNPR, only the Amharic language was used. The questionnaires were pretested on a few respondents to improve clarity. Two breeders, a socio-economist, a pathologist and an agronomist were involved in facilitating and collecting data. Both primary and secondary data were collected for this study. Semi-structured questionnaire and FGD were used to collect the farmers' responses based on their 2020 finger millet farming experience. Semi-structured questionnaires were used to collect the following data: demographic attributes of the households, crops produced, roles of finger millet, improved varieties and local landraces, cropping system, seed systems, production constraints, drought coping mechanisms and farmers' varietal and trait preferences. FGDs were held to complement and confirm data gathered through interviews. The discussion topics for FGD were crops produced in the study areas, various roles of finger millet, improved varieties and local landraces, cropping system, seed systems, crop production constraints, coping mechanisms for drought, farmers' varietal and trait preferences and cost and cash income from finger millet production. Secondary data such as long-term weather data were collected from the National Metrological Agency of Ethiopia, while altitude, major crops grown and their area coverage and productivity were collected from the respective district Bureau of Agriculture.

2.4. Data Analysis

The qualitative data collected were coded into a suitable category and captured with quantitative data across the variables. Both data sets were subjected to data analysis using the Statistical Package for Social Sciences (SPSS) version 23 [46]. Descriptive statistics such as frequencies and percentages were computed using the cross-tabulation procedure. Significant tests were done with the chi-square test for qualitative and quantitative data sets. Contingency chi-square tests were employed to make statistical inference at the 0.05 level of significance to assess the relationship among variables. Conversely, the quantitative data for cost-benefit analysis were summarized using Microsoft excel to calculate the ratios. Regarding the finger millet production constraints and farmers' trait preferences, they were labelled and tallied in a matrix, both in rows and columns, and the scores were obtained from pair-wise ranking based on one-to-one comparisons. The scores are equivalent to the frequency of respondents. Lastly, the scores were counted and used to conduct chi-square analysis and principal component analysis (PCA) for finger millet production constraints and farmers' trait preferences in the same order. PCA plots were developed to summarize the interrelationships of farmers' trait preference and their order of importance. Plots were done using the "FactorMineR" procedure [47] of R studio [48].

2.5. Cost Benefit Ratio Analysis

To appraise the monetary values of finger millet and other major crops production, the benefit to cost ratios were computed based on data collected in the study districts. The benefit to cost ratios were computed following the procedure of Adhikari [49] and Abraha et al. [37]. Microsoft excel was used to summarize the quantitative data sets of the different variables for the cost-benefit analysis.

$$Cost\ benefit\ ratio = \frac{\textbf{Total income}}{\textbf{Total production cost}}$$

Note: the total income included grain and straw sale, while the total production costs included the costs of seeds for planting, fertilizers, labour for land preparation, weeding, hoeing, thinning, harvesting and threshing.

3. Results

3.1. Demographic Attributes

The demographic attributes of respondents and their households were summarized during the interviews (Table 2). There were significant differences (X^2 = 17.8; $p < 0.05$) in gender representation among the different districts. The majority (82.9%) were male farmers across all the study districts. The highest (15) and lowest (3) frequencies of female farmers were interviewed at Shala and Siraro, respectively.

Table 2. Proportion of respondents' gender, age, family size and level of education in the study districts.

Variables	Categories	Districts						Frequency	Percent
		Atote Ulo	Wera	Shala	Siraro	Habro	Daro Lebu		
Gender of household head	Female	9	4	15	3	5	5	41	17.1
	Male	31	36	25	37	35	35	199	82.9
	Chi-square test		X^2 = 17.8		df = 5			p-value = 0.003	
Age of household head (year)	18–40	29	31	24	31	33	26	174	72.5
	41–50	8	7	14	8	7	10	54	22.5
	>50	3	2	2	1	0	4	12	5
	Chi-square test		X^2 = 11.0		df = 10			p-value = 0.358	
Number of children	≤2	5	18	6	5	13	5	52	21.7
	3–5	14	8	7	11	19	13	72	30
	≥6	21	14	27	24	8	22	116	48.3
	Chi-square test		X^2 = 38.4		df = 10			p-value = 0.000	
Educational status of household head	Illiterate	12	5	16	4	16	6	59	24.6
	Read and write	0	2	5	2	4	3	16	6.7
	Grade 1–5	16	10	7	20	7	15	75	31.3
	Grade 6–8	4	5	6	11	6	12	44	18.3
	High school	5	10	6	2	6	3	32	13.3
	College	3	8	0	1	1	1	14	5.8
	Chi-square test		X^2 = 66.1		df = 25			p-value = 0.000	

Note: X^2 = chi-square test, df = degree of freedom, p-value = probability value.

The age groups of farmers did not show significant differences across the sampled districts (X^2 = 11.0, *p*-value = 0.36), with the majority of respondent farmers (72.5%) being between 18 and 40 years old. Only 5% of the farmers were older than 50 years, with none of the famers at Habro older than 50 years. There were significant differences (X^2 = 38.4; *p*-value = 0.000) in family sizes of respondents across the districts. Almost half (48.3%) of the respondents had households with more than five children. Habro and Wera districts had the lowest frequencies of farmers with more than five children, while Atote Ulo, Daro Lebu and Siraro had the lowest number of farmers with less than two children.

There were significant differences across districts (X^2 = 66.1, *p*-value = 0.000) in the levels of education. The highest proportion of farmers (31.3%) had attended school grades 1–5, while 24.6% had not attended any level of formal education. The highest frequency of respondents both with high school and college education was found at Wera at 10 and eight, respectively (Table 2).

3.2. Major Crops Grown in the Study Areas

Maize, tef and finger millet were the most important cereal crops grown in the study districts except in Daro Lebu and Habro, where sorghum was the most important and widely grown crop. There were significant differences among districts for a total area of production of finger millet (X^2 = 20.3, *p*-value = 0.03), maize (X^2 = 96.8, *p*-value = 0.000) and tef (X^2 = 28.5, *p*-value = 0.002). Similarly, significant variations were observed among districts for productivity of finger millet (X^2 = 64.392, *p*-value = 0.00), maize (X^2 = 34.255, *p*-value = 0.000), tef (X^2 = 31.862, *p*-value = 0.000) and sorghum (X^2 = 23.424, *p*-value = 0.009). The majority of the respondents allocated <0.25 ha of agricultural land each to finger millet (68% respondents), tef (51%) and sorghum (67%) production. About 10% of the respondents in Shala, Atote Ulo and Habro allocated a sizeable amount of land (>0.5 ha) to finger millet production. Conversely, about 83% of respondents in Siraro had a smaller land allocation (<0.25 ha) for finger millet (Table 3; Figure 2). Unlike the other main crops grown in the districts, nearly half of the respondents (46%) allocated large areas (>0.5 ha) of farmland to maize. Only 31% of the farmers in the study areas allocated <0.25 ha for maize production.

Table 3. Proportion (%) of respondents' farmland size (ha) allocation and productivity of major crops in the study districts during 2020/21 cropping season.

Districts	Crops											
	Finger Millet			Maize			Tef			Sorghum		
	Production Area (ha) of Crops and Proportion of Respondents (%)											
	<0.25 ha	0.25–0.5 ha	>0.5 ha	<0.25 ha	0.25–0.5 ha	>0.5 ha	<0.25 ha	0.25–0.5 ha	>0.5 ha	<0.25 ha	0.25–0.5 ha	>0.5 ha
Shala	53	38	10	15	30	55	46	43	11	100	–	–
Siraro	63	28	10	8	36	56	48	29	23	100	–	–
Atote Ulo	70	20	10	16	21	63	24	38	38	–	–	–
Wera	83	18	–	18	30	53	60	28	13	50	50	–
Habro	80	18	3	89	5	5	75	15	10	65	26	10
Daro Lebu	63	38	–	92	4	4	85	8	8	62	29	10
Mean (%)	68	26	5	31	24	46	51	30	19	67	25	8
Chi-square	X^2 = 20.3, df = 10, *p*-value = 0.03			X^2 = 96.8, df = 10, *p*-value = 0.000			X^2 = 28.5, df = 10, *p*-value = 0.002			X^2 = 4.6, df = 10, *p*-value = 0.800		

Table 3. *Cont.*

Districts	**Finger Millet**			**Maize**			**Tef**			**Sorghum**		
	Production Area (ha) of Crops and Proportion of Respondents (%)											
	<0.25 ha	**0.25–0.5 ha**	**>0.5 ha**	**<0.25 ha**	**0.25–0.5 ha**	**>0.5 ha**	**<0.25 ha**	**0.25–0.5 ha**	**>0.5 ha**	**<0.25 ha**	**0.25–0.5 ha**	**>0.5 ha**
	Productivity (t/ha) of crops and proportion of respondents (%)											
Districts	<1.5 t/ha	1.5–3.0 t/ha	>3 t/ha	<1.5 t/ha	1.5–3.0 t/ha	>3 t/ha	<1.5 t/ha	1.5–3.0 t/ha	>3 t/ha	<1.5 t/ha	1.5–3.0 t/ha	>3 t/ha
Shala	25	50	25	21	29	50	100	–	–	75	25	–
Siraro	58	33	10	21	64	15	100	–	–	100	–	–
Atote Ulo	8	58	35	3	40	58	87	14	–	57	14	29
Wera	3	33	64	5	47	47	97	3	–	14	43	43
Habro	11	61	29	–	30	70	63	38	–	15	44	41
Daro Lebu	38	38	24	13	33	53	85	15	–	18	55	27
Mean (%)	24	45	31	11	42	48	90	10	–	28	41	31
Chi-square	X^2 = 64.392, df = 10, *p*-value = 0.000			X^2 = 34.255, df = 10, *p*-value = 0.000			X^2 = 31.862, df = 5, *p*-value = 0.000			X^2 = 23.424, df = 10, *p*-value = 0.009		

Note: X^2 = chi-square, df = degree of freedom, t/ha = ton per hectare and *p*-value = probability value.

Figure 2. Finger millet seed production in western Ethiopia (photo H. Shimelis).

The majority of the respondent farmers reported yields in the range of 1.5–3.0 t/ha for finger millet and sorghum. A higher proportion of respondent farmers (90%) reported yields <1.5 t/ha for tef. Some 48% respondents reported yields >3.0 t/ha for maize. Farmers in Wera (64%) and Atote Ulo (35%) districts achieved finger millet yields of >3 t/ha (Table 3) due to the favorable growing conditions. The use of different crop management methods such as weed management practices, crop rotation and row planting are the most favorable growing conditions and essential drivers for high yield gains. Furthermore, farmers in these districts had access to improved seed through the Bureau of Agriculture and research institutions, which allowed higher yield gains.

3.3. Roles of Finger Millet Production in the Study Areas

Finger millet is a multi-purpose crop in the study areas. It is used for household consumption, cash income, feed, construction material and combinations of the various roles of the crop. The roles of finger millet significantly varied across the study districts (X^2 = 101.55; *p*-value = 0.00) (Table 4). A relatively higher number of respondent farmers (38.8%) used finger millet for a combination of food, feed and cash, followed by food and feed (14.5%), food and cash (13.7%), food (11.5%) and food, cash, feed and construction material (9.7%). About 11.5% of all the respondent farmers reported using finger millet for food only, while 19.4% in Shala district reported multiple purpose uses. A relatively higher number of farmers (22.5%) in Siraro district used the crop for food only, followed by food and feed (20%). Higher proportions of respondent farmers in Wera (65%), Atote Ulo (55%), Habro (40%) and Daro Lebu (38.9%) used finger millet for a combination of food, feed and cash (Table 4).

Table 4. Proportion (%) of farmers who grow finger millet for various roles in the study areas.

Roles of Finger Millet	Districts						Mean (%)	X^2	df	*p*-Value
	Shala	Siraro	Atote Ulo	Wera	Habro	Daro Iebu				
Food	8.3	22.5	2.5	5.0	14.3	16.7	11.5	101.55	35	0.00
Feed	–	–	–	–	–	–	–			
Cash	–	–	–	–	–	–	–			
Food and feed	13.9	20.0	15.0	2.5	14.3	22.2	14.5			
Food and cash	8.3	10.0	5.0	7.5	31.4	22.2	13.7			
Food and construction material	5.6	2.5	–	–	–	–-	1.3			
Food, feed and cash	13.9	17.5	55.0	65.0	40.0	38.9	38.8			
Food, feed and construction material	11.1	12.5	5.0	5.0	–	–	5.7			
Food, cash and construction material	19.4	2.5	7.5	–	–	–	4.8			
Food, income, feed and construction material	19.4	12.5	10.0	15.0	–	–	9.7			

Notes: X^2 = chi square test; *p*-value = probability value, df = degree of freedom.

3.4. Socio-Economic and Environmental Factors Affecting Finger Millet Production in the Study Areas

Table 5 outlines the different constraints affecting finger millet production as perceived by the farmers. Constraints to finger millet production showed significant differences across the study districts (X^2 = 100.5; *p*-value = 0.00) (Table 5). About 41.5% of farmers reported drought stress as the foremost constraint affecting finger millet production, followed by a lack of improved varieties (12.9%), a lack of financial resources to purchase inputs (11.3%), land size limitations (10.8%), and limited access to seed (10.0%), shortage of fertilizers (5.4%), poor soil fertility (4.6%), shortage of draught power (1.3%) and labour shortage (1.3%).

Table 5. Proportion of farmers (%) who ranked the constraints to finger millet production in six districts of Ethiopia.

Constraints	Districts						Mean (%)	df	X^2	*p*-Value
	Atote Ulo	Daro Lebu	Habro	Shala	Siraro	Wera				
Drought stress	47.5	35.0	35.0	40.0	35.0	55.0	41.3	45	100.5	0.000
Lack of improved varieties	7.5	30.0	12.5	10.0	7.5	10.0	12.9			
Lack of financial resources	15.0	–	–	30.0	22.5	–	11.3			
Land size limitation	10.0	5.0	25.0	2.5	12.5	10.0	10.8			
Limited access to seed	10.0	–	10.0	15.0	12.5	12.5	10.0			
Shortage of fertilizers	2.5	15.0	2.5	–	10.0	2.5	5.4			
Poor soil fertility	–	12.5	10.0	2.5	–	2.5	4.6			
Shortage of draught power	–	2.5	2.5	–	–	2.5	1.3			
Labour shortage	2.5	–	2.5	–	–	2.5	1.3			
High labour costs	5.0	–	0.0	–	–	2.5	1.3			
Mean (%)	100	100	100	100	100	100	100			

df = degree of freedom; X^2 = chi-square; *p*-value = probability level.

3.5. Farmers' Trait Preferences of a Finger Millet Variety

Farmers' trait preferences of finger millet were assessed and compared using PCA (Table 6). The first three principal components with eigenvalues greater than 1.00 explained 85.3% of the total variability in the desirable attributes of finger millet. The first principal component (PC1) accounted for 44.0% of the total variation, while the second and third PCs explained 26.1 and 15.2% of the variation, respectively. High grain yield (0.99) had the highest positive loading value on PC1, followed by compact head shape (0.94), large head size (0.93), pleasing aroma and taste of food products (0.75) and 'enjera'-making quality (0.60). Tolerance to lodging (−0.89), tolerance to shattering (−0.88), high tillering ability (−0.70), brew-making quality (−0.68), medium plant height (−0.54) and disease resistance (−0.53) had negative contributions to PC1. Insect pest resistance (0.77), early maturity (0.72), large grain size (0.7) and drought and heat tolerance (0.61) accounted for the highest variation on PC2. The ease of harvest and threshing (−0.84) had a negative loading on PC2. Only tolerance to weeds (0.84) and high marketability (−0.91) made large contributions on the third PC.

Table 6. Principal components and their contributions to finger millet agronomic and quality attributes reported in six districts in Ethiopia.

Variables	PC1	Contribution	PC2	Contribution	PC3	Contribution
High grain yield	**0.99**	**12.50**	−0.09	0.16	0.02	0.01
Large head size	**0.93**	**10.86**	−0.13	0.34	0.09	0.30
Weed tolerance	0.09	0.10	0.36	2.79	**0.84**	**25.65**
Disease resistance	**−0.53**	**3.54**	−0.31	2.05	0.40	5.82
Ease of harvest and threshing	−0.27	0.94	**−0.84**	**14.87**	0.36	4.85
Large grain size	0.64	5.10	**0.70**	**10.29**	0.33	4.02
Compact head shape	**0.94**	**11.03**	0.17	0.58	0.28	2.89
Insect pest resistance	−0.57	4.04	**0.77**	**12.65**	0.27	2.69
Tolerance to lodging	**−0.89**	**9.92**	−0.30	1.94	0.23	1.89
Brew-making quality	**−0.68**	**5.87**	−0.61	7.91	0.13	0.57
High tillering ability	**−0.70**	**6.23**	0.59	7.47	−0.06	0.11
Early maturity	0.59	4.34	**0.72**	**10.87**	−0.08	0.26
Pleasing aroma andtaste of food products	**0.75**	**7.13**	−0.57	6.91	−0.18	1.19
Drought and heat tolerant	−0.20	0.51	**0.61**	**8.03**	−0.23	1.95
Medium plant height	**−0.54**	**3.72**	0.45	4.39	−0.26	2.47

Table 6. *Cont.*

Variables	PC1	Contribution	PC2	Contribution	PC3	Contribution
Tolerance to shattering	**−0.88**	**9.65**	−0.09	0.18	−0.36	4.74
'Enjera'-making quality	**0.60**	**4.46**	−0.55	6.51	−0.54	10.53
High marketability	−0.07	0.06	0.31	2.08	**−0.91**	30.05
Eigenvalues	7.9		4.7		2.7	
% of total variance	44.0		26.1		15.2	
Cumulative variance (%)	44.0		70.1		85.3	

PC = principal component, bold face values denote high score values.

Figure 3 presents the variables and study areas where the variables are connected with the biplot origin through the line vectors. The plot shows that high grain yield has the smallest angle with large head size followed by compact head shape, pleasing aroma and taste of food products, 'enjera'-making quality, large grain size and early maturity. Furthermore, the variables mentioned above have an angle less than 90° with high grain yield. On the other hand, the rest of the variables have an angle greater than 90° with high grain yield.

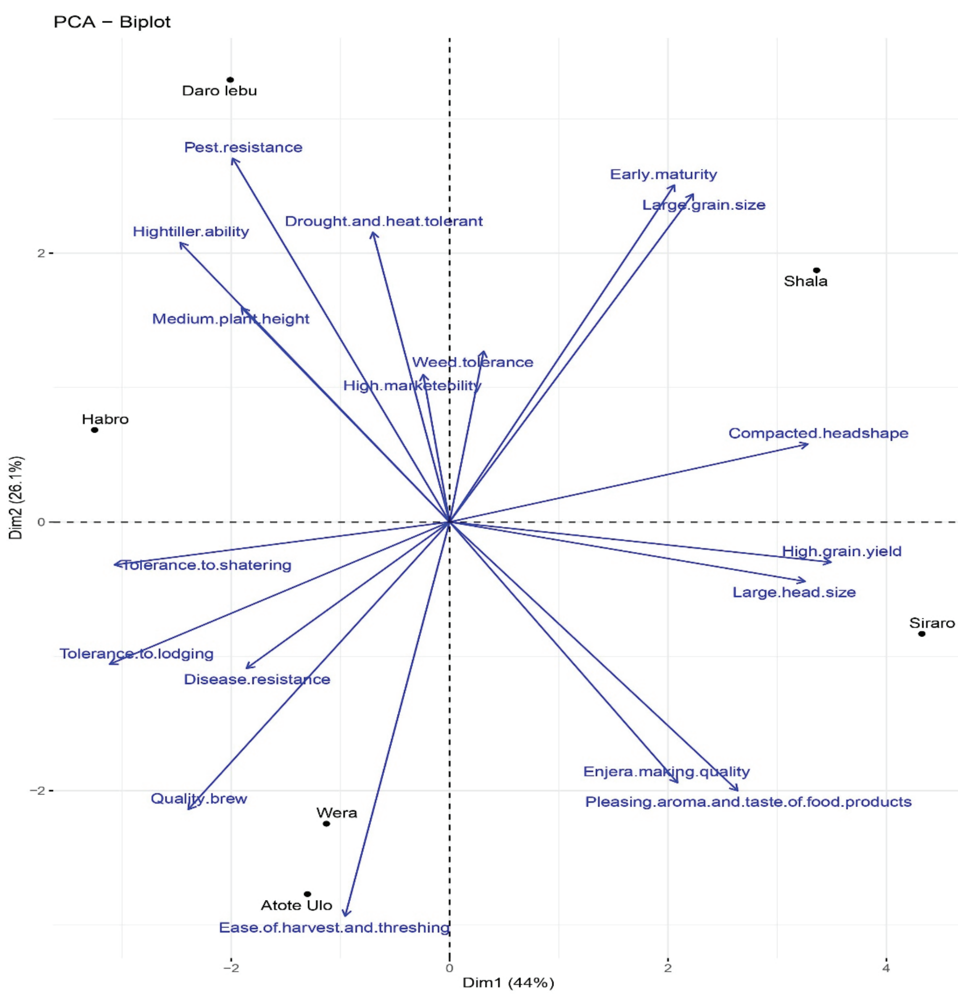

Figure 3. Biplot showing the interrelationships among the variables.

3.6. Crop Management Practices in Finger Millet Production

Respondent farmers reported the common crop management practices of finger millet. There were significant differences in finger millet growers' management practices across the districts (Table 7). About 40.3% of the respondents used a combination of hand weeding and chemical herbicides to control weeds, while 59.2% used hand weeding only. The largest proportion of respondent farmers (78.8%) used hand weeding in the Daro Lebu district. Shala and Siraro districts had the highest proportion of farmers at 65 and 55%, respectively, who controlled weeds using a combination of hand and chemical methods. Finger millet was planted as a sole crop by 97.0% of farmers. In all districts, a higher proportion of finger millet farmers (75.6%) practiced crop rotation with haricot bean, green pepper and potato. In Habro district, there were a lower proportion of farmers (20%) who practiced crop rotation. Direct field sowing was the major planting method of finger millet reported by 69.1% of respondents, followed by transplanting seedlings at 4–6 leaf stage. About 88.0% of the respondent farmers used row planting, while 12% practiced broadcasting. Some 51.4 and 15.4% of respondent farmers in Habro and Daro Lebu, respectively, used a broadcasting method of finger millet sowing (Table 7).

Table 7. The proportion (%) of respondents who used different crop management practices in finger millet production across the districts during 2020/20121 cropping season.

Districts	Crop Management											
	Weeding			Cropping System			Crop Rotation		Transplanting		Planting Methods	
	Hand Weeding	Chemical Herbicides	Hand Weeding and Chemical	Sole	Mixed	Sole and Mixed	Yes	No	Yes	No	Row	Broadcasting
Atote Ulo	55.0	–	45.0	100.0	–	–	100.0	0.0	–	100.0	100.0	–
Wera	77.5	–	22.5	100.0	–	–	100.0	0.0	–	100.0	95.0	5.0
Shala	35.0	–	65.0	91.9	2.7	5.4	100.0	0.0	100.0	–	100.0	–
Siraro	45.0	–	55.0	97.5	–	2.5	72.5	27.5	80.0	20.0	97.5	2.5
Habro	67.5	2.5	30.0	–	–	–	20.0	80.0	–	100.0	48.6	51.4
Daro Lebu	78.8	–	21.2	100.0	5.4	–	58.8	41.2	–	82.5	84.6	15.4
Mean (%)	59.2	0.5	40.3	97.0	1.7	1.3	75.6	24.4	30.9	69.1	88.0	12.0
Chi-square test	X^2 = 30.7 df = 10 *p*-value = 0.00			X^2 = 12.7 df = 10 *p*-value = 0.24			X^2 = 111.3 df = 5 *p*-value = 0.00		X^2 = 203.0 df = 5 *p*-value = 0.00		X^2 = 70.4 df = 5 *p*-value = 0.00	

Notes: X^2 = chi-square test; *p*-value = probability value, df = degree of freedom.

3.7. Finger Millet Varieties Grown and Sources of Seed

3.7.1. Attributes of Varieties Cultivated by the Farmers

There have been 20 finger millet varieties officially released in Ethiopia since 1998. However, only a few of these varieties are presently grown in the study areas (Table 8), such as Tadesse, Tessema, Axum, Meba and Bareda. However, late maturity, susceptibility to disease (head blast), insect pests and shattering problems were among the released varieties' major drawbacks (Table 8).

Table 8. Lists of released finger millet varieties and landraces, their preferred traits and drawbacks reported by respondent farmers in 2020/21 cropping season.

Name of Variety or Designation	Preferred Traits	Drawbacks
	Released Varieties	
Tadesse (KNE#1098)	Easy to thresh, high yielding, medium plant height, lodging resistance, compact head, large grain size, high biomass, erect tillers, good for feed	Late maturing, susceptible to insect pests and diseases, shattering problem, low human health value
Tessema (ACC#229469)	High yield, compact head, high biomass, easy to thresh	Susceptible to insect pests and diseases, late maturing, low medicinal value
Axum	High yielding, drought tolerance	Susceptible to root rot disease, low human health value
Meba	Disease resistant	Low yielding
Bareda	High yield, good biomass	Low human health value
	Landraces	
Amaracha	Good food quality, insect and disease resistance, human health value	Low yield, susceptible to lodging, low biomass production
Dagusa	Good food quality, insect and disease resistant, human health	Difficult to thresh
Dima (red seed type)	Good food quality, insect and disease resistant, better in medicinal value	Low biomass
Dalecha (dark brown seed)	High tillering capacity, medicinal value	Low yielding
Ejeru	Lodging resistance, early and good 'enjera'-making quality	Susceptible to disease
Guracha (black seed)	Good for 'enjera' and high yielding	Susceptible to drought
Habesha	Good food quality	Low yield
White	High yield and good for 'enjera'-making	Susceptible to disease, late maturing

Farmers also cultivated landrace or local finger millet varieties (Table 8). The main distinguishing features used in the selection of the local varieties were local names and seed colour. Respondent farmers preferred the landraces for their higher perceived nutritional and human health values than the released varieties. The farmers mentioned that the local finger millet varieties are also preferred for their tolerance to disease and insect pests. However, the local landraces are cultivated on small areas because they have low yield and biomass production, susceptibility to lodging and are difficult to thresh. The harvested seed from the local landraces is not true-to-type due to genetic admixtures.

3.7.2. Sources of Finger Millet Seed

There were significant differences (X^2 = 191.597, p-value = 0.000) among respondent farmer seed sources (Table 9). The Bureau of Agriculture (BOA) was the primary source of finger millet seed. About 49.1% of respondent farmers across the districts accessed seed from the BOA. In the Atote Ulo and Wera districts, 88 and 93% of respondents, respectively, used BOA as their seed source. The next important source of seed was farmer-to-farmer exchange. On average, 22% of the respondents used seed obtained from other farmers. Daro Lebu (reported by 50% of respondents) and Siraro (35%) had the highest frequencies of farmers who exchanged seed with other farmers. Research institutions such as the Ethiopian Institute of Agricultural Research (EIAR) and Oromia Agricultural Research Institute (OARI), local producers and self-saved seed were also mentioned as seed sources by 32, 28 and 22% of respondents at Shala, Siraro and Habro, in that order (Table 9).

Table 9. The proportion (%) of respondents and corresponding seed sources of finger millet varieties in the study districts in 2020/21 cropping season.

Seed Sources	Districts						Mean (%)
	Atote Ulo	Wera	Shala	Siraro	Habro	Daro Lebu	
Research institutions	5.0	–	32.0	–	2.7	–	5.8
Bureau of Agriculture	87.5	92.5	35.50	22.5	35.1	15.8	49.1
Local producers	2.5	2.5	6.50	27.5	2.7	2.6	7.5
Farmer-to-farmer seed exchange	2.5	–	22.60	35.0	24.3	50.0	22.1
Own saved seed	-	5.0	–	–	21.6	18.4	7.5
Cooperatives	2.5	–	–	–	–	–	0.4
Local market	–	–	–	7.5	5.4	7.9	3.5
Unknown source	–	–	3.20	7.5	8.1	5.3	4.1
Chi-square test	X^2 = 191.597, df = 35, *p*-value = 0.000						

3.8. Cost Benefit Analysis of Major Crops Grown in the Study Areas

The economic importance of the major crops grown in the study areas was assessed through cost-benefit analysis. In this regard, the principal crops were compared concerning achieved yield (t/ha), total income realized from sales of grain and straw in United States dollars per hectare (USD/ha), total production costs (USD/ha), revenue (USD/ha) and benefit to cost ratios. The highest grain yield (3.00 t/ha) was obtained from finger millet followed by maize (2.93 t/ha) and sorghum (2.20 t/ha). Conversely, tef had the least yield (0.65 t/ha) followed by haricot bean (1.74 t/ha). The total income (USD/ha) generated from finger millet was the highest at 2139 USD/ha followed by sorghum (1612 USD/ha) and haricot bean (1033 USD/ha). Total income generated from haricot bean and maize sales were 1033 and 1003 USD/ha, respectively, lower than the average price of all crops (1329.8 USD/ha) (Table 10).

Table 10. Income, cost and cost-benefit analysis of finger millet and other major crop production in the 2020/21 cropping season in the study districts.

Crops	Price of Grain (USD/ton)	Grain Yield (t/ha)	Income from Grain Sell (USD/ha)	Income from Straw Sell (USD/ha)	Total Income (USD/ha)	Total Production Cost (USD/ha)	Profit (USD/ha)	Benefit/Cost Ratio
Finger millet	630.67	3.00	1892.00	247.00	2139.00	1249.00	890.00	1.71
Haricot bean	566.67	1.74	986.00	47.00	1033.00	268.00	765.00	3.85
Maize	303.75	2.93	890.00	113.00	1003.00	743.00	259.00	1.35
Sorghum	646.36	2.20	1422.00	190.00	1612.00	689.00	923.00	2.34
Tef	1189.23	0.65	773.00	89.00	862.00	509.00	353.00	1.69
Mean	667.30	2.10	1192.60	137.20	1329.80	691.60	638.00	2.19

The total cost of finger millet production (1249 USD/ha) was at least twice as high as the average cost of production of all other crops grown (691.6 USD/ha) in the study areas. Sorghum was the most profitable crop, with an average profit of 923 USD/ha, followed by finger millet (890 USD/ha). Tef growers realized significantly lower profits of 353 USD/ha, while maize growers attained the least profit of 259 USD/ha (Table 10).

The principal crops were also compared in terms of benefit/cost ratio. On average, haricot bean producers with a higher benefit to cost ratio of 3.85 had the highest benefit, followed by sorghum growers (2.34). The benefit/cost ratios for finger millet, tef and maize were 1.71, 1.69 and 1.35, respectively. The significant costs of finger millet production were the costs of the seed for planting, fertilizers, labour for land preparation, weeding, hoeing, thinning, harvesting and threshing.

3.9. Cultural Practices to Cope with Low Moisture Stress

The respondent farmers developed a range of agronomic solutions to finger production challenges, mainly drought stress (Table 11). As a result, farmers in the study areas used various cultural methods to cope with moisture stress. Ploughing varied in terms of frequency, depth and date as a moisture stress coping strategy. Hoeing at the right stage, weed control and supplemental irrigation, if available, were also used to mitigate moisture stress. Moreover, adjustment of sowing dates, tie ridging and relatively deep sowing were used to manage moisture stress. Farmers planted at higher than recommended seeding rates to attain optimal plant populations. Varietal selection, application of inorganic fertilizers and the use of mulching and cattle dung were also used to manage moisture stress (Table 11).

Table 11. Various methods used by finger millet growers to cope with moisture stress, reported during the focus group discussion.

Methods to Cope with Moisture Stress	Perceived Advantages
High ploughing frequency before the onset of rainfall	Assists in infiltrating the available soil moisture, exposure to sunlight of eggs of insect pests present in the soil.
Deep ploughing by using tractor	Improves moisture-holding capacity of the soil, exposure to sunlight of eggs of insect pests present in the soil
Early ploughing and land preparation as soon as the onset of the first rain shower after harvesting	Effective use of the available soil moisture
Hoeing at the right stage	Maintains the available soil moisture
Weed control	Protects the crop from the competition of the soil moisture and other nutrients
Irrigation if available	Provides supplemental moisture required by the crop
Adjustment of sowing date	Manages flowering time so as not to coincide with drought times and utilizes the available soil moisture
Sowing in tie ridging	Holds available soil moisture
Row planting	Manages the appropriate plant population
Sowing the seed relatively deep in the soil	Assists the seed to access the available soil moisture for germination
Use of higher seed rate than the recommended one	Assists to get the required plant population during low moisture period
Soil mulching using different grass species	Increases soil fertility and water holding capacity and lowers soil temperature
Use of cattle dung and application of urea fertilizer after the first weeding and when there is a relatively good soil moisture	Increases soil fertility and moisture-holding capacity and provides healthy and vigorous crop to cope with low moisture stress period
Varietal selection	Better and cheap alternative to alleviate the problem of low moisture stress

4. Discussions

4.1. Demographic Attributes

The demographic characteristics of the respondents were documented (Table 2) because they influence farming practices, intervention strategies and technology adoption among farming communities. The most significant proportion of respondents were male, which is concomitant with the fact that most households in the study area were male headed (Table 2). Patriarchy is dominant in the study area, with a negligible number of females having decision-making powers. The disenfranchisement of females, as discovered in other PRA studies, also reflects their peripheral roles in decision-making in agricultural activities and their ongoing exclusion from social services such as training and agricultural extension services [50], despite their active participation in farming operations such as ploughing, weeding and harvesting.

In terms of age, most of the interviewed farmers were within the active age group of 18–40 years (Table 2). This group consists of young and middle-aged adults that participate in the economy by providing labour and engaging in economic activities, such as trade, and in decision-making. Mulalem and Melak [22] also identified this group as vital for agricultural functioning as an active, productive age group. The young adults in this group can adopt new agricultural technologies, given their high literacy level and lack of prior experience [51]. The middle-aged adults in the active productive group were involved in decision-making and influenced choices of agricultural technologies, which in turn have an impact on crop production and productivity [36].

The respondent farmers had large families of more than five children per household, which positively impacts the provision of labour for crop production but is a concern for food insecurity in the study districts. Large families provide readily available labour for farming activities in subsistence farming systems because the farmers cannot afford to hire external labour [43]. Smaller households struggle to implement essential activities such as ploughing and weeding, given that most operations in smallholder farming are manual. Provision of labour is also related to the age of family members. Families composed of mostly young children struggle to provide the required labour. However, large families require more significant amounts of food for sustenance, and the risk of food insecurity increases in subsistence farming where crop productivity is generally low. Tadele [52] noted that large families have an adverse impact on food security, especially in Africa, where the population growth rate is very high.

The low literacy levels among the sampled farmers are of concern, especially for the successful introduction of new technologies and dissemination of information. A low level of education has been identified as a significant factor leading to poor adoption of agricultural technologies and access to information in rural and smallholder farming communities. Interventions such as farmer training and provision of information have less impact on agriculture systems where farmers have low levels of literacy [50,53]. Farmers who have a higher level of literacy are likely to adopt improved technologies and improve their farming practices for higher crop productivity and have the potential to engage in more profitable markets or negotiate for better prices with service providers [50,54].

4.2. Dominant Crops Cultivated in the Study Areas

Crop production was dominated by maize and finger millet (Table 3), consistent with previous reports showing that smallholder farmers cultivated mainly maize and other cereals crops [55]. The land allocated for finger millet production by a household was equivalent to the national average of 0.25 ha [17], showing that the selected study sites could represent finger millet production systems in Ethiopia. The production of finger millet is essential for mitigating the impact of drought stress on food security. Finger millet is more drought tolerant than crops such as maize. However, the dominance of cereals is a concern for nutritional security. Cereal-based diets are carbohydrate-rich, leading to hidden hunger caused by deficiencies in essential nutrients such as specific amino acids, minerals and vitamins. Finger millet, and sorghum to an extent, are high in micronutrients, and farmers in the study areas get the various health benefits in their food sources from the two crops. The farmers reported trading their grains for cash income generation to buy other foods containing proteins, vitamins and minerals to supplement their cereal diets. However, low productivity and a lack of surplus grain yield frequently limit potential income generation. Yields below 1.5 t/ha have been commonly recorded in the study areas, below the national average for all crops. The dominance of maize in production systems of the study areas has been enhanced by its potential due to its early sowing dates, where green maize is grown to avert food shortages in the lean season (when the previous season's grain harvest becomes depleted but the new crop is not available), and its relative ease of marketing compared to finger millet or other cereals.

4.3. Various Uses of Finger Millet

Foremost, finger millet is used as a food crop in the study areas (Table 4). It is commonly ground into flour for making leavened bread known locally as 'enjera'. However, finger millet has relatively poor 'enjera'-making qualities and the farmers usually blend the finger millet flour with maize flour. Alternatively, finger millet is coarsely ground to make porridge. However, porridge made from finger millet is not common in Habro and Daro Lebu districts, where the farmers mentioned that they do not use finger millet to make porridge. Cultural differences and access to information influence the uses of finger millet. Training and awareness campaigns on the potential uses of finger millet and bio-fortification of finger millet could improve its utilization and contribute to food security.

Finger millet straw is also vital for livestock feed (Table 4). The farmers have small land holdings, and their livestock are raised on communal grazing lands. After harvest, the livestock are allowed into the fields to graze on crop residues. Most of the farmers in the study areas harvested the stover to feed the livestock when there was scarcity. While this stover's nutritional value and palatability are relatively low relative to a green fodder crop [56], its impact on animal health is vital given the lack of alternative grazing in the dry season. Mululam and Melak [22] reported that 69% of farmers in North-Western Ethiopia used finger millet straw for animal feed, while 12% used the straw as a construction material. Studies in China showed that the replacement of other straws like corn straw with finger millet straw improved the growth of sheep and was recommended in fattened lamb production [57].

4.4. Socio-Economic and Environmental Factors Affecting Finger Millet Production

While the ranking of the importance of production constraints varied across the districts, erratic rainfall, a lack of improved varieties, a lack of financial resources to procure inputs, land shortages, a limited supply of seeds of improved varieties, a lack of access to fertilizers and declining soil fertility were the most common challenges affecting finger millet production (Table 5). Erratic rains were also identified as a major production constraint in Kenya [58], Myanmar [59] and Ethiopia [60,61]. A lack of financial resources has been previously identified as the single most crucial socio-economic challenge affecting crop production in most sub-Saharan African countries [62]. Limited access to agricultural inputs such as fertilizers, pesticides and improved seeds is related to limited financial resources and has been widely reported in Africa [63] and, particularly, Ethiopia [53,64,65].

Smallholder farmers face a multitude of production constraints that limit crop productivity. Biotic and abiotic constraints, such as pests and diseases and declining soil fertility, may be mitigated with breeding for varieties with the necessary resistance or tolerance level to support crop production in stress-prone environments. On the other hand, socio-economic constraints can be rectified by implementing necessary policy changes, training intervention and improving extension services. Both policy regulations to improve the socio-economic environment and breeding are still lagging, which significantly compromises crop production in general, particularly finger millet.

4.5. Farmers' Trait Preferences of a Finger Millet Variety

The most desirable traits of finger millet were compared and their order of importance were assessed via PCA. The biplot shows the interrelationship among the variables. The cosine of the angle between the vectors of two variables is almost equal to the correlation coefficient between them [66]. The angle between the two variables is an indication of how closely or distantly related the variables are. Therefore, the smaller the angle between them the stronger the relationship they have and vice versa. Comparison of the angles in Figure 3 and the principal component analysis of Table 6 showed a high correspondence between them. Identifying farmer-preferred traits is an essential step for variety design and development. High grain yield, 'enjera'-making quality, large head size and compacted head shape can be prioritized in variety development to meet the aspirations of the farmers (Table 6). The inclusion of farmer-preferred traits in variety development is essential to promote cultivar adoption but also to mitigate production constraints. Traits such as insect pest and disease resistance and drought and heat tolerance are vital for inclusion in new varieties, given that the farmers alluded to the impact of biotic and abiotic constraints on finger millet production (Table 6). While the ranking of farmer-preferred traits varied across the districts, the identified traits were consistent and could potentially be pyramided into a single variety. After identifying farmer-preferred traits in finger millet, the next step would be to understand the genetic basis of the traits and devise suitable strategies for their improvement in new cultivars. Traits such as high grain yield and drought tolerance are quantitative traits that are difficult to improve due to their polygenic nature and high environmental variance. They will require the collection of diverse genetic resources for evaluation and selection to develop suitable varieties. For traits such as blast disease resistance, additive gene action has been predominant for finger millet and showed that progress would be made through recurrent selection [67].

Similarly, traits like high 'enjera'-making quality are likely to be governed by a few major genes; the selection process and variety development may be relatively easier and faster than high yield and drought-tolerant variety development. Given that farmers desired multiple traits in a single finger millet variety, breeding an ideal variety will not be a straightforward process. This process of soliciting information from farmers can be conducted periodically and iteratively at all stages of variety design to incorporate new ideas and insights and respond to changes in environment and lifestyle. Owere et al. [24] also reported that high grain yield, compact head shape and early maturity were the most preferred attributes of finger millet. Likewise, high yield, drought tolerance, early maturity and big heads were key farmer-preferred traits reported by Ojulong et al. [68] and Tracyline et al. [69].

4.6. Cropping Patterns of Finger Millet and its Management Practices

Weed control was one of the major tasks carried out by farmers, and the use of manual labour to control weeds is both inefficient and time-consuming (Table 7). The combination of herbicides and manual labour is more efficient but was limited by the farmers' shortage of inputs and lack of financial resources. Finger millet was planted as a sole crop, which agreed with another report showing that finger millet is commonly grown as a sole crop [9]. Unlike maize, which is sometimes intercropped with legumes, there are very few cases where finger millet is intercropped with legumes. The most common practice is to rotate finger millet with other cereals or legumes, which farmers in the study areas practiced. During group discussions, the respondents pointed out that finger millet was planted as a sole crop but in rotation with haricot bean and hot pepper. In addition to crop rotation, farmers used double cropping systems involving tef and haricot bean. However, the double cropping system was not possible with finger millet because the currently cultivated finger millet varieties are too late-maturing to fit into a double cropping system. Developing and deploying early maturing varieties would facilitate its inclusion in a double cropping system for enhanced food production.

4.7. Seed Source of Finger Millet

Currently, there is a poorly developed seed system industry for finger millet in Ethiopia. A significant dependence on BOA and farmer-to-farmer seed exchange is linked to poor access to seeds of improved varieties (Table 9). Farmer saved seeds are not pure, have low germination rates and often carry seed-borne diseases [70], contributing to yield losses. While the BOA was a seed source for most farmers, it often has limited supplies and cannot reach all the farmers simultaneously for planting. It is imperative that as breeding programs commence, they can be developed in parallel with a commercial seed system to ensure efficient and effective distribution. There are also few registered finger millet varieties in Ethiopia despite the importance of finger millet as a crop. This is concordant with previous reports on the neglect of traditional cereals in breeding programs compared to crops such as maize and wheat. Of the 23 released varieties, only five were in production, which begs the question why the farmers poorly adopt them. A possible reason is lack of farmer involvement in previous breeding programs that focused on product development with little regard to farmer input. Recently, most programs have developed varieties that were high yielding but lacked other vital and complementary attributes desired by farmers, leading to their rejection by the market. In this regard, Jerop et al. [51] reported that the significant seed sources of finger millet in Kenya were self-saved seed and the government extension program, which corroborate the findings of this study. Tsehaye et al. [9] reported that most farmers in Northern Ethiopia also used self-saved seed or obtained seed from the local informal market.

4.8. Cost-Benefit Analysis of Major Crops Grown in the Study Areas

The high cost of production for finger millet was probably driven up by the high labour costs for weeding due to its susceptibility to weed competition during its early stages of growth. Manual weeding was practiced at a higher frequency for finger millet than other crops, requiring more man hours and increasing production costs. In addition to weeding, harvesting and threshing of finger millet are tedious and labour-intensive. In general, weeding, harvesting and winnowing were the significant labour demanding tasks in finger millet production. Even though finger millet is a highly profitable crop (890 USD/ha), the respondents expressed reluctance to produce it on a large scale, citing the high labour requirements as an impediment. Higher labour requirements for finger millet production than other crops have been identified as a major deterrent to its production, productivity and market potential [40]. In India, the average cost of production for finger millet was estimated to be 544.3 USD/ha, with average yield productivity of 1.44 t/ha and a net profit of 138.1 USD/ha [71]. The cost-benefit ratio calculated for finger millet was similar to 1.05 reported by Adhikari [49] and within the range of 1.05–2.15 that was reported by Kaushal and Choudhary [71]. There is a need to increase the benefit to cost ratio to motivate the farmers to adopt finger millet production. Improved resistance to weeds, increased thresh ability and early maturity would reduce labour costs associated with the respective agronomic practices and encourage farmers to adopt the crop. Therefore, there is a need for finger millet improvement to deliver high yielding and farmer-preferred varieties to enhance the economic benefits of the crop. Maize is one of the major crops in Ethiopia, including in the study areas. Nevertheless, farmers are not deriving profits from the production and marketing of this crop due to various reasons. The primary reason is that, in the country, the grain prices of maize are unpredictable due to the high market supply during the production season. This condition is the major constraint for maize farmers given that most of them have access to the local markets to sell maize [72]. In addition, there are no adequate postharvest infrastructures in the country, including transport, storage and processing.

4.9. Cultural Methods to Cope with Low Moisture Stress

Production of drought-tolerant crops such as finger millet has been promoted as a strategy for climate change mitigation [73]. Farmers in the study areas were aware of climate change, its adverse effects and possible mechanisms to cope with its effects. As a result, they used various strategies to cope with low moisture stress to minimize crop loss and food insecurity. These included various soil moisture conservation and soil fertility enhancement technologies (Table 11). The frequency, depth and period of ploughing and the timing of crop management practices such as planting, weeding, and adjusting plant population were used to mitigate the impact of moisture stress, with various levels of success. Similarly, during the period of low moisture stress, most farmers in South and North Welo grew early maturing sorghum to escape drought stress [42]. The breeding of short duration finger millet varieties would also help the crop to escape drought stress. Mulching and the use of tie ridges were practiced because these practices are commonly used for moisture conservation. Early planting, use of organic inputs, adoption of new tillage practices and applying tied ridges have been previously reported among strategies used by smallholder farmers to mitigate the impact of low soil moisture [74].

5. Conclusions

Finger millet is one of the staple food crops in Ethiopia, but its productivity is constrained by a range of biotic and abiotic stresses and socio-economic factors. Drought stress was considered to be the most important constraint in all the districts, followed by a lack of improved varieties, limited access to seed and a lack of financial resources. Land size limitations, poor soil fertility and a lack of access to fertilizers were also ranked important constraints affecting finger millet production. The most critical farmer-preferred traits in finger millet were high grain yield, compact head shape, 'enjera'-making quality, high marketability and early maturity. Therefore, to enhance finger millet productivity, plant breeding aimed at solving the above-mentioned production constraints and incorporating the farmer-preferred traits needs to be undertaken in Ethiopia.

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Evolution of Short Food Supply Chain Innovation Niches and Its Anchoring to the Socio-Technical Regime: The Case of Direct Selling through Collective Action in North-West Portugal

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Abstract: This paper employs MLP (Multi Level Perspective) applied to a study on the transition to SFSC (short food supply chain) innovation taking place in North-West Portugal. MLP allows capturing transition phenomena and analysing them from a perspective that posits intervening factors and events on a three-level scale. Emphasis is laid on the institutional actors and factors that influence these processes, namely the Three Interrelated Analytic Dimensions and Types of Anchoring. Methodologically, personal interviews were conducted with 34 farmers who either are carrying out SFSC initiatives, or have dropped out, or even have never considered participating in them. A process of anchoring the innovation to the local socio-technical regime has been identified, characterised by a low buy-in from institutions and stakeholders. The anchoring that has been found has the peculiarity of occurring only in some points of the intersection between niche and regime, in a process in which it survives bordering this threshold, thanks to the mobilisation of multiple innovations. This type of anchoring, not yet described in the literature, draws attention to a possible pathway that innovations can follow, and brings implications for projects and for policy proposals to support the agroecological transition.

Keywords: transitions; multi-level perspective; short food supply chains; anchoring

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1. Introduction

Transitions motivated by sustainability that several socio-technical systems are currently undergoing explain the growing interest and developments around Transition Theory. The study of such transition processes has focused on understanding what triggers them and how they are developed, namely to ascertain how they can be accelerated by public policies. Transition Theory originated in studies on the sociology of technology like Rip and Kemp's [?], illustrating the role played by technology in society and vice-versa. In 2002, the theory acquired a schematic perspective and a graphic representation, following Geels' improvements, which resulted in the *Multi-Level Perspective* (MLP) [? ?]. According to Geels, the MLP results from the integration of different contributions and establishes a novel theoretical framework that combines "analytical and heuristic concepts to understand the complex dynamics of sociotechnical change" [?] (pp. 1259). Geels [?] proposes a dynamic combination of events structured in three levels leading to the heuristics that can explain the evolution of technological transitions triggered by introducing innovation in sociotechnical regimes.

In the present study, MLP will be used to look into a non-technological innovation, encompassing changes in organisational, marketing and value-chain aspects, configuring the creation of a Short Food Supply Chain (SFSC) [?] in order to understand how it unfolds as an agri-food system transition in the northwest of Portugal. This Portuguese region is particularly marked by its vocation for horticultural and fruit production activities usually developed in small family farm holdings. Especially after 2008, this region has taken on an innovation within the SFSC, in which groups of small family farmers organised themselves to directly supply final consumers with products from their farms [? ?]. This direct selling innovation, which incentivises farmers to cooperate with each other, was introduced by Local Development Associations (LDAs) aiming at increasing small family farmer income while helping them market their products. It is, then, an organisational and collaborative innovation aiming at changing the way farmers do business and one which can, therefore, be looked at as a way of innovating both marketing and the value chain.

Under the MLP, one can assume that in the area under study, direct selling of fruit and vegetable baskets is an innovation, which, at the time of the empirical research, in 2018, represented a link to the local socio-technical regime. In other words, it corresponded to an initiating transition conventionally referred to as anchoring. In this sense, the present study is in line with Smith's [?] and Elzen's et al. [?] view that these initiating transitions must be looked into and systematised using several case studies in order to identify and clarify those processes which have not yet been dealt with in specialised literature [?], as well as to identify whether there are patterns that represent them [?]. The present research paper introduces an original contribution to develop the understanding of the anchoring processes in the MLP framework. It presents a case of marginal anchoring, where only a few niche actors connected to the mainstream regime, where farmer bulk sell prevails, by combining the direct selling of fruit and vegetable baskets with the development of an array of other complementary innovations. Thus, it was possible to continue innovating, albeit in an incremental mode.

From a theoretical viewpoint, MLP and its analytical levels of the socio-technical system will be combined with other aspects on which transitions are also based, such as infrastructural and institutional aspects and the collaboration between stakeholders and organisations [?]. To that effect, the Three Interrelated Analytic Dimensions proposed by Geels in 2004 [?] will be used; emphasis is put on individual and collective action-related aspects (human actors, organisations, and social groups) as well as on regulatory and institutional aspects (rules and institutions) and factors that need to be taken care of so that innovation may be structured and pave the way to transition. Elzen et al. [?] also drew attention to the fact that transitions imply having the necessary institutional conditions and a suitable actor-network to unfold positively, which one can refer to as Types of Anchoring and which will also be looked into in greater detail. Although Three Interrelated Analytic Dimensions have an analytical character, as its name suggests, here they will also be applied from a structural perspective, assuming that for an innovation to succeed, both human and organizational aspects and regulatory and institutional ones must affect the elements of the socio-technical system.

In general, the present paper is a contribution to the development of MLP, in need of further research as regards the agri-food system [?]. Moreover, studies on initiating transitions may help enrich MLP and its explanatory power. By depicting a specific transition event – in which innovation anchors to the socio-technical regime–the present study helps create a scientific framework, albeit still in its early stages, to explain the peculiarities of the anchoring phenomenon [? ?]. The concept of anchoring is operationalised by using MLP and by observing and analysing the trajectories of innovation niches, understood by gathering the path narratives of the interviewed farmers. Due to its particular nature, this paper also pioneers the describing of an innovation event capable of surviving in the threshold between niche and regime by the ability of farmers leading the innovation niches to develop complementary innovations that strengthen their innovative approach of direct selling despite conventional bulk selling that prevails in the regional agri-food regime.

The methodological sequence combines the analysis of statements gathered from 34 interviews of farmers, including: (a) those who have developed basket direct selling and anchored to the regime (the "adopters"); (b) farmers that introduced the innovation but that abandoned (the "droppers") and returned in most of the cases to their previous status quo; and, (c) farmers that didn´t even considered adopting the innovation, despite being aware of it (the "non-adopters").

Special attention has been given to the actions of farmers and regulatory and institutional structures dedicated to supporting the consolidation of innovations, aligning these farmer experiences and reports with a set of conditions that go beyond innovation itself or the socio-technical system to describe the transition attempt.

The paper is, then, structured as follows, from Section **??** presents the theoretical framework related to socio-technical transitions and the principle of linking niche innovations to the socio-technical regime described in the literature as anchoring; and Section **??** presents the theoretical approach concerning the innovation of basket direct selling as a SFSC. Section **??** lists the resources and methods used and presents the region under survey characterising the innovation of basket direct selling. Section **??** provides the results of the study. Section **??** explains the marginal anchoring process, considering the institutional dimensions and the stakeholders involved. Finally, the conclusions of the article are presented.

2. Theoretical Approach

2.1. From Transition Theory to Anchoring

The word transition comes from Latin and refers to the process of going from one form, state, style, or place to another [**?**]; due to the notion of crossingthat it entails, the word has been used in studies referring to technical and social change [**?**]. For analytical purposes, Transition Theory has been operationalised through MLP. MLP is an analysis perspective for transition cases [**?**] that articulates three conceptual levels known as niche (micro-level), regime (intermediary level), and landscape (macro-level); it is used to explain what causes innovation processes to emerge and how they can reconfigure already stabilised socio-technical regimes [**?**]. The three levels shape the socio-technical system, and the transition takes place when innovations occur at the niche level and manage to override the regime and reconfigure it. The whole process always takes place under the influence of the socio-technical landscape [**?**].

In short, the niche, MLP's micro-level [**?**], represents the locus of radical innovations, or the protected environments in which innovations are endowed with investments, resources, knowledge, and skills to structure themselves [**?**]; this may entail pilot-projects, market segments, and research and development networks [**?**]. The niche is also acknowledged as an environment that enables innovations to develop outside the scope of market pressure [**?**]. The regime is MLP's intermediary-level [**?**]. It refers to practices, technologies, rules, and institutions already in place in society that guide and legitimise how science and technologies are produced [**?**]. It also refers to a system of interaction practices and structures that have reached a certain relative stability and status quo within a given sector [**?**]. The landscape, MLP's macro-level [**?**], represents the context variables [**?**]. In a broad sense, it may be described as the exogenous socio-technical scenery composed of the ideologies, macro-economic patterns, cultural and climate changes, and demographic tendencies that influence niches and regimes [**? ?**].

However, before innovations and regimes are totally superimposed, there is a stage Elzen et al. [**?**], inspired by Loeber [**?**] and Smith [**?**], called anchoring. Anchoring means the set of facts or events that cause innovations to adhere to the regime. Therefore, it depicts a phenomenon that is usually surrounded by uncertainty because innovations leave the protected space of the regime to meet a new dynamics dictated by the latter's peculiar stability. Innovations may be rejected by regime actors and disappear, or, on the contrary, be accepted and cause the regime to change. Smith [**?**] notes literature treats these links as random and coincidental, stressing that there should be a theory (which he calls the Theory of Linking) to deal with these phenomena, but, so far, none has been suggested. Elzen et al. [**?**] believe unravelling these anchoring dynamics must be one of the concerns of current research to ascertain whether these events obey patterns and whether or not it is possible to predict their unfolding.

The transition from a socio-technical system is commonly represented schematically through MLP [**? ?**]. To this graphic representation, the anchoring event was added to make explicit the emergence of innovative dynamics, their possible link to the regime, and the changes they may cause under the socio-technical landscape in the space versus MLP levels (Figure **??**).

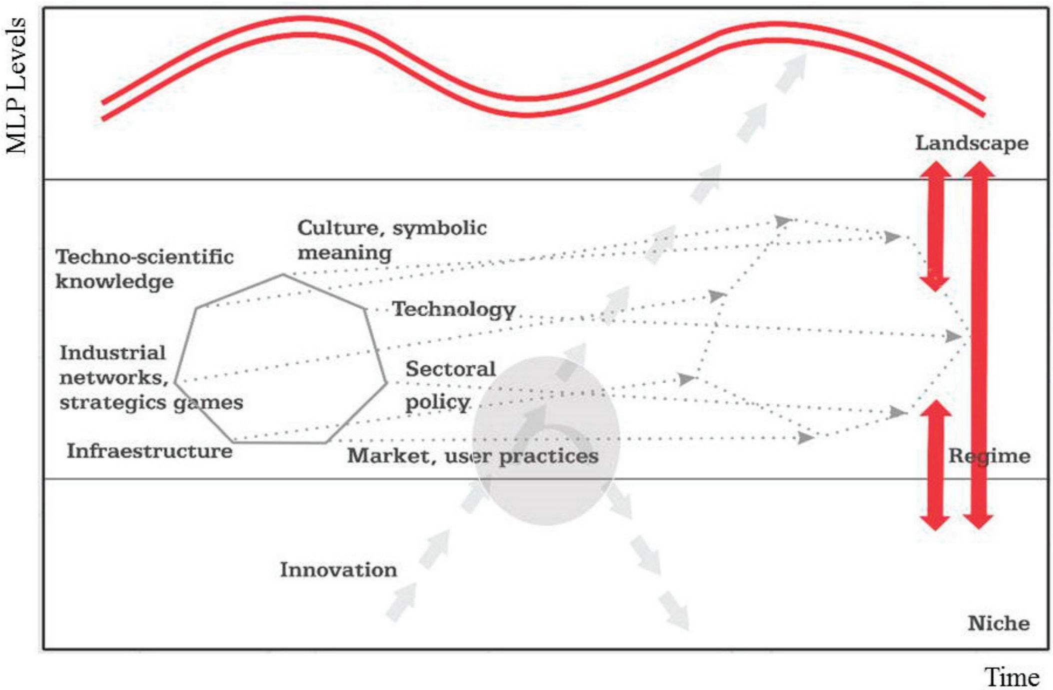

Figure 1. MLP's conceptual and dynamic levels (interpreted according to Geels [?] expressing an anchoring process. (Figure produced by the authors).

The figure shows the niche, regime and socio-technical landscape conceptual levels (a socio-technical system) in a space versus MLP level representation. Innovations (grey arrows) may go on different paths. They may have a regressive trajectory or may progress and enter the regime. In the latter case, they may start changing the regime, here represented by the heptagon the extremities of which are its stable elements. As innovations go on, there may occur a reconfiguration of the regime, the dotted line on the right representing its future composition. The central grey halo is the anchoring event or set of events which mark the beginning of the innovations' link to the regime. At the top level are the context socio-technical variables (the landscape) which both influence and are influenced by the other levels (illustrated by the red arrows on the right).

It is important to note that an anchoring process is not only the linking of niche innovations to the regime. It may also be their linking to several other niches [?]. As it has been suggested by Ingram [?] and Ingram, Maye, and Kirwan [?], anchoring processes regard not only niche agent efforts to anchor to the regime, but also to answer to the actions and pressures of the niche, a process that is reflexive and entails learning processes, actions, and network formation. Table **??** shows a compilation of studies on MLP's conceptual levels applied to certain types of transitions in agriculture. It is worth mentioning these articles do not always explicitly refer to anchoring processes, but their analysis reveals the presence of a dynamic that occurs in the niche-regime interface. In general, the summary of articles includes anchoring issues or the dynamic interactions in the interface, which, so far, have not made their way into specialised literature.

Table 1. Studies on anchoring or relations between levels in agriculture-related transitions.

Reference	Contribution to Studies on Anchoring
Elzen, van Mierlo and Leeuwis (2012) [**?**]	This study suggests anchoring is an analytical concept to explain the continuous process of establishing and breaking relations between niches and regimes and among niches.
Diaz, Darnhofer, Darrot and Beuret (2013) [**?**]	This study emphasises the social role of transitions, highlighting that neither niches nor regimes are static entities; on the contrary, they act and react with and to each other. It suggests anchoring is not a sequential process but a continuous and recurrent one.
Slingerland and Schut (2014) [**?**]	This study shows niche-regime interactions need efficient conditions if they are to be implemented.
Ingram (2015) [**?**]	This study deals with anchoring as an adaptive process, whereby niches and regimes adapt to each other as a result of reflexive and learning processes on the part of the actors involved.
Ingram, Maye, Kirwan, Curry and Kubinakova (2015) [**?**]	This study suggests transition to sustainable agriculture may be looked at as interactive and adaptive complex changes rather than a regime shift.
Sutherland, Peter and Zagata (2015) [**?**]	This study addresses multiple regimes of renewable energy production by the agricultural sector, suggesting the emergence of a new regime out of the political role of this type of process.
Bui, Cardona, Lamine and Cerf (2016) [**?**]	This study identifies common anchoring phases or patterns in four studies regarding agency and governance factors.
Vankeerberghen and Stassart (2016) [**?**]	This study develops the concept of insularisation to characterise the process whereby a niche develops within a regime and gradually and steadily detaches from it.
Belmin, Meynard, Julhia and Casabianca (2018) [**?**]	This study does not explain what an anchoring process is, but it gives an example of a relation between niche and regime in which innovations are not necessarily aligned with the niche, but are a subsystem of the regime. This perception even suggests new transition concepts.
López-García, Calvet-Mir, Di Masso, and Espluga (2019) [**?**]	This study stresses the importance of creating hybrid forums that may become interaction loci between niche actors and regimes. Through these forums, innovations could overcome the regime by linking themselves to different types of actors.
Schiller, Godek, Klerkx and Poortvliet (2020) [**?**]	This study creates a time line to explain the development of a specific niche: the agroecological niche. The conclusion is that the agroecology did not necessarily create a transition but was incorporated into the regime.

In short, the above-mentioned articles suggest anchoring processes both rest on conditions that emerge from the niche-regime relationship, and depend on other factors like the institutional context and the relationship between actors. Consequently, the present analysis will depart from the Types of Anchoring proposed by Elzen et al. [**?**]. Elzen and his collaborators [**?**] admit that the linking of innovations to the regime, that is anchoring, must take place in three areas: technological, institutional, and network-related. The present study will disregard technological anchoring since the direct selling of fruit and vegetable baskets is not exactly technological innovation.

The areas or Types of Anchoring are based on Geels' studies [**?**]. Geels [**?**] has suggested innovations happen through the articulation of the socio-technical context—the object of analysis of the MLP—with two other dimensions: the rules and institutions, and the human actors, in other words, the organisations and the social groups. Together, these two dimensions are what Geels calls Three Interrelated Analytic Dimensions although the Three Interrelated Analytic Dimensions correspond to the Types of Anchoring suggested by Elzen et al. [**?**]. If Three Interrelated Analytic Dimensions are essential in an innovation process, it is to be expected that they are also important at the beginning of the transition. Table **??** shows Three Interrelated Analytic Dimensions and the Types of Anchoring composing elements that need to be articulated for a transition to take place.

Table 2. Elements that compose Types of Anchoring and Three Interrelated Analytic Dimensions.

Three Interrelated Analytic Dimensions	1. Socio-technical systems: involve actor networks gathered around a specific institutional structure to disseminate a technology; they also include knowledge flows or skills required by the technology [**?**].
	2. Rules and institutions: refer to normative, cognitive, and regulatory aspects [**?**] of how innovations emerge.
	3. Human actors, organisations, and social groups: may refer to enterprises that create technologies, or political actors who legislate it, or the users of a novelty [**?**].
Types of Anchoring	1. Technological: concerns technological innovations when actors define the technical features of the novelty [**?**].
	2. Institutional: represents the universe of rules (cognitive, interpretative normative, and economic) mobilised, adapted, or created to support innovations [**?**].
	3. Network-related: means a shift in the relationship between actors (contacts, exchanges, interdependencies, and coalitions) that change as a novelty develops [**?**].

According to Three Interrelated Analytic Dimensions and Types of Anchoring, both innovation and anchoring must have agency and governance components, organised in innovation design and using networks if they are to take place [**?**]. They also share the need for an institutional dimension that regulatorily supports them (such as laws, sanctions, protocols, and power and governance systems) [**?**]. Ergo, Three Interrelated Analytic Dimensions and Types of Anchoring are practically equivalent.

2.2. Basket in Direct Selling as Short Food Supply Chains (SFSC)

As regards basket direct selling, we can refer to it as a methodology of organising farmers into small groups to assemble and distribute agricultural product baskets directly to the final consumers (restaurants or individuals). This type of innovation clearly has a collaborative feature since the aim of the methodology is to motivate farmers to work collectively in assembling and distributing baskets directly to consumers, besides managing the project. The basket direct selling were originally proposed within the Equal Community Initiative. In Portugal, this initiative was launched and managed by Local Development Associations (LDAs). It was formally established in 2004 and planned to develop in three stages: identification, development, and dissemination. These stages went on up to 2009 and the initiative was expected to last until 2012 within the LEADER Programme financed by the Portuguese Rural Development Programme (RDP) [**?**]. The structuring of the initiative implied farmers should assemble baskets of fresh agricultural products and deliver them directly to final consumers. The baskets should include only seasonal products of local varieties produced according to traditional farming methods. Besides making the supply chain shorter, direct selling would establish a deeper link and commitment between farmers and consumers, allowing the former to aggregate value onto their products and increase their income. After enrolling participants and publicising the program through various media, responsibility for its management ceased to be that of the Local Development Association and became that of the farmers [**? ? ?**].

Basket direct selling characterises a SFSC, which can be described as direct-to-consumer marketing practices in which food product distribution has few or preferably no intermediaries [**?**]. They became popular worldwide as an opportunity to generate income and help small farmers sell their products, especially those who have difficulties accessing the markets and who otherwise obtain low-profit margins [**? ?**].

According to specialised literature, it was only in the last two decades that SFSCs began to receive more attention [**?**]. The available scientific literature currently relates SFSCs to potential gains in sustainability insofar as they would be capable of: promoting reduction of food waste, improving food safety, and increasing farmer profits and product quality [**?**]. Other gains would be, for instance, establishing a relation between SFSCs and social issues, mentioning the increase of the level of employment, and the building of a sense of belonging to a group or a community [**?**]. Some studies refer to SFSCs as models to broaden sustainability by granting farmers fairer payments. This makes them promoting factors of local development [**?**]. The use of more sustainable agricultural practices due to the increase of biodiversity and the adoption of more ecological methods is also an advantage of SFSCs. Farmer direct contact with the final consumer helps them comply with the latter's demand for more sustainable products [**? ?**].

Recent research shows that SFSCs express themselves as heterogeneous phenomena, and that their members perceive them as a form of distribution capable of conferring greater sustainability to the agri-food system, as well as being potentially beneficial to farmers in economic terms. They also identify that farmers tend to participate in several SFSCs at the same time, trying to obtain benefits from several of them, and even that they are able to attribute greater gender equity at work in certain operations [**? ?**]. Malak-Rawlikowska et al. (2019) [**?**] even state that when taking into account market evolutions, SFSCs tend to develop to the point of competing with long supply chains, forcing them to offer better conditions for farmers.

SFSCs can be said to have a collaborative dimension, as farmers have to work together in assembling and distributing their agricultural products for direct-to-consumer marketing purposes, and in personally managing their own supplier and customer groups. As Ziegler has pointed out [**?**], collaborative innovation obeys human dynamics, in the course of how people work, as they exchange content, information, and knowledge with other people from other groups who sometimes share concepts and practices of different—even opposite—areas and disciplines. By implying the integration of people and users, these collaborative practices consolidate in the form of trans- and multidisciplinary exchanges of knowledge, requiring participants to have the skill to learn, integrate and co-create from previously acquired knowledge [**?**]. Thus, collaborative innovation goes beyond the mere access to information; it is an integral part of the dynamics of new skills building and acquisition [**?**] and results from mutual learning experiences generating new knowledge and solutions [**?**].

3. Materials and Methods

3.1. Presentation of the Region under Study and Characterisation of the Novelty

The study area, Tâmega e Sousa (NUTS III—The Nomenclature of territorial Units for Statistics) is located in northwest Portugal, more specifically between the Sousa River Valley, near Porto, and the region to the east known as Baixo-Tâmega (Figure **??**). It was selected because of an innovation dissemination process that had been going on there for some years: the direct selling of farm product baskets. The basket direct selling has been considered an innovation process in keeping with Rogers' studies [**?**]. The author sees innovation as a concept or idea, as technical information or an actual practice that is perceived by the individual or unit adopting it as something new, stemming from new routines in the ways farmers work introduced through the group dynamics of organising, distributing and attracting clients. Note that small farms prevail in this region, of which 84% have less than 5 hectares [**?**].

3.2. Data Collection

Data collection took place between April and October 2018 through personal interviews of 34 farmers who either are currently involved in developing the basket direct selling innovation, have given it up, or have never even considered doing it. Interviewees were selected according to the convenience criterion using non-probabilistic sampling techniques resorting to reference chains [**?**], known as snowball, whereby each interviewed farmer indicated another. The number of interviewees was determined by exhausting the introduction of new information.

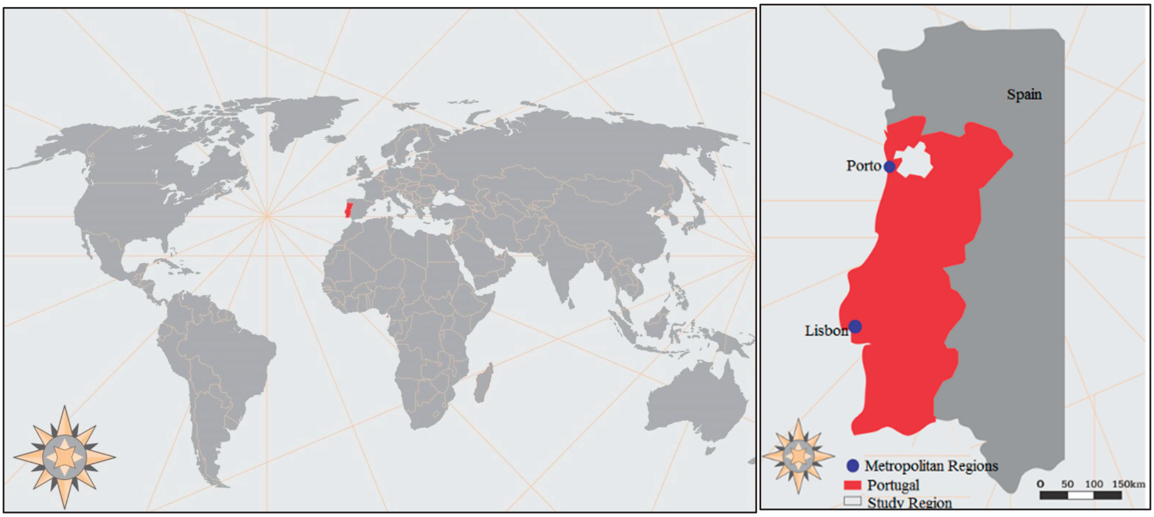

Figure 2. Relative position of the study region, in northwest Portugal, regarding Porto metropolitan area and the capital, Lisbon.

The interview script was developed within the AgriLink Project [?] englobing 53 topics and combining qualitative and quantitative open and closed questions structured to: 1. characterise the farm; 2. identify the farmers' sociodemographic profile; 3. capture information on farmer business model and farm structure; and 4. understanding the interviewee's relationship with innovation. (The AgriLink Project—Agricultural Knowledge: Linking farmers, advisors and researchers to boost innovation, was developed within the Grant Agreement n° 727577 of the Horizon 2020 Projects (https://www.agrilink2020.eu/, accessed on 31 January 2021). The empirical research for the present article was conducted within the context of the mentioned project, following its conceptual and empirical methodology to gather qualitative and quantitative data, although only the former was used.) Interviews were conducted with the purpose of capturing farmer narratives regarding the innovation-related practices and concepts they develop. This was done in a perspective of understanding how innovation evolves and the path it takes (farmer narratives on their own innovation path). Note that the content of the interviews was registered on paper and recorded, according to the interviewees' permission. Farmer narratives on describing their innovation paths were transcribed to be analysed through the technique of content analysis [?].

Historical information gathered from scientific papers, documents, and reports has been added to complete the data and to understand the context where the innovation took place. This way, based on researcher observations and comments, an innovation's evolutionary path was built, revealing the changes it caused. In the present analysis, priority was given to relating narratives and the gathered data with innovation pathways proposed by MLP by integrating events with Three Interrelated Analytic Dimensions and Types of Anchoring.

It is emphasised that, as pointed out by Geels [?], there isn't a methodology specifically designed for transition empirical studies using MLP. The author also mentions that it is up to the scientist to delineate the empirical framework and that this should be creative in combining techniques and interpretations to link the facts, from different origins and levels, as well as the analyses.

For clarification purposes, MLP's analysis levels have been delimited. Thus, basket direct selling represents niche innovation, and the regime is the agri-food sector of the NUTS III Tâmega e Sousa, in the northwest of the country (Figure **??**). In the present case study, the landscape has a quality that is both supranational and European.

4. Results

4.1. Implementing Innovation

Basket direct selling was introduced in Portugal as pilot-projects close to the capital, Lisbon, under the designation "PROVE—Promover e Vender" (Promote and Sell) in the middle of 2006. (In Portuguese, by joining the beginning of the verb "promover", which means promote, and the beginning of "vender", which means sell, one gets the word "prove", which means taste. Naturally, the wordplay is lost in translation.) These projects consisted of structuring farmers in small groups to collectively assemble fruit and vegetable baskets to deliver to urban consumers. Each farmer would supply their production specialties or their seasonal surplus [**?**]. In 2008, the initiative attracted supporters from other regions of the country as part of the project's expansion strategy. The Local Development Associations became, then, responsible for launching and managing the proposal in its pilot stage. Thus, innovation reached Tâmega e Sousa, a region deemed promising for the project's development because of its proximity to Porto's urban centre and its residents, the potential buyers of the baskets. Over time, innovation incorporated other resources: buyers were able to select from a list of products available those they would be consuming and started ordering through online apps.

In general, basket direct selling gained visibility and supporters among the interviewees between 2012 and 2013; some even mentioned having been practicing some type of direct selling for longer, more precisely since 1980. Farmers reported that, initially, when it was being divulged and implemented, the initiative could count on the support of LDAs and other local actors such as municipalities. Only after 2008, when basket direct selling experienced their greatest expansion and implementation, did farmers begin to diverge regarding how to try to manage this novelty.

4.2. Distinguishing between Pathways

Farmer narratives show that their experiences with direct-to-consumer marketing vary widely, breaking down as follows: 35.3% of respondents chose to give up the basket direct selling innovation, especially between 2012 and 2014; 44.1% of respondents continue to sell their products directly to consumers, although the groups now have fewer participants (the groups started with 6 to 8 farmers and, at the time of the research, were reduced to only 1 or 2); 20.6% of the interviewees had never even considered direct-to-consumer marketing as an outlet for their products. These are mainly farmers who are also winegrowers, and members of a cooperative, which means they guarantee the sale of their production to local wine cooperatives.

Table **??** presents the characterisation of the 34 interviewees, their relation to the novelty (whether they adopted it, gave it up, or had never even considered it), their age group, university degree, and the crops mainly developed by them. Sequentially, Table **??** complements Table **??** by providing more detail on the reasons why farmers either stopped or kept developing the innovation.

Table 3. Characterisation of the interviewees and their relationship with the innovation. Based on research data.

Relation to the Novelty and Coding		Period	Age Group (Years)	University Degree	Main Crops	Complementary Innovations
Supporters	01	Since 2012	51–60	No university degree	Fruit, vegetables, and small animals	Introduction of new crops Selling animal products
	02	Since 2018	31–40	University degree	Berries	Introduction of new crops Fruits and vegetables processing Marketing differentiation
	03	Since 2012	61–70	University degree	Fruits and vegetables	Introduction of new crops Developing tourism activities
	04	Since 2013	31–40	University degree	Vegetables, and "gourmet market products"	Selling to gourmet restaurants and markets Developing new tools or technologies aimed at improving productivity
	05	Since 2010	31–40	No university degree	Mushrooms	Teaching farmers to work with a new crop
	06	Since 2013	31–40	No university degree	Beef cattle, grapevines, and vegetables	Introduction of new crops
	07	Since 2011	51–60	No university degree	Fruits and vegetables	Introduction of new crops
	08	Since 2009	41–50	No university degree	Beef cattle, grapevines, and vegetables	Introduction of new crops
	09	Since 2008	51–60	University degree	Fruits, vegetables, and asparagus	Introduction of new crops
	10	Since 2009	31–40	No university degree	Grapevines, berries and kiwis	Introduction of new crops
	11 *	Since 2010	31–40	No university degree	Vegetables, grapevines, and beef cattle	Opening a own store
	12 *	Since 2010	31–40	University degree	Berries	Introduction of new crops Selling to gourmet restaurants and markets
	13 *	Since 2012	31–40	No university degree	Fruits and vegetables	Developing tourism activities Fruits and vegetables processing
	14 *	Since 2009	51–60	University degree	Fruits and vegetables	Innovating in management
	15 *	Since 2012	51–60	University degree	Fruits and vegetables	Introduction of new crops
						Limitations of basket direct selling pointed out by farmers who gave it up (more descriptions in Table **??**)

Table 3. *Cont.*

Relation to the Novelty and Coding		Period	Age Group (Years)	University Degree	Main Crops	Complementary Innovations
Have given it up	16	2012–2014	51–60	University degree	Fruits and vegetables	Insufficient production and buyers
	17	2012–2014	21–30	University degree	Grapevines, kiwis, and mushrooms	Specialised productions Group dynamics, management, and leadership
	18	2010–2012	61–70	No university degree	Fruits, vegetables, aromatic and medicinal herbs	Group dynamics, management, and leadership
	19	2014–2016	51–60	University degree	Aromatic herbs	Specialised productions Group dynamics, management, and leadership
	20	2012–2014	41–50	No university degree	Vegetables	Group dynamics, management, and leadership
	21	2007–2017	41–50	No university degree	Chestnuts	Specialised productions Lack of profit
	22	2011–2018	41–50	No university degree	Chickens for rearing, and vegetables	Group dynamics, management, and leadership Insufficient production and buyers Lack of profit
	23	2008–2009	41–50	No university degree	Aromatic herbs	Specialised productions
	24	2008–2011	41–50	No university degree	Vegetables	Group dynamics, management, and leadership Lack of profit
	25	2006–2007	61–70	No university degree	Vegetables	Lack of profit
	26	2009–2014	41–50	No university degree	Vegetables	Group dynamics, management, and leadership Lack of profit
	27	2009–2010	41–50	No university degree	Vegetables, kiwis and grapevines (hereafter “vines”)	Lack of profit
						Reasons why farmers never wanted to join the innovation
Non-supporters	28	Does not apply	61–70	University degree	Vines whose production is sold to a cooperative	Guaranteed sale to wine cooperatives and age of the farmer
	29	Does not apply	41–50	No university degree	Vines whose production is sold to a cooperative	Guaranteed sale to wine cooperatives
	30	Does not apply	41–50	No university degree	Vines whose production is sold to a cooperative	Guaranteed sale to wine cooperatives

Table 3. *Cont.*

Relation to the Novelty and Coding		Period	Age Group (Years)	University Degree	Main Crops	Complementary Innovations
Non-supporters	31	Does not apply	51–60	No university degree	Vines whose production is sold to a cooperative, and flowers sold to middlemen	Guaranteed sale to wine cooperative Age of the farmer
	32	Does not apply	51–60	No university degree	Kiwis, and vines whose production is sold to a cooperative	Guaranteed sale to wine cooperative Age of the farmer
	33	Does not apply	71–80	No university degree	Vines whose production is sold to a cooperative	Guaranteed sale to wine cooperative Age of the farmer
	34	Does not apply	71–80	No university degree	Vines whose production is sold to a cooperative	Guaranteed sale to wine cooperatives Age of the farmer

* Farmers who at the time of the study were delivering baskets collectively. The remaining participants chose to do it individually of their own free will or because the groups they were included in had broken up.

Table 4. Shortcomings of basket direct selling pointed out by farmers who gave it up. Based on narratives obtained during the field research stage.

Limitations	Description	Narrative Extract
Specialised productions	The baskets included a few aromatic herbs and mushrooms. Namely mushrooms were delivered in small quantities although they represented a high percentage of the basket's final cost.	"In the case of *Prove*, I only produced mushrooms. I mean, it's one thing to add a product that, at the time, cost five Euros per kilo, but quite another to add one kilo apples which cost sixty cents [. . .] If we look at the percentage, in a ten to fifteen Euro basket, [. . .] for me it was already ten percent, I get it. I get it that I was delivering a product which cost ten percent of the final price, which is a lot, I know . . . " (Interview 18). "In my case, direct selling didn't mean much after all, and it didn't feel right, either; since I only contributed with a very small amount, because I was only supplying aromatic herbs, I wasn't very interested." (Interview 20).
Insufficient production and buyers	Basket inadequacy for customer food and gastronomic preferences and demand, and customer failure to become regular buyers. Additionally, competition from similar products from other suppliers such as fairs and supermarkets.	"But then, after a while, there are disadvantages to that basket-buying thing because it becomes a routine, and after some time people are tired; they like to change, every now and then. In fact, after two or three years, they begin to be a little fed-up." (Interview 23). "Baskets are fewer because of the competition. Right now, many firms that have nothing to do with *Prove* are increasing the supply of vegetables and advertise biologic vegetables that are not biologic at all, but that they claim they are. So, this is a terrible mess." (Interview 19).

Table 4. *Cont.*

Limitations	Description	Narrative Extract
Group dynamics, management, and leadership	Disagreement, among participants, as to the program's underlying philosophies of supplying only seasonal products, and concentration of basket delivery in the hands of a few participants (who began acting as product brokers); Lack of time and preparation on the part of the farmers to deal in commercial activities, for instance not knowing how to handle customer complaints and demands; Lack of leadership that might have taken over the project after LDAs were no longer responsible for it; Lower acceptance of baskets in rural areas due to residents having, in some other way, access to fresh, organic, and seasonal products; Farmer difficulty transporting the baskets from production sites to distribution areas due to a lack of appropriate vehicles.	"There must be trust between the people who supply the baskets [. . .] sometimes that is a limitation because, deep down, we are responsible for the food security of a basket that is not only ours, and that may have its implications." (Interview 20). "In the middle of all that, one or another producer would buy bananas and add them to the basket. Ok, let's not say bananas but goods . . . Personally, I think that if I don't have the goods, it's no use inviting me because I am not going to invent them, but that is not how it goes with some people, they don't mind going to the market to buy or sell, but that doesn't work with me. People have to understand that if you don't have the product, you just don't; if you cannot supply the basket this week, you can't. "(Interview 21). "But there is always a producer who has the most responsibility, who monopolises and manages the group. As it happened with *Prove*, in the end, they decided what to add to the basket. And then, there is the greed." (Interview 17). "Here, in Marco, the situation was different because it is a rural area, and most baskets were meant to Porto and Gaia. Ok, everybody has vegetables, everybody has a little of everything. Marco is a small town, and most baskets went to Porto, Vila Nova de Gaia, and that has costs. Nobody works for free; you have to pay for tolls, oil, and, at the end of the day, the business was not lucrative. "Interview 24). "[. . .] besides, everybody has an uncle, or a father-in-law who has a vegetable garden, so it is difficult to sell, unless, of course, you do something different [. . .]." (Interview 22). "What was difficult for me was the distance, having a distribution point, and, at the same time, sustaining the project because I had to guarantee some income. I didn't produce enough vegetables and had to rely on other colleagues and all that logistics to ensure we had quality goods, especially biological ones. So, it became more and more difficult. "(Interview 19).
Profit limitations	The small amounts that were delivered, besides the time farmers spent assembling the baskets made the activity less lucrative and the programme less attractive.	"It's just that everything is very fussy, and one spends much time on the road to deliver the baskets; in my case, I had no time to grow the goods. Perhaps there should be teams to deal with one thing and the other. Also, there were no clients. Let's say, perhaps, that the highest number of baskets I ever delivered was fifteen, seventeen, but mostly we did it as a favour, you know, to help out. And then, we were delivering seven, eight baskets, which is complicated. Five farmers delivered eight baskets . . . " (Interview 21). "As you know, the programme rests on delivering baskets, but the number of baskets I expected to need was small; therefore it was not worth my selling directly half a dozen kilos lettuce, half a dozen kilos tangerines or tomatoes . . . (Interview 25).

Farmers say that, in the beginning, basket direct selling was very well-received (a group of farmers used to deliver almost 300 baskets per week in the zone of Porto). Over time, factors like the breaking up of the groups ended up limiting the initiative's success, and indeed various narratives mention this. Table **??** presents a list of those factors, grouped according to the type of limitation, and some narrative extracts explaining why farmers gave up direct selling and the baskets project.

As can be seen, farmers usually mention more than one problem to account for their giving up the programme; however, market limitations, product inadequacy to respond consumer demand and low profitability are the most recurrent. Those having access to more urban areas like Porto and its surroundings somehow continued delivering basket direct selling even after groups had split up. They were able to ensure customer loyalty and maintain baskets as an important way of marketing their products. Regarding those farmers who chose to deliver their baskets to customers in small towns, they failed to ensure customer adherence. In these areas, people have other means to get fresh, quality goods at low prices due to resident strong bonds with agriculture and all things rural.

The data show that the experience of the farmers who ultimately gave up the programme lasted for two years. Groups began to split up, especially between 2010 and 2014, due to a lack of support, leadership, and clear guidelines, which caused farmers to have different understandings of how the novelty should be operationalised. Adopting the novelty also failed because of the particular crops being offered. Winegrowers were never particularly interested in direct-to-consumer marketing, given that they rely on the region's wine cooperatives to sell their product. The fact that many participants grow the same type of crops accounts for the absence of product diversity and a certain competition among farmers. Another constraint was crop seasonality. In conventional markets, consumers got used to having regular supplies of certain products and they demanded the same from farmers supplying the baskets. The latter, in an attempt to ensure customer loyalty and be able to offer baskets with various products, were forced to acquire them from conventional markets, thus corrupting the project's initial ideology.

The age of the farmers also influenced their decision to adopt or not adopt the innovation. Farmers who did not adopt it are, in general, older than those who adopt, including the innovation droppers. Having a university degree seems to be also associated with accepting the novelty and implementing it. While the group of farmers adopting it is composed of individuals with and without a university degree in the same proportion, among those who gave up the basket direct selling the number of farmers without a university degree is higher. The same is true in the case of the farmers who have never tried direct marketing. It seems to indicate that, at the time of the study, adherence and maintenance of direct marketing trough the basket scheme were associated with a set of skills and competencies acquired through qualifications.

This focus of this paper is the group composed of those who continued the activity, either collectively or individually, and are responsible for anchoring the novelty. In addition to possessing the necessary conditions (family support, a vehicle to transport goods, being in closer proximity to Porto's urban centre), they managed to continue implementing the novelty because they engaged a learning process to address it, thus developing parallel strategies to further develop the innovation. Often, baskets became attractive to farmers who kept their customers while the collective initiative was expanding, because they managed to innovate, departing from the novelty itself. In other words, keeping the basket direct selling initiative afloat required farmers to possess innovation capacity. In those cases that met with success, it is possible to say farmers proved to be capable of conjugating product innovation, service and marketing [**? ?**], aiming at overcoming the limitations previously mentioned (presented in Table **??**). In 2014, Baptista, Cristóvão and Rodrigo [**?**] had already observed farmers were adapting to direct selling of baskets in the region when they began introducing new crops, implementing and adapting new technologies, expanding greenhouses and installing irrigation systems. In the course of the present study, a broader set of associated novelties was identified, which is listed and schematised in Figure **??**.

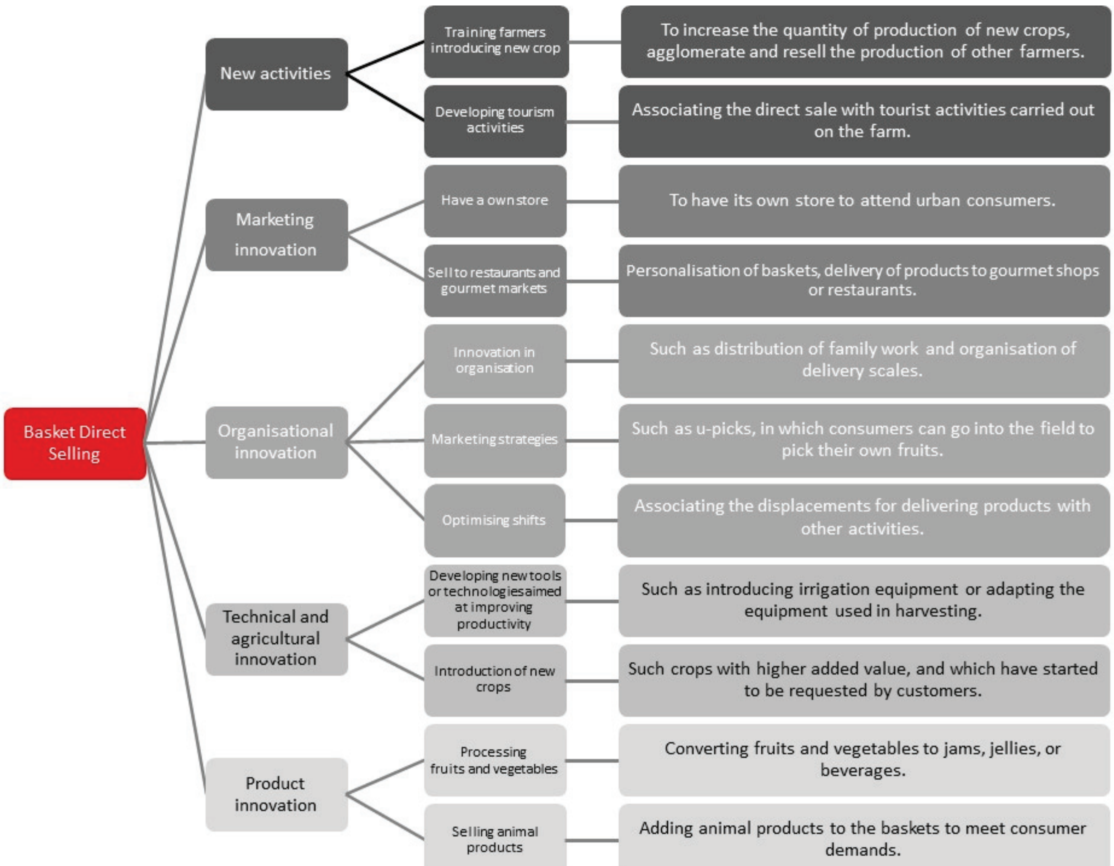

Figure 3. Schematic representation of basket direct selling—associated novelties mobilised by farmers adopting the initiative. Based on research data.

Figure **??** shows a list of innovations adopted by farmers to allow continuing selling baskets directly to consumers. Innovations were grouped according to their typology as follows: diversifying activities in the farm; marketing innovations; organizational innovations; product innovations. These complementary innovations enabled successful adopters overcoming and easing the reported constraints that lead many to abandon the innovation. This innovation strategy of complementing direct marketing with a series of technological and non-technological innovations lead by farmers themselves was a response to survive to the end of support by the LDAs. Adopters' business became unprotected innovation niches and they have to entail new innovation strategies, where education degree and younger age favored.

The high rate of innovation dropping highlights that a support system was needed, including farm advisory able to deliver advice on logistic and legal issues and to help farmers to develop collaborative arrangements fitting-in the direct marketing specificities in the study region (contextual features). It is worth mentioning that the innovations presented in Figure **??** may have been developed individually or through a consortium, in different combinations, aiming at differentiating innovators products from those sold in conventional markets or even to make baskets more profitable.

5. Discussion

The main reason underlying farmer adherence to the novelty was the opportunity it represented to sell their production surplus. Meanwhile, it took them six months to one year to prepare themselves and acquire the necessary knowledge to join the programme. Probably, they were not expected to have many qualifications and skills to act collaboratively in direct-to-consumer marketing. Given the high number of farmers who quit the programme, it is fair to assume the six month-to-one-year period of learning and preparation was not enough for farmers to know and accept it. Besides, the product they were offering did not have the necessary differentiation (regarding either the type of goods offered or other attractive aspects) to compete with other forms of food consumption and distribution, nor did it reach the right momentum to become economically sustainable for many of the early adopters.

As it has already been mentioned, not all the farmers adapted to the fruit and vegetable basket direct selling model (due to various reasons such as type of crops, management of labour to ensure production, distribution, and sales; availability of a vehicle to make deliveries; ability to attract and manage clients, and adapt to their needs). While for those who quit, the model represented profit losses, for those who kept on, it was a means of establishing connections with consumers and obtaining differentiated income. In a study published in 2014, regarding basket delivery in the area under survey, Baptista, Cristóvão, and Rodrigo [**?**] had come across an average income of approximately four hundred and seventy-eight Euros a month per farmer, varying from a minimum of hundred and fifty-seven Euros to a maximum of one thousand, five hundred and ninety-three Euros. In this sense, the farmers who maintained the basket direct selling activity did not have insignificant profits. Besides, they took advantage of the contact with customers, using it as a learning strategy, while creating new ways to present their products or associate them with services in order to make them more differentiated and attractive. [**? ?**].

In terms of MLP, one can say the basket direct selling initiative in the study region illustrates a novelty that had its incubation niche in the LDAs. After this novelty somehow stopped being managed by the LDAs, the transition path also stopped growing. Moreover, the novelty anchored to the regime only marginally because only some of the farmers composing the initial group kept delivering the baskets, and only a few customers continued buying them. Several aspects may account for the transition failure. They can be addressed from the MLP perspective, in terms of the sociotechnical levels, or the Types of Anchoring and Three Interrelated Analytic Dimensions one, looking into the case from the institutional elements and actors involved.

The first aspect that stands out is the exogenous question of innovation. The novelty was proposed by a European Community initiative and met with success in other metropolitan areas, which led to the recognition and praise of the baskets project. The PROVE received the following recognitions, considered: Project of the Month by the European Rural Network; High potential Social Entrepreneurship Initiative by the IES (Social Entrepreneurship Institute); first place in the category of "Support to the development of ecological markets and resource efficiency" in the 10th edition of the European Enterprise Promotion Awards. It was also selected to represent Portugal in the European Conference on Rural Development in Cork, Ireland, and chosen by INHERIT as a promising European agricultural and environmentally sustainable practice [**?**]. However, the implementation of the novelty in places away from urban settlements without a more detailed evaluation showed the basket direct selling initiative's inadequacy to foster an agri-food transition in the study region, despite it being classified as an intermediated region and being close to a metropolitan area (Porto city conurbation).

The second question consists of the analogy that can be established between the innovation niche and the LDAs. Assuming that niches are innovation incubation loci capable of progressing regardless of the regime's direct pressure, one accepts LDAs operate as such. When basket direct selling enters the regime as goods in search of a market, they lose in structuring, and the experience collapses. Besides, when farmers become responsible for managing the novelty, the groups become weaker and start breaking up, thus contributing to the novelty's regressive pathway.

From this point on, a marginal anchoring process begins to take place. Under some conditions, only some farmers (farmers codded as 1–10, introduced in Table **??**), who had innovation skills, were able to anchor the exogenous innovation to their practices, knowledge, and routines, thus adapting it to their realities and keeping it alive. In this case, basket direct selling represents a novelty that in the niche-to-regime permeability anchors only to some points due to the link between innovations. On the other hand, they show farmer innovation skills since these can join other network participants and develop a process of innovation creation that differentiates and maintains the anchoring points [**?**]. This innovation adequacy, linking it to other innovations, stands out because, in 2018, of the initial group working collectively, only five farmers are still participating in the programme. The rest chose to assemble and deliver the baskets individually. These findings are in keeping with Hultine, Cooperland, and Curry's observations (2007) [**?**] that the success for developing local food systems depends on farmers' specific skills, their dynamics, creativity, competence, good communication, and relationship with other actors and entities, as well as persistence to build a relationship of trust with consumers.

Regarding the analysis of the socio-technical landscape, there are pressures and transformation trends that influence the other two levels. While the niche tended to accommodate this aspect, the regime was characteristically rigid and stable, given that only a tiny market segment was mobilised, represented by the few loyal consumers. However, on the one hand, are consumers interested in the basket direct selling philosophy while, on the other hand, the proposal generally did not fit the majority's demands. The weak adherence of the regime to the innovation was not enough to induce a full, lasting integration but rather a marginal anchoring. Within the Three Interrelated Analytic Dimensions and Types of Anchoring, namely in what concerns the institutional question (rules, and cognitive, interpretative, normative, and economic institutions), the following stand out:

Some farmers reported a lack of contractual instruments to participate in the basket direct selling initiative, as well as clear rules to operate it;

It appears there were no strategies to ensure product origin and quality control, which created an impression of disrepute among consumers and members of the niche themselves. Therefore, in this type of innovation, the proposal of initiatives is not enough. It is necessary to create effective structures for innovations to last and institutionally adapt over time;

Those farmers who succeed in assimilating the new cognitive and interpretative framework, and engaged in the basket direct selling programme, used it as a learning strategy to a goal, a springboard to create and operationalise other innovations.

In turn, human factors (networks, actors, organisations, and social groups) structured and developed around innovation also exhibited some weaknesses:

Farmers lacked a leadership that would coordinate the initiative after LDAs ceased to do so;

At a particularly busy period, one of the groups tried to expand the delivery area and get a larger market share. This attitude, representing the expression of the group's self-organisation, did not meet with the approval of the Local Development Association in charge that put an end to it.

Despite some previous briefings on the philosophy and functioning of the basket direct selling, it appears that farmers were not qualified enough to work collaboratively. Given the high number of farmers who gave up the initiative, and according to their evaluation, it is fair to assume they did not possess the necessary decision-making criteria.

Figure **??** schematically lists Three Interrelated Analytic Dimensions and Types of Anchoring sociotechnical elements representing anchoring in the MLP.

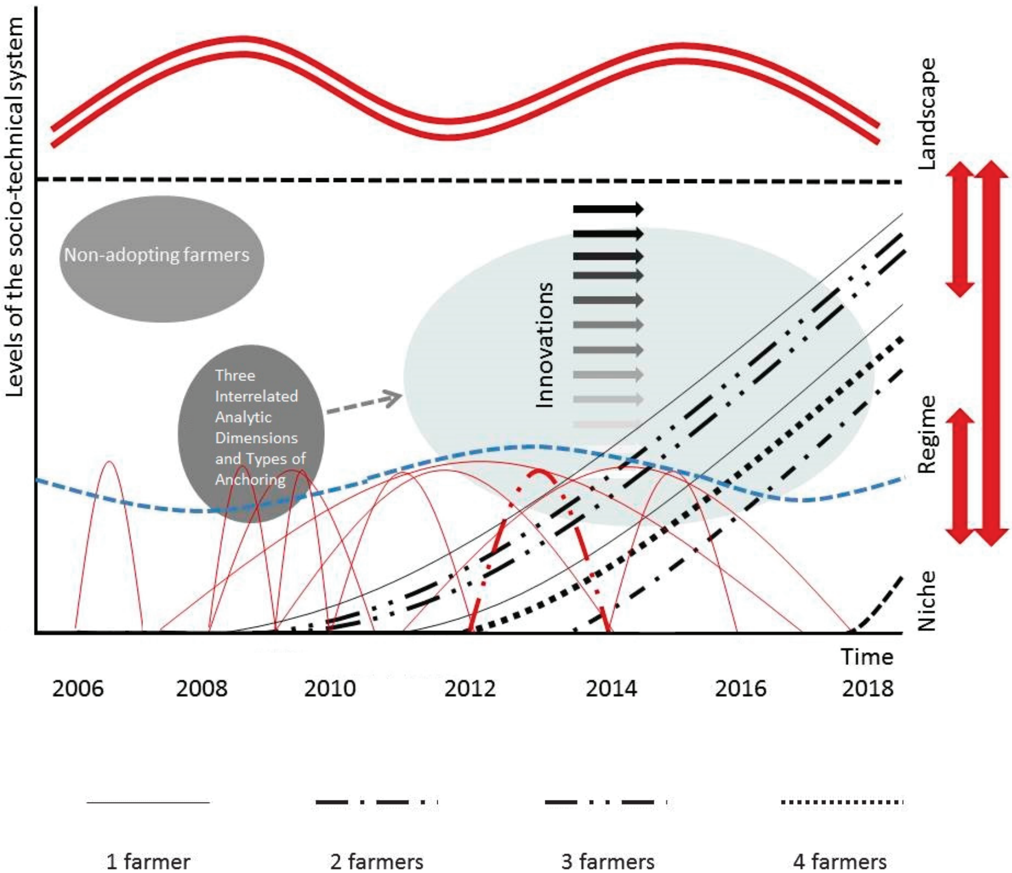

Figure 4. Individual pathways of basket direct selling innovation under MLP in a sociotechnical system, showing the influence of other innovations and of Types of Anchoring and Three Interrelated Analytic Dimensions on anchoring.

The scheme in Figure **??** shows the sociotechnical system under survey, composed of its conceptual levels of niche, regime, and landscape. Next, we will look into its dynamism from basket direct selling anchoring and Three Interrelated Analytic Dimensions and Types of Anchoring development.

First, it should be pointed out that the novelty studied was born out of a European initiative, which characterises it as exogenously concerning the system where it was applied. It, therefore, indicates the presence of a landscape movement over the dynamics of the sociotechnical system in question. Bearing in mind that the basket direct selling model was conceived externally to the local regime, it follows that LDAs and the farms adopting the novelty worked as incubation niches. Regarding the regime, first, it includes the group of farmers who chose not to participate (represented in dark grey) due to their being suppliers of local cooperatives, and so, part of an already established regime. Besides, the regime did not help the anchoring of the novelty much, neither in terms of rules and institutions nor within the human actor framework (Three Interrelated Analytic Dimensions and Types of Anchoring).

Three Interrelated Analytic Dimensions and Types of Anchoring are represented by a grey eliptical form. They slightly influence the anchoring process, pictured here through a discontinuous grey arrow. They cross the regime level because, as mentioned before, LDAs, also acting institutionally in the regime, in this case, somehow operated as innovation niches.

Basket direct selling links to the regime represents an anchoring process, depicted here in the shape of a light grey ellipse. The phenomenon may be described as anchoring because it relies on a weak adherence of elements from the niche and the regime. This weak adherence may even cause the novelty to go back in its path and gradually disappear in the region in question. However, this anchoring only happens because the farmers, still engaged in direct-to-consumer marketing and interested in keeping it alive, gathered their skills to innovate from other innovation examples. They endowed their baskets with artifacts that made them more linked to the regime, and, at the same time, more prone to face the latter's rigidity. These other innovations represent various practices and strategies, and each farmer may have resorted to more than one to keep supplying the baskets. They are represented in Figure **??** by horizontal arrows illustrating the anchoring process. This integration of an array of innovations may have been farmers' response to Three Interrelated Analytic Dimensions and Types of Anchoring failure to develop the basket direct selling initiative. In the absence of support from actors and institutions, farmers came up with alternative solutions to continue selling their baskets directly to consumers.

The niche-regime interface is represented by a discontinuous wavy curve drawn in blue. It appeared to be the best way to picture its permeability and the exchanges that exist between levels. Also, it indicates this interface may have a peculiar, non-static dynamism, full of action-reaction movements and instability of a level towards another. The best way to capture it is to analyse the individual pathways of adopting or giving up the novelty, here represented by curves drawn in red for farmers who were no longer engaged in direct marketing at the time of the survey and in black for those who continued to do it. Thus, the lines in black refer to pathways that had some anchoring, thanks to the support of other innovations. One of the pathways, beginning in 2018, is a dotted line because it describes the uncertain path of the farmer from the date of the interview.

Successful pathways of adopting the novelty overlap unsuccessful ones. In general, the former began to happen after 2010. However, the farmers who adhered to the initiative from the very beginning did not have the same results, which shows it had to be tested regionally, besides confirming the roles of LDAs and farms as experimentation niches. Moreover, although overlapping, pathways differ, indicating that locally, there was a dissemination and learning process regarding the novelty. Those who adhered at a later stage certainly had previous knowledge from farmers that had quit the programme regarding the positive and negative aspects of basket direct selling. Thus, despite the weakness of the Three Interrelated Analytic Dimensions and Types of Anchoring component, there are informal exchanges of content, experiences, information, and knowledge between farmers and it allowed the novelty to last in the study area for 12 years.

6. Conclusions

Specialised literature often argues the direct buying of local products resulting in short food supply chains (SFSCs) is an important strategy for the survival of farmers who cannot compete in larger-scale markets [**?**]. The present study looked into a SFSC experience in northwest Portugal and shows there may be limitations to the success of this strategy.

The study focused on contributing to map anchoring situations in need of further scientific research. The case studied portrays a situation not yet described in the literature in which niche innovations manage to survive in the regime's marginal zone by adhering to it thanks to the articulation between innovations.

Farmer experience regarding the basket direct selling programme reflects the existence of anchoring conditions because, in this case, the novelty did not change all the regime's aspects, attracting only some of its customers. The novelty's future path is marked by uncertainty regarding its survival. It may develop and become more successful, or it may fail to overcome the regime, in which case it will decline and disappear. Contrarily [**?**], it may perpetuate itself in the MLP levels versus time representation between niche and regime as a marginal anchoring. For now, basket direct selling remains an innovation that has achieved weak actor anchoring and little institutional anchoring in the study region.

Yet, even if the direct selling of baskets does not promote a transition, it is, nevertheless, important for farmers who earn income from it. In the long term, however, and thinking that the innovation when launched to the regime no longer belongs, conceptually, to the niche, we can think that this threshold "space X time", between niche and regime, may offer an opportunity for innovation to mature. Thus in the future, it may find promising conditions to resurface.

The lifespan of basket direct selling is related to farmer innovation skills. Not being able to change the regime or get its support, farmers found ways to anchor to it, obtaining market benefits according to their interests and productive skills. Because of the novelty's exogenous quality, which prevented the initiative from developing locally, farmers felt motivated to associate it with other innovations. It was a sort of "cross-pollination" combining knowledge and learning, as suggested by Zurbriggen, and Sierra (2017) [**?**]. Thus, on the one hand, the novelty's exogenous quality limited its reach, while on the other hand, it reflects the regimes' heterogeneity. Even when regimes fail to fully incorporate innovations, they have a market component which accommodates them, albeit marginally.

The present study shows that the novelty's reach concerning scale and scope to generate a transition (as suggested by Three Interrelated Analytic Dimensions and Types of Anchoring) depends on institutional and actor dimensions for linking and overlapping innovations to the regime. These findings may help decision makers formulate better innovation and political proposals regarding transitions for future implementation that also entail changes in actors and institutional conditions.

From the viewpoint of anchoring, the study contributes to mapping yet another typology that places the niche-regime interface in a configuration of innovation overlapping, in which one strengthens the other so that they can endure. The phenomenon points to dynamism in the said interface and shows that the threshold between levels may not be so clear and stable. This dynamic interface is rich in events that may be further developed to improve the MLP and the anchoring. Not only has a different type of anchoring been identified, but many others are likely to be described, which will no doubt broaden the research on these events. Identifying these typologies is essential if one wishes to understand innovation pathways from their conception. Studies should also look into the dynamics that may occur in the niche-regime interface since, from the moment the levels and anchoring are conceptualised, they may seem more static than they are and marked by the regime's perviousness and imperviousness to niche innovations. The present study suggests the niche-regime relationship may occur under many other patterns; therefore, mapping them must continue. In doing so, by trying to understand how innovations anchor to each other, one may help them develop positively and boost the intended transition.

Although the novelty did not meet with much success, a significant group of farmers has embarked on the programme and has exchanged knowledge and learning experiences so expressively that since 2008 it has been spreading through the local socio-technical tissue, trying to anchor to it. In fact, on the threshold of the niche-regime interaction, the project's initial expectations were not generally met. Farmers expected to sell their products and generate a higher income, which did not happen.

In this case, SFSC did not induce a transition. Unlike technological innovations, innovations like the basket direct selling, when operating on complex regimes like the agri-food one, need constant renewal and adequacy to the market's oscillation demands. It may require a more dynamic concept of a niche than merely an incubator of innovations that may or may not be incorporated by the regime in a given context at a given moment. Therefore, niches must be both of the following: 1. evolutionary and dynamic and capable of constantly qualifying innovations; and 2. articulators, managing to link innovations from various niches to provide adequate responses in collaborative contexts operating in complex landscapes and regimes. Additionally, of course, developing the skill to count on the participation of institutions and actors (Three Interrelated Analytic Dimensions and Types of Anchoring) to better place innovations regarding their linking to the regime before they even begin to show their weaknesses. It should be noted that, in this case study, the innovation was not radical in nature. Therefore, it did not have the potentiality to cause radical changes in the regime. The intention of the members was only to make an outflow of their productive surplus. This allows the niches to be characterised as having only the potential to exist on the margins of the regime.

Hence, Three Interrelated Analytic Dimensions and Types of Anchoring are crucial to a successful transition and to help innovations face highly stable regimes. Failure to grant appropriate support from actors and institutions caused the anchoring to be weak and the novelty to decline slightly. It is possible to say this weakness was also responsible for farmers mobilising other innovations. They did it alongside the direct selling of baskets, which resulted in their better anchoring and survival, either as a result of their calls to a differentiated product or their increase of productivity and competitiveness. In a way, mobilising innovations appeared as a strategy adopted by some farmers to deal with Three Interrelated Analytic Dimensions and Types of Anchoring weaknesses revealed along with the programme. It is also a means of making up for the lack of institutional support and articulation, the right adherence of actors, and the appropriateness of exogenous innovations to a new application environment. Those farmers who failed to find the necessary strategies to make up for the lack of support ended up giving up the novelty. On the contrary, at least to a group of farmers, the initiative paid out, although they had to work alone. Studying these "pollination" phenomena from the perspective of MLP may be a field worth exploring.

However, even if our study suggests that there may be specificities in the processes of innovation development and anchorage, we imagine that similar anchorages may be repeated elsewhere. This is especially so if the innovation possesses a design character that is exogenous to the regime in which it is deployed, and if part of the supporters mobilise their skills and resources to keep alive an innovation that brings them benefits, even if it is in the regime's threshold environment. Our sample of interviewed farmers originated from a purposive logic. It was not intended to be representative. Although by the end of the interviews we had interviewed practically all the farmers who were, or had been, involved in the development of the innovation in the study region, it is possible that a greater diversity of non-supporters could have provided us with new information.

Future studies on this subject should carry out in-depth research to explain the relationship between the skills farmers possess and their knowledge of skills that would allow them to innovate and thus take them in a different direction from the one originally planned. Moreover, further studies on anchoring should be developed to identify other cases likely to reveal unexpected innovation pathways and marginal survival strategies that can add a peculiar dynamism to the niche-regime interface so vital for the success of a transition. Also, an evaluation of how similar innovations may occur in the study area is indispensable, looking into the reasons underlying the failure of the basket direct selling initiative, given that people invested money and skills on the programme and the agri-food system still needs sustainable solutions.

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Determinants of Fixed Asset Investment in the Polish Farms

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Abstract: The aim of this study was to determine the factors affecting the level of investment activity of agricultural producers in Poland. Detailed studies included 4309 farms that kept accounts within the Farm Accountancy Data Network (FADN) accounting system in the years 2010–2018. The study uses Person's linear correlation method, the multiple correlation method, and regression analysis. For the regression analysis, both static and dynamic models were applied. The level of expenditure on agricultural investment varied in the surveyed households and showed an upward trend during the years 2010–2018. Studies have shown that the investment activity of Polish farms largely depends on the possibility of raising funds from European Union programs dedicated, inter alia, to the development of agricultural holdings. The regression analysis demonstrated that the principal factors affecting the level of agricultural investment include: the amount of long-term liabilities, the family income of the farm, and the amount of investment subsidies. Preferential loans are an important parameter in a dynamic investment model. This study suggests that agricultural policy factors should be taken into account to ensure the appropriate development of Polish farms.

Keywords: development; agriculture; holdings; income; investment subsidies; liabilities; static and dynamic models

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1. Introduction

In a market economy and in the agricultural sector, the functioning of enterprises is associated with the continuous improvement of competitiveness, as well as the improvement of production efficiency. Meeting the requirements, which is an implication of the ongoing changes, requires taking actions that ensure the development of firms in the long term. These actions are based on investments in fixed assets. Equipping farms with production assets has a significant impact on their economic situation, and the structure of production assets determines their production capacity. It is also important to adapt farm equipment to the current directions of production.

The rationale for enlarging the resources of machinery and equipment is the existence of potentially cost-effective options to increase production and reduce costs by choosing more capital-intensive production methods [1]. Investments form an integral part of the process of both simple and extended reproduction, and they ensure the implementation of the principles of sustainable development in the practice of agricultural holdings.

According to J. Mikolajczyk, investment is needed to reproduce and develop production capacity and improve the profitability and competitiveness of Polish agriculture [2]. Productive investment decides the development opportunities of farms. It indicates the expansion of fixed asset inventory or an increase in its quality, which contribute to the growth of the farm's potential in the future. Improving technical working materials, as well as the introduction of modern machinery and equipment in agricultural production, results in increased productivity in both crop and livestock production. With the spread of the sustainable paradigm in agriculture, the nature of investments will change, from those aimed strictly at increasing productivity to pro-environmental investments, which at the same time will also translate into an increase in the farm efficiency (e.g., investments in biogas plants or renewable energy).

Investment projects are mainly substitutes for human labor. This is due to changes in the cost factors of production, among which the labor costs are the most dynamic [3]. This has consequences for the economy and organization of farms, consisting of the preference for labor-saving, but also capital-intensive techniques and technologies [4]. The increasing use of capital-intensive technologies contributes to the growth of agricultural production by promoting the substitution of both land and labor inputs with capital. According to K. Zielinski, limited demand for raw materials of agricultural origin should lead to the lower employment of both labor and land resources [5]. This is stressed in the official publications of the EU administration. Investments in buildings, machinery, and equipment, are considered to be the main factors of productivity growth and therefore are effective substitutes for labor [6].

Investments in infrastructure are often seen as a solution to the problems of unemployment and depopulation of rural areas, and are also considered as a way of stimulating the economic situation [7]. In contrast, no investment activities may lead to divestment processes that involve the reduction of production resources or the restriction of the number (or range) of operations [8].

Agricultural investment should be also considered in a broader sense, pertaining to the whole sector. According to A. Kowalski, the objectives of the investment measures that are implemented in agricultural holdings should be in line with the adopted directions of structural changes in agriculture [9]. They involve, among others, the provision of adequate size and structure of food production, the improvement of living and working conditions of rural population, and environmental protection. The last of these issues matters with regard to the growing importance of sustainable agriculture. This concept strongly accentuates the model of agricultural production that is goal-oriented in terms of both production and the implementation of environmental and social objectives.

Management of investment activities on farms is associated with incurring greater or lesser financial expenses. The selection of appropriate sources of financing the investment is the key element influencing the investment cost, and thus its profitability in the long term. The basic source of financing investments in the agricultural sector is self-financing [10]. Nevertheless, the agricultural sector has little capacity to accumulate capital [11], so there is a need for external support for investment activities. Poland's accession to the EU has resulted in increased investment activity in farms. This is mainly due to the necessity to adapt them to EU requirements in the fields of production hygiene, environmental protection, animal welfare, and food safety. For the implementation of investments in this area, agricultural producers have received financial support from EU funds under various programs [12]. Subsidies from the funds allocated to the common agricultural policy of the European Union and the growing demand for Polish agri-food products in the single European market are the main reasons for the change in farmers' approach to investment.

Given the importance of investment in agricultural holdings and agriculture in general, the aim of the study is to determine the factors differentiating the level of investment activity of agricultural producers in Poland. This research investigates the hypothesis that of the many factors affecting the level of farm investment, the most important one is the availability of loans, particularly those granted on preferential terms for farmers.

2. Factors Influencing Farmers' Investment Decisions—Literature Review

The reference books describe many models taking into account the investment behavior of business entities, from those preceding neo-classical models (e.g., the accelerator model or the cash flow model) to modern concepts incorporating irreversibility and uncertainty (real options).

In the accelerator model, one of the main factors influencing investment is consumption. The first economist who drew attention to the importance of consumer demand in the creation of investment demand was T. N. Carver [13]. However, it was mainly J. M. Clark who popularized the model [14] and introduced "the principle of acceleration" to economics. This principle holds that relatively small changes in demand for consumer goods cause major changes in the level of investment. Hence, what matters for the dynamics of investment is the situation in the economy and the real disposable income of households, which determines consumer demand, whereas the measure of changes in consumer demand, which is important for agriculture (including the dynamics of investment in the sector), are changes in the consumption of food and other groceries.

According to the of cash flow theory, the level of investment depends primarily on cash flows, i.e., the possibility of financing investment from the investor's own resources [15,16]. Enterprises that have high financial constraints are characterized by greater sensitivity of investment to cash flows. The neoclassical theory of investment formulated by Jorgenson assumes that investment decisions depend on the cost of capital [17]. Additional capital units are bought to the point at which the marginal benefit of capital is equal to the marginal cost of capital, which is the price of the rent. In contrast to the accelerator model, the Jorgenson model assumes that investment is a function of the rental price of capital. In line with the information asymmetry theory, J. Stiglitz and A. Weiss found that the price of credit is not necessarily at the market equilibrium level, which is usually determined by the law of supply and demand under perfect information conditions [18]. Financial markets are characterized by imperfect information, which leads to credit rationing (this restricts the availability of credit), and this leads in turn to a reduction in investment activity. B. Greenwald, J. Stiglitz, and A. Weiss found that in the conditions of credit rationing, it is the availability of capital and not its cost that is of major importance for investment decisions [19]. In turn, the 'real options' method involves changing the method of assessing the effectiveness of investment. It suggests to look at the investment project not as a string of time-ordered cash flows, but as a set of real options. This approach allows the assessment of tangible investments through the prism of their flexibility and the value that they carry in themselves [20]. Various theories or models of investment behavior generally relate to one or more determinants, and they are therefore most commonly considered as complementing one another.

Basically, the investment decisions made by farmers result from the impact of both exogenous and endogenous factors. The exogenous factors may include factors related to the demand for the given products, the expected and current level of prices for agricultural products, supply conditions and in particular the level of incurred costs, the availability of production factors and their prices, the current economic conditions and those anticipated by farmers, systemic (financial, economic, institutional) solutions; economic, fiscal, monetary, and especially agricultural policy; the inflation rate and interest rates on the capital acquisition cost, the degree of openness of the economy to international connections, regulations, requirements on environmental protection, and others [21–23].

Endogenous factors result from the productive potential of agriculture (land, labor, and capital resources), the degree of fixed asset depreciation, the level of modernity of production techniques, the level of knowledge of farm managers and their age, the economic and financial situation of holdings, and, in particular, the level of generated agricultural income [21,24–26]. Both external and internal factors have an impact on farmers' decisions to implement or abandon projects.

Among the determinants of farmers' investment behavior identified in the literature on the subject, the following should be mentioned:

- the phase of the business cycle (boom/bust in agriculture) [22,27];
- factors related to the macroeconomic and political environment [28];
- features of investment projects (including start time, duration, source of financing);
- characteristics of commodity markets as well as factor markets (e.g., credit market);
- features of a family farm [29,30];
- the attitude of the agricultural producer.

The scale of an investment activity thus depends on many determinants related to the undertaking and its socio-economic environment. E. Ostrowska conducted an analysis of these factors in terms of macroeconomics and microeconomics [31]. The first group included: economic situation and state policy, technological development, and geographic and socio-demographic conditions. The mesoeconomic factors included the situation in the sector and the competitive environment of the undertaking. The microeconomic determinants involved the type of manufacturing and marketing factors, as well as capital (financial) resources and human resources.

According to A. Woś, the driving force behind investment is the projected income earned from the realized investments [32]. It is the farm's income that determines the level of investment, which is turned into new technologies, thereby providing multiplication of income, and this in turn gives rise to new investments. The importance of agricultural income as a driving force for the development and expansion of agricultural holdings was also indicated in the studies of D. Kusz, S. Gędek, and M. Ruda [33]. In turn, G. Thijssen pointed out that agricultural investments are very sensitive to changes in prices, costs of capital, and production technology [23]. The pricing policy is therefore a useful tool for influencing the investment behavior of farmers. This is due to the fact that changes in these factors affect the level of agricultural income. Due to various theories regarding the factors that determine investments in farms, this research was conducted in this area.

3. Materials and Methods

The study was based on both secondary research using previous literature, and on the data collected in the framework of the Polish Farm Accountancy Data Network. This system includes representative samples of farms producing 93.03% of the standard output (SO) of all classified holdings in Poland. The minimum threshold for the Farm Accountancy Data Network field of observation is an SO of 4000 euros, which means that there are developmental units that will affect the shape of Polish agriculture in the future. Hence, the resulting conclusions can be generalized.

Detailed datasets included 4308 holdings that consistently kept accounts within the Farm Accountancy Data Network in the years 2010–2018. Due to changes in the value of investment goods over time, the level of investment in the surveyed households was discounted by the price deflator of investment goods in individual holdings published by the Central Statistical Office in Poland.

To identify the determinants of the level of investment, this study uses Person's linear correlation method, the multiple correlation method, and a regression analysis. The Pearson's linear correlation coefficient is a symmetric measure, i.e., it measures the strength of dependency of the characteristic y on the characteristic x and vice versa, of the characteristic x on y (hence $r_{XY} = r_{YX}$) [34]. It is expressed by Formula (1).

$$r = \frac{\sum_{i=1}^{n} (x_i - \overline{x}) \sum_{i=1}^{n} (y_i - \overline{y})}{S_X S_Y}, \quad (1)$$

where: S_X, S_Y are population standard deviations x and y; $\overline{x}$ and $\overline{y}$ are average values of the features x, y.

The values of Pearson's linear correlation coefficient are in the range $[-1, 1]$; the closer they are to the extremities of the range, the greater the strength of linear correlation between the variables.

The multiple correlation coefficient refers mainly to a multidimensional correlation. It is a measure of the strength of correlation between the characteristic y and the other characteristics $x_1, x_2, \ldots, x_n$, and its values are in the range [0, 1]. The multiple correlation coefficient does not show the correlation's direction and it only measures its strength. This measure is equal to the root of the determination coefficient (the study gives its value as multiple R), as it informs what variation part of the Y characteristic is explained by the regression relative to the characteristics $x_1, x_2, \ldots, x_n$ [35]. The multiple correlation coefficient is calculated according to the Formula (2).

$$R_{y|x_1,x_2,\ldots,x_n} = \sqrt{1 - \frac{\det(R)}{\det(R_{yy})}}, \quad (2)$$

where:

- det (R)—determinant of the matrix of Pearson's linear correlation coefficients;
- det (R_{yy})—determinant of sub matrixes resulting from plotting the y-th row and y-th column from matrix R.

The study also used multiple regression analysis. Two regression models were applied that use investments at two different levels:

- static, in order to determine the factors that differentiate the level of investment outlays in agricultural holdings,
- dynamic, in order to determine the impact of given factors that impacted changes in the amount of investment outlays in farms over the analyzed period.

To estimate the models, a backward stepwise regression approach was used. Firstly, the study evaluated the significance of individual parameters of the model and its goodness of fit. In static and dynamic terms, the value of investment outlays in a farm (y), which includes the value of purchased and manufactured fixed assets, was adopted as the variable explained for the models. As a response variable in the static and dynamic models, the study adopted the value of investment in a farm, which includes the value of purchased and manufactured fixed assets. Then, based on the previous literature review, a set of factors was distinguished that could significantly affect the value of investment outlay. Out of many variables, the study took into account only those variables that have a substantial impact on the investment outlays. The endogenous factors that were considered in the analysis, most often included:

- the potential of a business entity, expressed in land [3], labor, and capital resources [36,37] or in its economic strength, and also other production factors such as, for example, technical equipment of holdings [38].
- the financial situation and the level of income [39,40], which determine the possibilities for internal and external financing [15,16].

Investment decisions of farmers are also affected by a number of exogenous factors. These include, among others, the accessibility of funds from the Common Agricultural Policy after Polish accession to the European Union [41,42], the supply of preferential loans, and commercial interest rates [43]. The variables used in this study are measured at the farm level and are taken from the Farm Accountancy Data Network.

To implement the model and identify the factors differentiating the level of investment in the surveyed holdings, the authors adopted the following set of variables:

x_1—economic size of the farm;
x_2—labor inputs per 1 ha utilized agricultural area [AWU/ha];
x_3—technical utilities of the land [value of fixed assets without land/ha];
x_4—technical equipment for work [value of fixed assets without land/AWU];
x_5—total debt ratio [total liabilities/assets];
x_6—share of costs in production value;
x_7—profitability ratio [income/production value];
x_8—value of investment subsidies;
x_9—long-term liabilities;
x_{10}—income from a family farm;
x_{11}—return on fixed assets (income/value of fixed assets); x_{12}—utilized agricultural area;
x_{13}—value of farm assets (fixed assets).

In order to find which factors determined the variability of investment outlays (dependent variable) in dynamic terms in the analyzed period, the following explanatory variables were identified:

z_1—income from a family farm without operating subsidies;
z_2—operating subsidies;
z_3—income from a family farm in the previous year [n − 1];
z_4—value of preferential loans;
z_5—value of other long-term liabilities;
z_6—value of investment subsidies;
z_7—value of short-term liabilities.

This research selected only those variables whose impact on the level of investment outlays can be substantively justified. The selected variables were also characterized by a sufficiently large range of variability. Then Pearson's correlation coefficients were calculated between the explanatory variables to eliminate variables that were correlated with each other.

For the construction of regression models, the "backward" stepwise elimination method was used, which means that variables for which the F-Snedecor test value is lower than the threshold value were removed from the model in subsequent steps. The procedure was repeated until the best model describing the dependent variable was obtained. Student's t-statistics were used to evaluate the significance of the model parameters. The econometric models were estimated using both MS Excel and Statistica software.

4. Results

The research covered 4308 farms that throughout the period of the study (2010–2018) kept accounting under the FADN. As a result of structural changes, macroeconomic factors, and investments made, the characteristics of farms were being transformed. The general characteristics of the surveyed entities in the base year, i.e., 2010, are presented in Table 1. The farms were divided into three quartile groups.

... Q1—25% of farms, with the lowest level of investment outlays;
... Q2–Q3—50% of farms, with an average level of capital expenditure;
... Q4—25% of farms, with the highest level of investment outlays.

The average economic size of the researched farms was 46.4 thousand euros SO (Standard Output). The share of plant and animal production in the total production value was similar and amounted on average to 43.7%. The average farm in the research generated income at the level of PLN 49.3 thousand, while the share of subsidies to operating activities in income was 37% (Table 1).

Table 1. General characteristics of farms for 2010.

Specifications	Q1	Q2–Q3	Q4	Total
Number of farms	1102	2104	1102	4308
Economic size (EUR SO)	20.9	35.4	83.0	46.4
Utilized agricultural Area (ha)	14.0	25.4	58.1	32.5
Total labor inputs (AWU)	1.7	2.0	2.6	2.1
Total production value (thous. PLN)	63.8	120.3	307.0	163.7
In it: plant production (%)	44	42	45	43.7
Total costs (thous. PLN)	52.0	92.9	231.5	125.5
In it: direct costs (%)	52	54	58	54.7
Agriculture income (thous. PLN)	17.4	37.3	93.1	49.3
Share of subsidies in income	45	34	32	37

Source: own study based on Farm Accountancy Data Network data.

The global level of investment in the sector of Polish agriculture consists of individual investment decisions of each farm. The decisions are influenced by numerous exogenous and endogenous factors. Larger changes in the level of expenditures relate to farms with higher investment outlays, which are due to their financial capabilities. In the surveyed households, the average level of investment in the years 2010–2018, calculated in constant prices for 2010 amounted to PLN 40.7 thousand per household. The level of expenditure on agricultural investment was characterized by an upward trend, although the dynamics of changes in individual years were quite varied due to the evolving economic situation in agriculture and the changes in the access to external financing, including promotional loans and funds from the Rural Development Program. In 2010, the average level of investment amounted to PLN 33.4 thousand per farm; in 2017, it peaked and was 85% higher (Figure 1). In 2018, there was a slowdown in the growth of capital expenditures. The increase in capital expenditures in 2017 and their high level in 2018 was caused by the increase of funds allocated for the purchase of land. This was related, among others, to the sale of land from the Treasury Agricultural Property Stock.

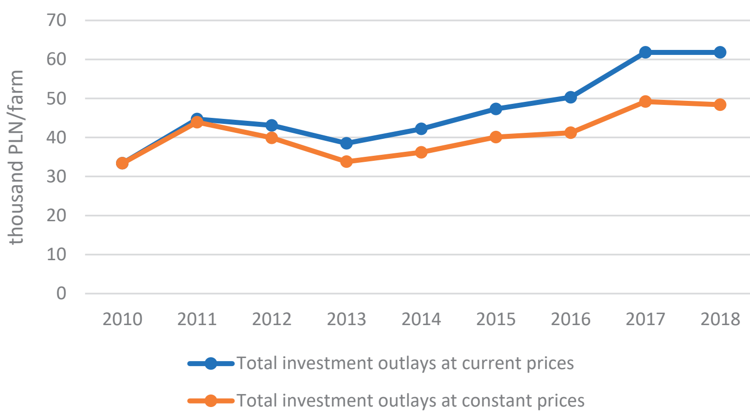

Figure 1. The amount of capital expenditures in the examined holdings at current and constant prices. Source: own study based on Farm Accountancy Data Network data.

The most significant item in the structure of agricultural investment after 2010 was machinery and equipment, which accounted for 25–35% (depending on the year) of the total value of investment outlays (Table 2).

Table 2. The structure of capital expenditures in the examined holdings in %.

Specification	2010	2011	2012	2013	2014	2015	2016	2017	2018
Land	11.7	10.7	15.1	17.9	18.0	18.8	21.5	26.7	32.8
Buildings and structures	25.4	35.1	30.9	21.3	13.3	16.5	14.5	13.6	16.5
Means of transport	19.2	21.9	21.8	24.4	31.0	26.6	25.7	25.9	20.4
Machines, tools, and technical facilities	26.6	25.5	25.5	30.4	33.2	34.7	34.5	30.1	26.9
Intangible fixed assets	2.7	2.2	2.3	1.3	1.2	1.1	1.2	1.3	1.5
Others	14.4	4.5	4.4	4.7	3.3	2.3	2.6	2.3	1.9

Source: own study based on Farm Accountancy Data Network data.

These investments related mainly to fixed assets used the crop production. Such investments are characterized by greater flexibility, and a high degree of reversibility in relation to investment in buildings and structures. Hence, there is a lower risk of loss due to bad investment decisions. Their value is strongly correlated with the value of purchased tractors, which forced the adjustment of the rest of the machine park equipment in terms of increasing tractive force. Purchases of agricultural machines were facilitated by aid programs implemented in the framework of the European Union funding. Within the framework of Rural Development Program measures “Modernization of agricultural holdings" in years 2007–2013, Poland drew the highest amount for investments in machinery and equipment of all the countries in the European Union.

In order to determine what household features are related to the value of investment, the authors carried out a statistical analysis, which consisted of examining the significance of individual parameters with respect to the response variable that is the value of the investment outlays (y). Pearson's linear correlation coefficients and multiple regression analysis were used to assess the relationship between the variables. The analysis of factors affecting the investment variation in holdings revealed what parameters affect agricultural investments and with what force. It also allowed the determination of which holdings invest more than others and what parameters they have. The correlation coefficients between the explanatory variables and the investment outlays (y), and between each of the variables, are presented in Table 3.

Table 3. The coefficients of correlation between the explanatory variables and the response variable (value of investment outlays).

	y	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}
y	1.00													
x_1	0.61	1.00												
x_2	−0.01	0.01	1.00											
x_3	0.06	0.08	0.68	1.00										
x_4	0.63	0.49	−0.03	0.16	1.00									
x_5	0.50	0.33	0.03	0.09	0.35	1.00								
x_6	−0.05	−0.06	−0.02	0.01	0.01	−0.02	1.00							
x_7	−0.01	−0.05	−0.08	−0.10	−0.11	−0.02	−0.62	1.00						
x_8	0.55	0.36	−0.04	0.00	0.52	0.21	0.00	−0.01	1.00					
x_9	0.80	0.58	0.05	0.18	0.54	0.70	−0.02	−0.06	0.33	1.00				
x_{10}	0.69	0.82	0.00	0.03	0.49	0.33	−0.19	0.12	0.40	0.58	1.00			
x_{11}	0.01	0.13	0.04	−0.03	−0.15	0.08	−0.26	0.31	−0.05	−0.01	0.29	1.00		
x_{12}	0.65	0.64	−0.11	−0.07	0.44	0.36	0.00	0.07	0.36	0.55	0.72	0.12	1.00	
x_{13}	0.80	0.74	0.04	0.23	0.76	0.38	−0.05	−0.09	0.53	0.73	0.76	−0.08	0.64	1.00

Source: own study based on Farm Accountancy Data Network data.

The highest level of correlation with the response variable (investment outlays) was given by: long-term liabilities (80%), the value of fixed assets (80%), and the income from the family farm (69%). The analysis also showed fairly significant levels of correlation of income (76%) and the long-term liabilities (73%) with the value of household assets. These results indicate a relatively high level of interdependence between these factors.

On the basis of the assessment of the significance levels of each of the parameters, using both a multiple regression analysis and a backward stepwise regression method, and having removed the interdependent (multicollinear) variables from the analysis, the following model was estimated:

$$y = 35.5 \times x_8 + 2.56 \times x_9 + 1.96 \times x_{10} - 11{,}499$$

$$(\mathrm{t} = 34.5,\ p = 0.00)\ (\mathrm{t} = 66.5,\ p = 0.00)\ (\mathrm{t} = 30.6,\ p = 0.00)$$

$$R^2 = 77.7\%,\ \text{multiple } R = 88.1\%,\ \text{standard error} = 330{,}379,\ p = 0.00$$

The regression model shows that the factors that significantly influenced the level of investment in the surveyed holdings were: the long-term liabilities, the income from the family farm and the obtained subsidies for investment. The estimated model explained about 78% of the sample variation. The resulting parameters were found to be statistically significant, as indicated by the value of the Student's t statistics, because the p value was lower than the adopted significance level ($\alpha = 0.05$). A high value of the multiple correlation coefficient (88%) confirms a significant effect of all these factors on the volume of investment.

The interpretation of the resulting econometric model suggests that an increase in the level of long-term liabilities on the farm by an average of PLN 1 helps increase investment by PLN 2.56, assuming the other factors are unchanged. The increase in the income level of the family farm by about PLN 1 results in an increase in investment outlays by PLN 1.96, assuming the other factors remain unchanged. An increase in investment subsidies by PLN 1 results in an increase in investment outlays by PLN 35.5, with the given level of other factors.

Taking into account the fact that investing in agricultural holdings is a complex process that is distributed over time, another econometric model was built for the years 2010–2018. The response variable and the explanatory parameters were measured as the arithmetic means in the considered time period.

The level of investment in global terms was, however, as the research indicates, quite varied in different years. The dynamics of these changes may have been largely affected by macro scale determinants, which are dependent on the farmer to a lesser extent. The first group may include, e.g., the amount of financial assistance for investment or the economic situation of the agricultural markets.

To determine the effect of individual factors on the level of investment during the studied period by using the dynamic approach, the authors used multiple regression analysis. As in the earlier statistical model, the model was estimated with the use of backward stepwise regression. Beside the model construction, the authors also assessed the significance of individual parameters and the model fitting (Table 4).

Table 4. Value of selected statistical variables adopted in the assessment of volatility of investment outlays in the years 2010–2018 (thousand PLN per farm).

Years	Investment Outlays	Additional Payments for Operating Activities	Income from a Family Farm without Subsidies	Income from a Family Farm in the Previous Year (n − 1)	Preferential Loans	Other Long-Term Liabilities	Investment Subsidies	Short-Term Liabilities
2010	33.4	15.9	30.6	42.0	11.4	2.5	4.1	5.2
2011	44.7	24.7	35.8	46.5	17.8	4.5	24.6	6.6
2012	43.1	20.5	53.0	60.6	17.3	2.9	9.7	4.6
2013	38.5	31.2	30.6	73.5	15.7	3.6	3.6	5.6
2014	42.2	35.0	24.8	61.7	14.4	6.2	15.5	5.5
2015	47.3	36.3	50.6	59.8	16.2	6.9	16.3	4.4
2016	50.3	41.7	63.4	86.9	18.0	6.1	12.1	4.5
2017	61.8	37.6	68.7	105.1	22.3	10.9	15.3	4.6
2018	61.8	43.6	56.7	106.3	24.1	8.8	8.3	3.9

Source: own study based on Farm Accountancy Data Network data.

The set of variables which might have affected the changes in the investment outlays in the years 2010–2018, the correlation coefficients between the explanatory variables, and the response variable (y), measured by the value of investment outlays, are shown in Table 5.

Table 5. Correlation coefficients of explanatory variables in the dynamic model.

	y	z_1	z_2	z_3	z_4	z_5	z_6	z_7
y	1.00							
z_1	0.76	1.00						
z_2	0.80	0.52	1.00					
z_3	0.87	0.80	0.72	1.00				
z_4	0.95	0.66	0.75	0.85	1.00			
z_5	0.91	0.80	0.64	0.80	0.77	1.00		
z_6	0.27	0.15	0.10	−0.14	0.21	0.31	1.00	
z_7	−0.57	−0.51	−0.72	−0.63	−0.47	−0.49	0.37	1.00

Source: own study based on Farm Accountancy Data Network data.

The estimation resulted in a model where the response variable was the value of investment outlays and the explanatory variable was the value of preferential loans:

$$y = 2.4 \times z_4 + 5233.8$$

$$(\mathrm{t} = 8.1, p = 0.00)$$

$$R^2 = 90.4\%, \text{ multiple } R = 95.1\%, \text{ standard error} = 3207.13, p = 0.00$$

Based on the values specified in dynamic terms, the constructed model explains 90% of the volatility of investment outlays in the examined period. A high value of the multiple correlation coefficient (0.95) points to an important influence of preferential loans on agricultural investment in a given year. The estimated model parameter (preferential loans) was statistically significant, as indicated by Student's *t*-test, because the *p*-value was lower than the accepted level of significance ($\alpha = 0.05$). However, due to a small number of observations (9 years), the presented estimation model should be interpreted with caution, as the volatility of explanatory factors in the following years could significantly affect the shape of the model. The developed model can be interpreted in such a way that an increase in the level of preferential loans in the given year by PLN 1 contributed to an increase in investment outlays in agricultural holdings by PLN 2.4.

On the basis of these results, it can therefore be concluded that increasing lending by means of preferential loans, and supporting investment activities through subsidies of interest were the most appropriate ways to create the conditions for the growth of investment in the agricultural sector. This is all the more significant as the importance of preferential lending is clearly emphasized by agricultural producers. The study conducted by the Food Economy Bank in 2011 on a group of 758 agricultural producers who had benefited from preferential loans shows that the vast majority of them (77%) would not use a commercial loan to finance investments in the absence of a preferential loan. As many as 97% of respondents attributed this to the higher cost of such a loan. Given the scale of negative responses, it can be concluded that a reduction of support in the form of subsidies for agricultural loans would adversely affect the level of investments in agriculture in the country.

The multiple regression analysis showed no statistical relationship between changes in agricultural income and the level of agricultural investment in the years 2010–2018, both in terms of their actual level in the given year and with a back-shift by one year ($n - 1$). The level of preferential loans (important parameter) in the surveyed households was also dependent on the amount of agricultural income, which has a significant impact on the creditworthiness of agricultural producers. The correlation coefficient between the amount of income without subsidies and preferential loans value was 0.76, which indicates a strong correlation between the examined characteristics. On the one hand, the parameter of preferential loans, as opposed to income, takes into account the aspect of farmers' willingness to take risk, which may be caused by non-economic factors, such as, e.g., the age of the farmer and the related problems of succession, education, health, etc. Therefore, it can be stated that not every farmer who is ready to take a credit will receive it for profitability reasons. On the other hand, not every farmer who could receive such a credit will apply for it for the reasons stated above.

5. Conclusions

The conducted research does not exhaust the problem of investments in farms, but on its basis, several conclusions can be drawn. In the surveyed households, the level of expenditure on agricultural investment was varied and showed an upward trend in the years 2010–2018. Dynamics of changes in individual years, however, was different due to the developing economic situation in agriculture, and due to changes in access to funds raised for investment. The increase in investment outlays in the years 2017–2018 resulted from the increase of funds allocated for the purchase of agricultural land. Throughout the examined period, the structure of agricultural investment was dominated by machinery and technical equipment, which accounted for 25–35% of the total value of investment outlays. This related mainly to fixed assets used for crop production.

The investment decisions made by farmers are a function of various factors related to the undertaking and its socio-economic environment. They are related to the anticipated benefits at the microeconomic or macroeconomic scales, which result from non-market functions of agriculture. The investment activity of Polish holdings hugely depends on the possibility of raising funds from European Union programs, dedicated, inter alia, to the development of agricultural holdings.

The regression model demonstrated that the principal factors that affect the level of agricultural investment include: the amount of long-term liabilities, the family farm income, and the amount of investment subsidies. In turn, an important parameter in the dynamic investment model proved to be the amount of preferential loans. On this basis, it can be concluded that the research hypothesis formulated in the paper has been positively verified.

The findings of this research suggest that the loans availability, especially of preferential loans, has the largest impact on the level of farm investment. Although the level of agricultural income is significantly related to the amount of preferential loans received, it did not prove to be a significant factor for the volatility of investment in Poland post-2010. Compared to income, preferential loans take into account a wider range of stimuli that influence the amount of investment outlays. These determine, among others, the agricultural producers' willingness to take risks, and they may be related to non-economic factors such as the age of a farmer and problems of succession, education, or health. Appropriate agricultural policy in respect to these factors will enable further development of investment holdings that will be also in line with sustainable development principles.

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Article

Research on Global Grain Trade Network Pattern and Its Driving Factors

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Abstract: Trading systems are essential in promoting global food security. With the growing proportion of global food consumption obtained through international trade, the global food trade pattern has become increasingly complex over recent years. This study constructed a weighted global grain network using the trade data of 196 countries in 2000 and 2018 to explore the structure and evolution based on the complex network theory. We established that the global grain network was scale-free. There was significant heterogeneity among nodes, and the heterogeneity of the out-degree was greater than that of the in-degree. The global grain network has a significant core-periphery structure, with the United States, Japan, Mexico, Egypt, South Korea, and Colombia as the core countries. Thereafter, by applying the quadratic assignment procedure model to explore the driving factors of the global grain network, we established that geographical distance had a positive impact on the food trade patterns in 2000 and 2018. This differs from the classical gravity model theory. Furthermore, grain trade had significant "boundary effects"; economic gaps, resource endowment, and regional free trade agreements had a positive impact on the evolution of the grain trade network, whereas cultural similarity and political differences had a negative impact on the grain trade network pattern.

Keywords: grain trade network; influencing factors; the QAP model

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1. Introduction

Factors such as rapid global population growth, climate change, frequent occurrence of large-scale natural disasters, and economic recession have caused significant uncertainties in the balance of food supply and demand; food security is currently facing global risks and challenges and will continue to do so for a long time [1–3]. Due to the unbalanced spatial distribution of grain production, global grain production mismatches spatial consumption. Therefore, the international grain trade has become an important way to adjust the regional imbalance in grain supply and demand [4,5]. The trading system is essential in promoting global food security by making the international food system more efficient and responsive to sudden shocks that might threaten food security [6,7]. Additionally, it provides a buffer against local variability of food resources because regions can import when they have a deficit and export when they have a surplus [8]. Trade can help address undernutrition by raising incomes, discounting food, and increasing the diversity of food available for consumption. However, global trade can expose countries to external supply shocks and degrade the environment [7].

The rate and scale of food trade have significantly increased over the past several decades [9]. Furthermore, the trade of agricultural products has increased significantly over the past decades [10], and cereal exports have increased from 79 to 480 Mt since 1961 [11]. With the increasing scale of the global food trade and the number of intricate links between countries, the global food trade network has been shaped. These interconnections may continue to increase as population growth increases the caloric demand, and greater affluence drives changes in consumption patterns [12–14].

The food trade network is a complex system that involves hundreds of countries and thousands of complex trade relationships. In this vast connected network, every country has direct or circuitous ties with other countries, which means that the food security of each country is linked. It is widely recognized that the stability of food trade networks is crucial in global food security.

Complex network models provide snapshots of the international trading system, enabling us to fully understand international trade. Additionally, it provides an approach to simulate the international trading system from multi-dimensional and dynamic perspectives by analyzing the dynamic process of each country's entry or withdrawal from the food trade market, the establishment or breakdown of trade relations, and the change in trade volumes. We can reveal the evolution of international trade from a global perspective and explain the interaction between countries using complex network analysis (CNA) tools.

This study attempted to use CNA to characterize and analyze the evolution of global grain trade network patterns. Therefore, we adopted the quadratic assignment procedure (QAP) model to explore the evolution mechanism of the global grain network and explain it from the aspects of geographical distance, economic gap, cultural similarity, political attributes, and regional free trade agreements. The remainder of this paper is organized as follows. Section 2 reviews previous studies on international trade networks and the drivers of trade flows. Section 3 introduces the research design and data sources. Sections 4 and 5 focus on empirical analysis and provide a reasonable explanation of the results. The conclusions and implications for further research are discussed in Section 6.

2. Literature Review

The use of CNA to study international trade systems has become a novel research direction. Serrano and Boguná [15] first introduced complex networks into international trade relations, and proved that the trade relations between countries were in accordance with the typical characteristics of complex networks including scale-free distribution, small-world characteristics, and high clustering coefficients. Fagiolo et al. [16] studied the topological characteristics of the world trade network using the weighted network method. Subsequently, scholars have studied the energy trade [17,18], mineral resources trade [19], manufacturing trade [20], and agricultural products trade [7,8,21] networks, using trade volume, trade value or value added, and input–output value as weights to construct types of weighted trade network models.

The complex network theory provides a scientific and effective method for analyzing trade flows between countries, and indicators such as network density, clustering coefficients, and average distance can be used to explore the scale and structure characteristics of trade networks. Shutters and Rachata [22], Cai and Song [23] as well as Wang et al. [24] studied the characteristics and evolutionary trends of global agricultural trade networks based on complex network methods. They established that the global agricultural trade network was becoming increasingly diversified and complicated. It presents a "core-periphery" structure at the regional level, and presents a closed, unbalanced, diversified, and multi-polar development trend at the national level. Through the analysis of indicators such as degree, intensity, and proximity centralities, we can explore the role and status of each country as a trading nation. Fan et al., Chen et al., Nuss et al., and Nie et al. [25–28] showed that France, the United States, Canada, the Netherlands, South Africa, and the United Kingdom were the core countries in the global food trade network, playing a crucial role in the global food trade network. In addition, we can use module and cluster analyses to divide trade communities, revealing the relationship between countries. Nie et al. [28] detected the five big trade communities as well as various small groups in the global food trade network. Each group was integrated with time change segmentation and differentiation evolution characteristics of the restructuring. Although these studies help us to understand the structural and topological characteristics of the international trade network, they do not address the influencing factors of the food trade network, and very little about the formation mechanism of the food trade network is known.

In addition, other scholars have discussed the economic incentives and drivers of trade flows. Geographical distance is an important factor affecting trade between economies [29]. Based on the gravity model, Anderson and Wincoop [30] established that trade volume was inversely proportional to the geographical distance, and the shorter the geographical distance between economies, the greater the trade volume. Regional free trade agreements (RTA) are important means for economies to promote economic integration and eliminate trade barriers, shaping the global trade pattern [31]. White [32] and Shi [33] demonstrated that cultural differences increase trade costs and inhibit the development of international trade. According to Feng et al. [34], economic attributes are important factors affecting trade relations among economies and determining international trade patterns. In addition, land proximity, tariff barriers, and monetary policies have important effects on trade flows [35]. These studies help to understand the factors that influence trade flows, but they assumed that trade between countries was independent and used gravity models to estimate the determinants of bilateral trade in services. Generally, the food trade relationship between countries is not a simple binary relationship formed with the development of globalization, but a complex and interdependent relationship [36]. The conventional gravity model cannot be used to estimate the complex relationships of trade networks.

Based on the above studies, this study used the data of the grain trade relations of 196 countries or regions in 2000 and 2018. First, CNA was used to characterize and analyze the evolution of the pattern of the global grain trade network. Thereafter, based on the assumption of the interdependence of service trade, the quadratic assignment procedure (QAP) model was used to analyze the factors affecting the evolution of the global grain network, which not only deals with the interdependence between each other, but also avoids the problem of systemic structural autocorrelation. A significant contribution of this study was to explore the evolution process and mechanism of global grain networks from the perspectives of resource endowment, geographical distance, economic attributes, political attributes, cultural attributes, and regional free trade agreements.

3. Materials and Methods

3.1. The Analysis Framework: Factors Affecting International Grain Trade

Resources endowment. Endowment of natural resources is the basic condition for the formation of a global grain production pattern. The uneven distribution of global natural resources such as water and land leads to a spatial imbalance in grain production patterns, which further promotes the formation of food trade and exchange.

Geographical proximity. Geographical distance is an important factor affecting trade between economies. Geographical distance is an important variable in conventional trade models. The premise of an economic entity connection is geographical proximity, which can significantly reduce transaction costs. Studies by Anderson [37] and Wincoop [30] demonstrated that the volume of trade is inversely proportional to the geographical distance. Because grain is a bulky commodity, the distance and transportation convenience directly affect the trade volume between two countries [38].

Adjacent land. McCallum [39] established that the adjacent land border made the trade volume between Canadian provinces much larger than that between Canada and the United States, known as the famous “border puzzle.” The emergence of the “border puzzle” phenomenon makes more scholars regard the contiguity of land as a crucial factor in measuring trade costs. Kimura [40] and Lee [41], as well as Gani and Clemes [42] established that a common geographical boundary could not only reflect the geographical distance between economies, but also better capture their geospatial relationships [43]. Therefore, in addition to geographical distance, a common land border is considered a crucial factor in measuring trade cost, which is used as a proxy variable of geographical distance.

Differences in economic developments. Economies choose trade partners according to the principle of homogenization, and those with similar levels of economic development are likely to trade with each other [44]. This can be explained by preference similarity theory. In general, economies with similar levels of economic development have similar preferences, and the demand for goods or services trade occur between these economies [45]. Moreover, income levels affect the grain consumption structure. The food consumption structure changes from a plant-based diet to a meat-based diet with an increase in income, and the per capita food consumption increases. Therefore, countries with similar levels of economic development also have similar food consumption preferences, and are more likely to trade with each other.

Political differences. Political differences affect food trade in two aspects: the differences in regulation, norms, and cognitive systems of national quality inspection will significantly inhibit international trade, and institutional distance will further cause trade friction, which is not conducive to the smooth development of bilateral trade and regional trade cooperation [37]. Additionally, institutional factors affect the comparative advantage and foreign trade pattern of a country by affecting the productivity among economies. Institutional factors such as economic freedom and government governance have a significant impact on the bilateral trade of different products [46]. Because of the essential nature of food crops, food trade has become an important aspect of cooperation, and the checks and balances between countries. Food trade has gone beyond the scope of pure commerciality, and become political [47], as its helps the global food trade system through the interaction of politics, trade barriers, and national interest games.

Cultural similarities. As a bond to strengthen exchanges and understanding between economies, culture is crucial in economic and trade development [48,49]. As the core components of culture and the embodiment of cultural connotations, language, and religion can directly affect the way and cost of communication in international trade. The new economic geography theory regards culture as an important economic intermediary element, and believes that communication costs in international trade reflect linguistic differences. A common language can reduce the communication cost between economies, trade cognitive blind areas of both sides, and the cost of access to information to promote export trade. In addition, countries with the same religious beliefs have similar cultural backgrounds, which can promote the improvement of credit and reduce the resistance caused by trade friction and trade barriers [50]. Thus, linguistic and religious relationships between economies are valid proxy variables for cultural similarity.

Regional free trade agreement. RTAs are important means for economies to promote economic integration and eliminate trade barriers [51,52]. The signing of formal regional trade agreements between economies will have a significant trade creation effect, which is beneficial to the development of their trade. Previous studies have demonstrated that the conclusion of bilateral free trade agreements on agricultural products can effectively eliminate the impact of negative factors, lead to high bilateral trade costs, help avoid tariff peaks and bypass unwritten access rules, promote trade liberalization to encourage the free circulation of agricultural products, improve bilateral economic and trade relations, and expand trade flows [53,54].

Based on the above analyses, we propose the following hypotheses for the evolution of the global grain network:

Hypothesis 1 (H1). *Countries with significant differences in resource endowment are more likely to trade with each other.*

Hypothesis 2 (H2). *Countries with similar levels of economic development are more likely to trade with each other.*

Hypothesis 3 (H3). *Countries that are geographically closer or with common geographical boundaries are more likely to trade with each other.*

Hypothesis 4 (H4). *Countries with smaller system differences are more likely to trade with each other.*

Hypothesis 5 (H5). *Economies with a common cultural background such as language or religion are more likely to trade with each other.*

Hypothesis 6 (H6). *Countries that sign the RTA are more likely to trade with each other.*

3.2. Complex Network Analysis Method

3.2.1. Constructing the Global Grain Trade Network

This study constructed a global grain trade-weighted trade network based on the import and export value of grain (USD). According to the complex network theory, the global grain trade network is summarized as a weighted complex network: G = (V, E, W), where V is the point set composed of grain trading countries or regions as network nodes; E is the edge set composed of grain trade relations between countries or regions; and W is the function set of trade quantity relations between countries. Suppose there are n nodes, m lines, and the n nodes form a weight matrix of order N by n. M is less than or equal to $n \times n$ as there is no connection between some nodes (i.e., no trade relationship). Weight matrix W^t is given according to the following formula:

$$W_{ij}^{t} = \left\{ \begin{array}{cccc} w_{11} & w_{12} & \dots & w_{1n} \\ w_{21} & w_{22} & \dots & w_{2n} \\ \dots & \dots & \dots & \dots \\ w_{n1} & w_{n2} & \dots & w_{nn} \end{array} \right\} \quad (1)$$

3.2.2. Node Degree and Distribution of Node Degree

Node degree refers to the number of nodes directly connected to a specific node in the trade network. It is an indicator of the number of nodes that it trades in the trade network [55]. Additionally, it can reflect the degree of diversification of the food trade objects of a country. The higher the node degree, the more countries or regions trade with the country. According to different trade flows in a directed network, node degrees can be divided into out-degree and in-degree. Out-degree refers to the quantity from node i to all other nodes, and in-degree refers to the quantity from all other nodes to node i. The sum of out-degree and in-degree is the node degree, which can be expressed as

$$k_i = k_i^{in} + k_i^{out} \quad (2)$$

$$k_i^{in} = \sum_{j=1}^{n} a_{ji} \ (j = 1,\ 2,\ 3,\ \dots,\ n) \quad (3)$$

$$k_i^{out} = \sum_{j=1}^{n} a_{ij} \ (j = 1,\ 2,\ 3,\ \dots,\ n) \quad (4)$$

where k_i, k_i^{in} and k_i^{out} are the degree, the in-degree, and the out-degree of node i respectively; a_{ji} represents the import relations form node j to i; and a_{ij} represents the export relations from node i to node j.

The distribution of node degree mainly describes the distribution characteristics of the number of connections between nodes and other nodes in a trade network [56]. For n nodes in the trade network, the node degree distribution is expressed as $p(k) = n_k/n$, if n_k represents the number of nodes with node degree k in the network. We sorted the node degree from small to large and drew the node degree distribution curve to reflect the degree of heterogeneity in the network directly.

3.2.3. Core-Peripheral Analysis

Core-peripheral analysis is mainly used to analyze the structure of a network with closely connected centers and sparse as well as scattered peripheries, which are composed of several interconnected elements. Its algorithm was first proposed by Borgatti and Everett [57], and it was divided into classification and continuous models. In this study, we used a continuous core-edge model to calculate the coreness of each member country in the trade network. To analyze the core-edge structure and evolution characteristics of the grain trade network further, we used Ucinet6 software to visualize the abstract core-edge trade network by showing the core-edge degree and trade flow of each country. The specific calculation formula is as follows:

$$\rho = \sum_{ij} a_{ij}\delta_{ij}, \quad \delta_{ij=c_i \times c_j} \tag{5}$$

where C_i and C_j are the core degrees of nodes i and j, respectively; δ_{ij} is the element of pattern matrix δ corresponding to the ideal core-edge model; a_{ij} is the element of the actual adjacency weight relation matrix A; and ρ is the correlation index between A and δ. When ρ reaches the maximum value, δ is the edge-core structure matrix of the nearest quasi-ideal model corresponding to the actual situation [58,59].

3.3. The Quadratic Assignment Procedure (QAP) Model

QAP is principally used to test the correlation between networks. Generally, one network is an observed network, whereas the other is a model or expected network. The algorithm proceeds in three steps. First, it computes the Pearson's correlation coefficient (plus simple matching, Jaccard, Goodman, Kruskal, Gamma, and Hamming distance) between the corresponding cells of the two data matrices. Second, it randomly permutes rows and columns (synchronously) of one matrix (the observed matrix, if distinction is relevant) and recomputes the correlation and other measures. Third, step 2 is repeated thousands of times to compute the proportion of times that a random measure is larger than or equal to the observed measure calculated in step 1. A low proportion (<0.05) indicates a strong correlation between the matrices that are unlikely to have occurred [60].

In this study, we established a QAP regression analysis model using the grain network in 2000 and 2018 as the explained variables, taking the geographic distance difference, resource endowment difference, economic gap, land border binary, cultural similarity binary, political difference, and free trade agreement binary networks as the explanatory variables. Thereafter, we used Ucinet 6 software to perform 2000 matrix permutation and regression analysis to obtain the results of the QAP analysis.

$$InTR_{ij} = \beta_0 + \beta_1 InRES_{ij} + \beta_2 InDIS_{ij} + \beta_3 InCON_{ij} + \beta_4 InECO_{ij} + \beta_5 InPOL_{ij} + +\beta_6 InCLU_{ij} + \beta_7 InRTA_{ij} + \varepsilon_{ij} \tag{6}$$

where TR_{ij} is the grain trade value; RES_{ij} is the national resource endowment; DIS_{ij} is the geographic distance; CON_{ij} is the contiguity; ECO_{ij} is the difference in national economic development; POL_{ij} is the national political differences; CUL_{ij} is the cultural similarity; RTA_{ij} represents regional free trade agreements; and β_0 and ε_{ij} are the constant term and random interference term of the model, respectively. Per capita cultivated land area is an important variable reflecting the resource endowment of food production [39]; therefore, we used it to measure resource endowment (RES_{ij}) and establish a resource endowment network. We used the spherical geographic distance (DIS_{ij}) and contiguity (CON_{ij}) to measure geographic proximity and establish the geographic distance network and contiguity of the land network, respectively. We used GDP per capita gap (ECO_{ij}) to measure the difference in national economic development and established a GDP per capita difference network. We selected six indexes including voice and accountability, political stability, and absence of violence or terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption from the global political governance indicators network database, and used them to calculate the national political differences (POL_{ij}) and establish the political difference network. In this study, we described the social and cultural similarity (CUL_{ij}) between countries based on whether they had a common official language or religious proximity, and established a cultural similarity network. We established a free trade agreements network based on whether they had signed the regional free trade agreements (RTA_{ij}).

3.4. Data Sources and Preparation

The data of grain trade values between individual countries for 2000 and 2018 derives from the United Nations Commodity Trade Statistics Database (comtrade.un.org/data/ accessed on 25 July 2020). The grain code in this database is HS10 including wheat and mixed wheat, rye, barley, oats, corn, rice, sorghum, and buckwheat. To present the main structure of the global grain network more clearly, we excluded some countries with low trade volumes and obtained 196 countries and regions. This had no effect on the analysis results. The data on the arable land per capita and GDP per capita of each country were obtained from the World Bank database (Table 1). Geographical distance, land borders, national comprehensive governance capacity, regional free trade agreements, religious beliefs, and official language data were obtained from the Cep II database (Table 1). Among them, whether land bordered on each other, regional free trade agreements were signed, they used the same official language, or they had the same religious beliefs were all dummy variables of 0 or 1 (Table 1). To reduce multicollinearity and dimensionality, logarithmic processing was performed on the data of per capita cultivated land, geographical distance, per capita GDP difference, and national comprehensive governance capacity difference (Table 1).

Table 1. List of variables, data source, and preprocessing of the QAP model.

Symbol	Description	Data Preprocessing	Data Source
RES_{ij}	national per capita cultivated land area differences.	logarithmic transformation	https://data.worldbank.org/ (accessed on 5 March 2021)
DIS_{ij}	spherical geographic distance.	logarithmic transformation	http://www.cepii.fr (accessed on 7 March 2021)
CON_{ij}	whether have a common geographical boundary contiguity.	binaryzation to 1 or 0.	http://www.cepii.fr (accessed on 7 March 2021)
ECO_{ij}	national GDP per capita gaps.	logarithmic transformation	https://data.worldbank.org/ (accessed on 7 March 2021)
POL_{ij}	national political differences.	logarithmic transformation	https://data.worldbank.org/ (accessed on 5 March 2021)
RTA_{ij}	whether sign the regional free trade agreements	binarization to 1 or 0.	http://www.cepii.fr (accessed on 7 March 2021)
CUL_{ij}	Whether have a common official language or religious proximity.	binarization to 1 or 0.	http://www.cepii.fr (accessed on 7 March 2021)

4. Grain Network Topology

4.1. Overall Network Characteristics

4.1.1. The Global Grain Network Has Scale-Free Properties

From the degree distribution maps of the global grain network in 2000 and 2018 (Figure 1), the degree distribution of the global grain network presents a "long tail" feature. This means that a few nodes have high degree values, whereas most have small and similar degree values. Power function fitting was conducted for the distribution in 2000 and 2018, and both passed the significance test, confirming that the degree distribution of the global grain network followed the power-law distribution, with significant heterogeneity among nodes, which was in accordance with the scale-free characteristics of the network. However, compared with that in 2000, the power ratio fitting value (R^2) of the distribution curve in 2018 decreased, indicating that the scale-free characteristics of the global grain network weakened and the heterogeneity of nodes decreased. Moreover, R^2 of the power function of the out-degree distribution was greater than that of the in-degree distribution in 2000 and 2018 (Figure 2), indicating that the heterogeneity of the out-degree was greater than that of the in-degree.

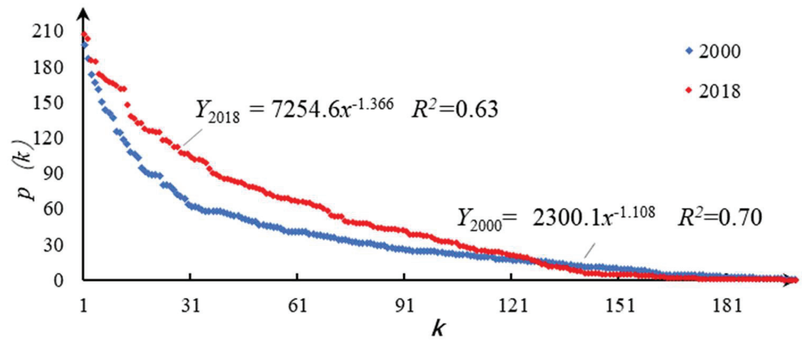

Figure 1. Distribution curve of node degree of the grain trade network.

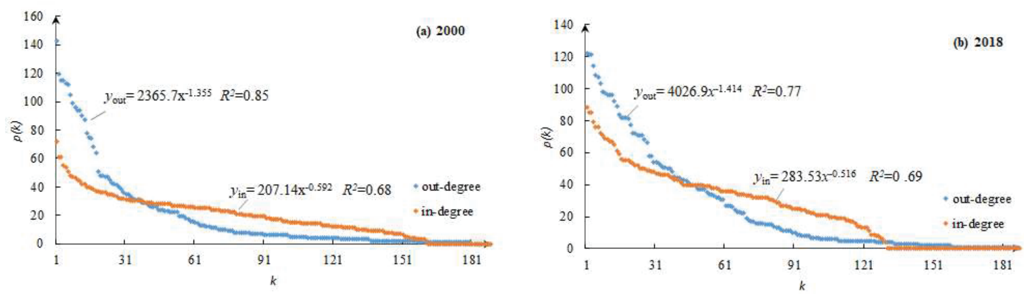

Figure 2. Distribution curve of in-degree and out-degree of the grain trade network in 2000 (**a**) and 2018 (**b**).

4.1.2. The Global Grain Network Presents a Significant "Core-Periphery" Structure

Figure 3 shows that the global grain network exhibits a significant "core-periphery" structure. In 2000, the core countries included the United States, Japan, Mexico, Egypt, and South Korea. The Philippines was the only semi-core country. The semi-marginal countries included 15 countries: the Philippines, Saudi Arabia, Algeria, Italy, Colombia, Canada, Venezuela, Nigeria, Israel, Russia, and Turkey. The remaining 175 countries were marginal. In 2018, the core periphery of the global grain network became more hierarchical because the number of core and semi-core countries increased and the number of semi-peripheral and peripheral countries decreased. In 2018, the core countries of the global grain network included the United States, Japan, Mexico, Egypt, the Republic of Korea, and Colombia. The semi-core countries included Venezuela, the Philippines, Peru, and Canada. There were 13 semi-marginal countries including Saudi Arabia, Egypt, Indonesia, Spain, Thailand, Ukraine, Italy, Nigeria, Russia, and the Netherlands. The number of peripheral countries was 173 (Table 2).

4.2. Node Features

4.2.1. Heterogeneity of the Out-Degree Nodes

The out-degree indicates the number of node egress relationships. Taking 2000 data as a reference and using the natural breaks (Jenks) method, the output degree was divided into five grade types with 12, 29, 51, and 99 as the thresholds. Generally, the number of countries with higher out-degree values increased, whereas those with lower out-degree values decreased. Figure 4b shows that in 2018, there were eight countries with the highest out-degree values including the United States, Argentina, France, Italy, India, Pakistan, China, and Thailand, whose output values were greater than 100. There was one country with the highest out-degree value in 2000. The higher out-degree values between 52 and 99 including Vietnam, Spain, Canada, the United Kingdom, Russia, Peru, Germany, Turkey, the Netherlands, Belgium, South Africa, Australia, and another 26 countries, with 15 more countries than in 2000. There were 27 countries with out-degree values between 30 and 51 in 2018 including Denmark, the Czech Republic, Myanmar, Mexico, Portugal, Indonesia, Philippines, Malaysia, Egypt, and Kazakhstan, with eight more countries than in 2000. There were 24 countries with out-degree values between 13 and 29 in 2018 including Saudi Arabia, Finland, Nigeria, Ireland, Israel, Slovenia, Colombia, Guyana, Sudan, Zambia, Uganda, and Laos, with four less countries than in 2000. The remaining 111 countries scored below 12, with 20 fewer countries than in 2000.

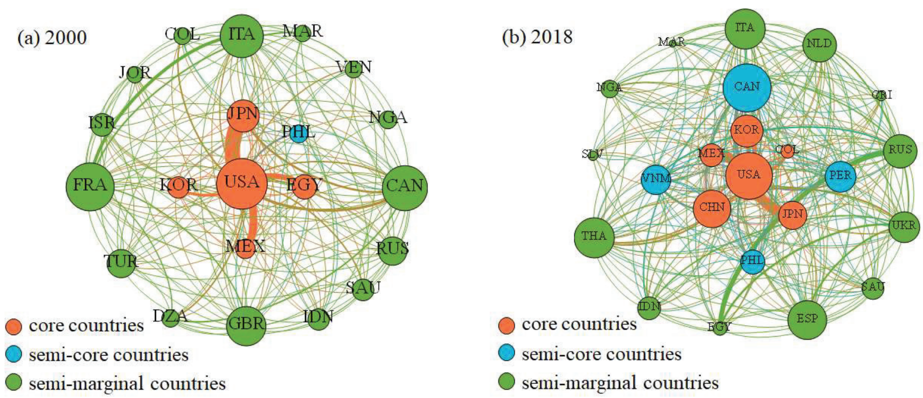

Figure 3. The "core-periphery" structures of the global grain trade network in 2000 (**a**) and 2018 (**b**).

Table 2. Quantitative of the four types of countries in the "core-periphery" structure in 2000 and 2018.

Year	Core Countries	Semi-Core Countries	Semi-Marginal Countries	Marginal Countries
2010	5	1	15	175
2018	6	4	13	173

4.2.2. Heterogeneity of In-Degree Nodes

In-degree indicates the number of node-import relationships. Taking the data of 2000 as a reference and using the natural discontinuity method, the in-degree was divided into five grades with thresholds of 7, 19, 32, and 48. Similar to the out-degree's characteristics, the number of higher in-degree value countries increased, whereas the number of lower in-degree countries decreased. As shown in Figure 4d, 29 countries had the highest in-degree values between 49 and 99 in 2018 including France, Canada, Germany, the United States, the Netherlands, and Spain. Compared with 2000, there were 23 more countries. There were 44 countries with higher in-degree values between 33 and 48 in 2018 including Japan, South Korea, Hungary, Thailand, Kuwait, Ukraine, Australia, Portugal, China, New Zealand, India, Nigeria, Indonesia, and Egypt. There were 27 more countries than in 2000. There were 36 countries with in-degree values between 20 and 23 in 2018 including Uganda, Zambia, Zimbabwe, Burkina Faso, Latvia, Brazil, Colombia, and Peru, with a decrease of 23 countries compared to 2000. Mexico, Ecuador, Paraguay, Uzbekistan, Cambodia, Afghanistan, and another 19 countries ranked fourth in terms of in-degree with in-degree values ranging between 8 and 19. This is 39 fewer countries than in 2000. The remaining 68 countries including Laos, Iran, Ethiopia, Guinea, Jamaica, Gabon, Libya, Haiti, and Bahamas had an in-degree values below 7, which is 18 more countries than in 2000.

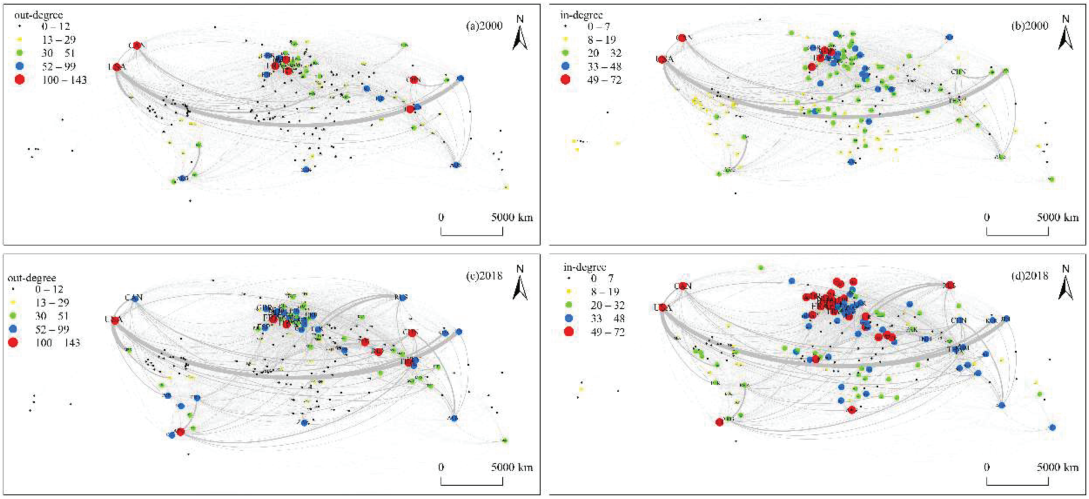

Figure 4. Evolution of in-degree and out-degree nodes of the global grain trade network in 2000 and 2018. Note: (**a**) out-degree in 2000; (**b**) in-degree in 2000; (**c**) out-degree in 2018; (**d**) in-degree in 2018. The gray line represents the trade flow among nodes. The thicker the line, the greater the trade flow.

5. Driving Factor for the Evolution of the Global Grain Networks

5.1. Results of QAP Model Regression

Table 3 presents a summary that QAP regression models passed the 1% significance test in both 2000 and 2018, and the goodness of fit of the 2000 and 2018 models were 88.61% and 87.70%, respectively, indicating that the models had high explanatory power. QAP regression analysis results indicate that the resources endowment difference, the difference of geographical approaches, economic development, the free trade agreement, and the national comprehensive management ability between 2000 and 2018 had a significantly positive impact on the global grain network evolution, whereas social and cultural similarity had a significantly negative impact on the global grain network evolution. Moreover, the driving intensity of geographical distance, national comprehensive governance capacity, and free trade agreement decreased significantly. In 2018, the elasticity coefficient of these two factors decreased by 9.25%, 5.71%, and 2.49% compared with 2000. The driving intensity of the resource endowment difference, land border difference, economic development difference as well as cultural similarity increased, and the elastic coefficients of the four factors increased by 1.77%, 1.95%, 4.46%, and 0.78%, respectively, in 2018.

According to the classical gravity model theory, the longer the distance between the two countries, the weaker the trade links. However, our results indicate that in 2000 and 2018, the geographical distance had a positive impact on the formation of food trade links, and countries with greater distance are more likely to form trade links. This result is not consistent with the expectations, reflecting the uniqueness of food trade. Grain production has significant regional characteristics, and strongly depends on natural conditions. Countries in close proximity may have similar natural conditions, similar resource endowments, and similar regional grain production structures, which could hinder the formation of close grain trade links. In contrast, differences in natural conditions and the production structure between countries far away promote them to adjust the surplus or shortage through food trade as well as to adjust variety. For instance, in the global grain network, the larger volume of trading partners is long-distance such as China and the U.S., the EU and the U.S., Brazil and China as well as India and the U.S. [37]. However, compared with 2000, the regression coefficient of the geographical distance factor decreased in 2018, mainly because of the improvement in the modern ocean transportation system. Thus, the freight cost was significantly reduced and the impact of geographical distance on grain trade was reduced.

Table 3. Results of QAP regression.

Indicators	2000	2018
$LnRES_{ij}$	0.05549 ** (6)	0.07321 ** (5) ↑
$LnDIS_{ij}$	0.49405 ** (1)	0.40154 ** (1) ↓
CON_{ij}	0.06416 ** (5)	0.08368 ** (4) ↑
$LnECO_{ij}$	0.34524 ** (2)	0.38982 ** (2) ↑
$LnPOL_{ij}$	−0.12001 ** (3)	−0.17706 ** (3) ↑
RTA_{ij}	0.07089 ** (4)	0.04597 ** (6) ↓
CUL_{ij}	−0.01824 ** (7)	−0.01047 ** (7) ↓
R2	0.886	0.877
AJ-R2	0.886	0.877
Model's significance	$p < 0.001$	$p < 0.001$
Observation items	38,220	38,220

Note: ** represents $p < 0.01$; The absolute value ranking of regression coefficients is in parentheses (the same below); "↑" and "↓" respectively indicate that the absolute value of the regression coefficient of variables in 2018 increased or decreased compared with that in 2000.

The grain trade had a significant "boundary effect." QAP regression results indicate that land border had a positive effect on the formation of food trade links in both 2000 and 2018, and the coefficient showed an increasing trend. That is, countries bordering on land have closer food trade links, and the effect is increasing. As neighbors on land have been close for a long time, their public opinion is similar, mutual trust is high, and trade is more frequent. Because railway transportation is highly flexible and has a lower transit time than ocean transportation, neighboring countries on land often take advantage of the geographical benefits to promote grain trade through border ports and land transportation facilities. For instance, in recent years, China has maintained increasingly close food trade ties with its neighbors such as Russia, Pakistan, and Vietnam. Additionally, the United States has maintained close food trade ties with its land neighbor, Mexico, for a long time.

The level of economic development had a positive effect on the evolution of the grain trade network shown by a statistical significance test of 1%, and the influence coefficient showed an increasing trend. Countries with larger differences in economic development levels had a closer grain trade relationship. Generally, international grain trade mainly occurs between high-income and low-income countries. High-income countries are usually net grain export regions [61], whereas slow-income countries have maintained a consistent trend in net food imports. With a high degree of mechanization and a high per capita grain output, high-income countries such as the United States, Canada, Australia, and France, mainly export grain. Most low-income countries are in the process of transforming from plant-based food consumption to animal-based food consumption structures, and their food consumption increases rigidly. Their domestic food cannot meet the demand because of low productivity, and they have to rely on imports for food consumption.

The difference in political attributes had a negative impact on food trade, which passed the statistical significance test of 1%. Countries with smaller differences in national governance capacity had closer bilateral food trade links. Compared with 2010, the absolute value of the influence coefficient of national comprehensive governance capacity on the grain trade network exhibited an increasing trend in 2018.

The impact of resource endowment differences on the grain trade network passed the statistical significance test of 1%, indicating a positive influence, and the coefficient showed an increasing trend. The resource endowment difference is still an important factor affecting food trade. Under the condition of existing technology, food production depends highly on natural resources, specifically land resources. The greater the difference in per capita cultivated land resources between countries, the greater the bilateral trade value. As global arable land decreases and land scarcity increases, differences in resource endowments have an increasing impact on the global food trade.

Regional free trade agreements had a positive impact on grain networks using a statistical significance test of 1%, and the coefficient exhibited an increasing trend. Regional free trade agreements play a positive role in food trade. Signing bilateral free trade agreements has provided legal guarantees for bilateral economic and trade cooperation, reduced the cost of bilateral trade, and improved the level of trade facilitation. This contributed to the formation of a mutually beneficial situation to strengthen mutual food trade links.

Cultural similarity had a negative impact on the formation of food trade links using a statistical significance test of 1%. Countries with larger cultural differences had fewer bilateral food trade links, which is consistent with the expected result. Compared to 2000, the absolute value of the regression coefficient of cultural similarity exhibited a decreasing trend in 2018, but the relative ranking remained unchanged, ranking seventh among all influencing factors.

5.2. Robustness Test

To test the robustness of the QAP regression results, two methods of removing variables and randomly deleting samples were used to conduct the QAP regression analysis.

The results of the variable exclusion test in 2000 indicated that the QAP regression was relatively robust. After a variable was removed in 2000, the regression coefficient symbols of the remaining variables were consistent with the original QAP regression results, and all p values were less than 0.01 (Table 4). In addition, the results of the variable exclusion test in 2018 indicated that the QAP regression was robust. In 2018, the sign of the regression coefficient of cultural difference variables changed from negative to positive when only land border variables were excluded, but it was not significant. In addition, when other variables were removed, the regression coefficient symbols of the remaining variables were consistent with the original results, and all p values were less than 0.01 (Table 5).

Table 4. Results of the variable exclusion test in 2000.

Indicators	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
LnRES_{ij}		0.03832 **	0.04968 **	0.04802 **	0.04833 **	0.04230 **	0.05646 **
LnDIS_{ij}	0.47128 **		0.45887 **	0.84713 **	0.64667 **	0.40053 **	0.49376 **
CON_{ij}	0.06190 **	0.05384 **		0.06720 **	0.07637 **	0.07440 **	0.06216 **
LnECO_{ij}	0.33375 **	0.75434 **	0.35725 **		0.27203 **	0.42114 **	0.34205 **
LnPOL_{ij}	−0.11397 **	−0.21721 **	−0.14651 **	−0.07978 **		−0.15989 **	−0.11660 **
RTA_{ij}	0.06427 **	0.03548 **	0.08411 **	0.09570 **	0.09461 **		0.06800 **
CUL_{ij}	−0.01976 **	−0.01790 **	−0.01012 **	−0.01496 **	−0.01186 **	−0.00917 **	
R2	0.884	0.877	0.882	0.880	0.882		0.885
AJ-R2	0.884	0.877	0.882	0.880	0.882		0.885
Model's significance	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$		$p < 0.001$
Observation items	38,220	38,220	38,220	38,220	38,220	38,220	38,220

Note: ** represents $p < 0.01$.

The results were tested using a random deletion of the samples. Based on the original samples in 2000 and 2018, 20% of the samples were randomly excluded to obtain 35,910 and 35,532 samples. QAP regression was performed for the new samples. The new QAP regression results indicated that in 2000 and 2018, the regression symbols of all variables were consistent, and the p values were all less than 0.01, which passed the significance test at the 1% level (Table 6). Therefore, the test results of the random deletion sample method also indicate that the empirical conclusion of this study is robust and credible.

Table 5. Results of the variable exclusion test in 2018.

Indicators	Model 8	Model 9	Model 10	Model 11	Model 12	Model 13	Model 14
$LnRES_{ij}$		0.06357 **	0.06268 **	0.06527 **	0.06433 **	0.06855 **	0.07417 **
$LnDIS_{ij}$	0.37491 **		0.32565 **	0.79360 **	0.65213 **	0.32627 **	0.40348 **
CON_{ij}	0.07974 **	0.07341 **		0.08931 **	0.10126 **	0.08728 **	0.08244 **
$LnECO_{ij}$	0.37053 **	0.73467 **	0.42639 **		0.25749 **	0.46590 **	0.38695 **
$LnPOL_{ij}$	−0.16940 **	−0.25540 **	−0.21765 **	−0.13003 **		−0.20275 **	−0.17506 **
RTA_{ij}	0.04010 **	0.01169 **	0.05806 **	0.08535 **	0.08339 **		0.04499 **
CUL_{ij}	−0.01350 **	−0.01270 **	0.00001	−0.00373 **	−0.00314 **	−0.00801 **	
R2	0.875	0.873	0.871	0.873	0.872	0.876	0.877
AJ-R2	0.875	0.873	0.871	0.873	0.872	0.876	0.877
Model's significance	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Observation items	38,220	38,220	38,220	38,220	38,220	38,220	38,220

Note: ** represents $p < 0.01$.

Table 6. Results of randomly deleting samples test in 2000 and 2018.

Indicators	2000	2018
$LnRES_{ij}$	0.04142 **	0.06995 **
$LnDIS_{ij}$	0.49925 **	0.39088 **
CON_{ij}	0.07030 **	0.08597 **
$LnECO_{ij}$	0.34104 **	0.39754 **
$LnPOL_{ij}$	−0.10828 **	−0.17727 **
RTA_{ij}	0.06927 **	0.04312 **
CUL_{ij}	−0.02331 **	−0.00844 **
R2	0.886	0.878
AJ-R2	0.886	0.878
Model's significance	$p < 0.001$	$p < 0.001$
Observation items	35,910	35,532

Note: ** represents $p < 0.01$.

6. Conclusions

This study constructed a weighted global grain network based on complex network theory using data from 2000 and 2018. First, we analyzed the topological properties of the evolution of the global grain network. We then investigated the evolution of the global grain trade and its spatial homogeneity for the years of 2000 and 2018 based on complex networks. Thereafter, we evaluated the impacts of six factors on the global food trade using the QAP model. We conclude that:

(1) The global grain network is scale-free. The distributions of degree, out-degree, and in-degree of the global grain network follow the power-law distribution. There was significant heterogeneity among nodes, and the heterogeneity of out-degree was greater than that of in-degree. There were eight countries with the highest output values greater than 100 including the United States, Argentina, France, Italy, India, Pakistan, China, and Thailand. There were 29 countries with the highest in-degree value between 49 and 99 including France, Canada, Germany, the United States, the Netherlands, and Spain.

(2) The global grain network has a significant core-periphery structure. The United States, Japan, Mexico, Egypt, South Korea, and Colombia are the core countries. Compared with 2000, the number of core and semi-core countries increased in 2018, whereas the number of semi-peripheral and peripheral countries decreased. This trend indicates that the "core-periphery" hierarchy of the global grain network is more obvious.

(3) Empirical research into trade network evolution mechanism with the six factors revealed several significant findings: (a) The geographical distance has a positive impact on the formation of food trade links in both 2000 and 2018, and countries with greater distance between them are more likely to form trade links. This is contrary to the classical gravity

model theory, reflecting the uniqueness of the food trade. (b) Grain trade has significant "boundary effects." Countries with land borders are more closely linked to the food trade, and this effect increases. (c) The level of economic development has a positive impact on the evolution of the grain trade network. Countries with larger differences in economic development have closer trade links, and the world grain trade mainly occurs between high-income and low-income countries. (d) The difference in resource endowment has a positive impact on the grain networks. Under existing technological conditions, food production is highly dependent on natural resources, specifically land resources. The scarcity of cultivated land increases with decreasing global cultivated land, and the impact of resource endowment differences on global food trade increases. (e) Regional free trade agreements have a positive impact on grain networks, and they play a positive role in food trade. In contrast, cultural similarity and differences in politics attributes have a negative impact on the formation of food trade links.

This study contributes to the literature by first addressing a gap in the global grain network research that focuses on structural and topological characteristics without considering its influencing factors. Second, the influence of geographical distance on grain trade is in contrast to the classical gravity model, which reflects the uniqueness of the food trade. Third, this study expands the application of the QAP model to the grain trade sector. In addition, this study can provide policymakers with a basis for the development of timely grain export and import strategy adjustments and policy-making processes.

There are several potential directions for future research. First, the impact of ocean liner transportation, tariff rates, currency interest rates, urbanization rates, and other factors on the global food trade should be considered. Second, innovative models such as the temporal exponential random graph model (TERGM) may be used to observe the endogenous structural and relational embeddedness effects. Third, it is necessary to add more cross-sectional data and improve the time resolution to observe more details of the variability for the 2000–2018 period in future research. Last, but not least, to explore the impacts of climate change on grain production and trade patterns. Global climate changes have multiple implications for the global food system by affecting food production, processing, packaging, storage, food prices, and retailing [62]. For example, climate change is projected to rise agriculture prices [63,64]. According to the Intergovernmental Panel on Climate Change (IPCC) global agricultural prices could increase up to 29% from the current levels by 2050 [65], which will aggravate financial burdens for food acquisition, particularly for net-importing countries [64]. Moreover, due to future climate change, many countries such as China [66], the United States [65], Bangladesh, and Myanmar [67] will suffer from decreases in crop production, while increases in precipitation and temperature will increase the yields and exports of wheat and rice in Kazakhstan [68]. The heterogeneous impacts of climate change across the world will change the relative competitive advantages in agricultural production, leading to significant adjustments of global grain trade patterns, and countries may experience the heterogeneous economic consequences depending on the position and the nodal relationship of each country in the global agricultural trade network [63]. Thus, the precise simulation of future changes in grain production and trade has important implications for stabilizing the international grain market and ensure food security.

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Re-Estimation of Agricultural Production Efficiency in China under the Dual Constraints of Climate Change and Resource Environment: Spatial Imbalance and Convergence

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Abstract: Climate change and farmland environmental pollution have put greater pressure on the sustainability of agricultural production. Based on the provincial panel data of mainland China from 1978 to 2018, climate variables such as precipitation, temperature, and sunshine hours are included into the input indicators, and agricultural non-point source pollution and carbon emissions are taken as undesirable outputs, the agricultural production efficiency (APE) under the dual constraints of climate change and the resource environment was estimated by the super slacks-based measure (SBM)-undesirable model. On the basis of the trajectory of the imbalanced spatiotemporal evolution of APE shown by Kernel density estimation and the standard deviational ellipse (SDE)–center of gravity (COG) transfer model, the spatial convergence model was used to test the convergence and differentiation characteristics of APE. Under the dual constraints, APE presents a "bimodal" distribution with a stable increase in fluctuation, but it is still at a generally low level and does not show polarization, among which the APE in the northeast region is the highest. The COG of APE tends to transfer towards the northeast, and the coverage of the SDE is shrinking, so the overall spatial pattern is characterized by a tendency of clustering towards the north in the north-south direction and a tendency of imbalance in the east-west direction. APE has significant spatial convergence, and there is a trend of "latecomer catching-up" in low-efficiency regions. The introduction of spatial correlation accelerates the convergence rate and shortens the convergence period. The convergence rate is the highest in the central and western regions, followed by that in the northeastern region, and the convergence rate is the lowest in the eastern region. In addition, the convergence rate in different time periods has a phase change. The process of improving the quality and efficiency of agricultural production requires enhancing the adaptability of climate change, balancing the carrying capacity of the resource environment, and strengthening inter-regional cooperation and linkage in the field of agriculture.

Keywords: agricultural production efficiency (APE); climate change; resource environment; standard deviational ellipse (SDE); center of gravity (COG); spatial imbalance; spatial convergence

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) showed in a special report released in 2018 that 1.5 °C warming may be reached early [1], and that unless emissions of carbon dioxide and other greenhouse gases are significantly reduced in the coming decades, the 21st century global warming will exceed 1.5 °C or even 2 °C [2]. Climate change has a natural and strong correlation with agricultural production and exerts a direct and far-reaching impact on it. Meteorological factors such as temperature, precipitation, and wind speed in climate change have already affected the growth and development of crops, planting structure, and product quality to different degrees [3–6], and caused differences in the geographical and environmental adaptations of different crops growing. The spatial-temporal heterogeneous impact of climate change on agricultural production is mainly reflected in changes in the geographical constraints of agriculture [7,8]. In China, the increase in temperature in the north is significantly higher than that in the south, while the decrease in sunshine in the south is significantly greater than that in the north, and precipitation also has the characteristic of "southern flood and northern drought" [9]. Significant differences in meteorology have led to complex and distinct regional adaptations in grain production, with different regions adapting differently to meteorological changes [10], and climate warming also led to the expansion of suitable planting areas for northern crops to higher latitudes and high altitudes [11]. Under the constraints of climate change such as temperature and precipitation in different regions, crop planting systems also show a differentiated regional distribution of wheat, maize, rice, etc., and the planting maturity system has undergone an evolutionary distribution of three crops a year to one crop a year from south to north.

As a basic industry of China, agriculture has made great achievements since the reform and opening up, and the production value and output of agriculture have grown significantly. However, under the impact of climate change, agricultural production methods need to be actively adjusted in order to achieve the sustainable development of agriculture [12], and the key to this is to improve agricultural production efficiency (APE), so that it can actively adapt to climate change. However, in the agricultural production process, in addition to necessary factor inputs, the carrying capacity of the resource environment also needs to be considered to satisfy the agricultural factor inputs and achieve the balanced coordination of economic benefits and environmental benefits, so as to ensure the sustainable development of agricultural production. Additionally, climate change poses many uncertain risks to grain production, and different climatic factors such as precipitation, temperature, and sunshine will have different effects on agricultural output, and agricultural production faces the need to adjust adaptive production behavior according to climate change [13], so it is necessary to consider the dual constraints of climate change and the resource environment in the measurement of APE. Therefore, considering that climate change is able to have a direct impact on agricultural production processes by affecting changes in crop fertility processes, suitable planting areas, cropping systems, photosynthesis, etc. [14], resources such as water, soil, light, and heat are the necessary material and energy sources for crop growth, so this paper includes climate factors as input indicators in the measurement system of APE. Specifically, focusing on agriculture in a narrow sense, i.e., plantations, using production factors such as machinery, fertilizers, and pesticides, and climate factors such as precipitation, temperature, and sunshine as input variables, agricultural output as the desirable output, and agricultural pollution emissions as the undesirable output, re-estimated APE under the dual constraints of climate change and the resource environment, with the aim of being able to objectively evaluate the sustainability of agricultural production within an integrated social-natural system. It further investigates the imbalance of the spatiotemporal evolution of APE under the dual constraints; the transfer characteristic, distribution trend, and regional differentiation of APE; whether there is convergence. The investigation can facilitate a full and comprehensive understanding of APE and its evolution law, as well as the inter-regional differences and convergence trend, which can provide theoretical references for further rational enhancement of agricultural production efficiency and sustainability of agricultural production in response to climate change and resource environment adaptation.

2. Literature Review

The current application of APE measurement methods is quite mature, and relevant methods, including data envelopment analysis (DEA), stochastic frontier analysis (SFA), three-stage DEA, and the SBM-undesirable model, have been widely used [15–18]. With the growing concern of agricultural ecological environment issues, agricultural non-point source pollution or agricultural carbon emissions as non-expectation outputs [19–21] was gradually applied to models for more accurate APE estimation. However, most existing research ignored the role of climate change on agricultural production. Gao [12] considered climate change for the first time in the input-output indicators of APE measurement but did not consider undesirable outputs of negative environmental externalities such as environmental pollution emissions from farmland. This limitation was improved in the present study to make the measurement system of APE more complete. In terms of the spatiotemporal evolution characteristics of APE, Hou and Yao [22] constructed traditional and spatial Markov transition probability matrices to explore the spatiotemporal evolution characteristics of agricultural eco-efficiency in China and predict the trend of its long-term evolution. Most previous research focused on the spatiotemporal dynamic evolution and differentiation characteristics of APE by Kernel density estimation [23], global or local Moran's I of exploratory spatial data analysis (ESDA) series methods, or hot spot analysis (Getis-Ord Gi*) [24–26] based on APE measured by DEA. However, little attention has been paid to the imbalance of the spatiotemporal transfer of the center of gravity (COG) and standard deviation ellipse (SDE) of APE, and therefore the spatial transfer dynamics of APE have not been deeply understood.

The convergence test was first proposed by Barro and Sala-I-Martin [27] and was widely used in convergence analysis of economic growth gap widening or narrowing, etc. It can also be used to test whether the gap in APE between regions is narrowing. The research on the convergence of production efficiency has gradually attracted the attention of scholars. Early studies applied σ-convergence or β-convergence to test the convergence of inter-provincial agricultural productivity [28–30]. Gao and Song [31] analyzed the spatial autocorrelation of the technical efficiency of grain production through Moran's I and Theil index and measured the efficiency differences between functional areas of grain production. However, the local spatial autocorrelation of efficiency was defined as spatial convergence in Gao's paper. Hou and Yao [32] introduced resource and environmental constraints into the APE measurement model and considered the spatial effect for testing the convergence of different regions and different periods through spatial β-conditional convergence. The present study can be regarded as a continuation and improvement of Hou's research. Zhuang et al. [33] studied the convergence of efficiency of rural development in China and showed that the regional development gap has been large for a long period of time.

Through literature combing, we have found that previous studies have achieved substantial achievements in the measurement of APE and the analysis of its spatiotemporal evolution and convergence. Although recently some scholars have continuously started to pay attention to the resource and environmental constraints of agricultural production, there is still much room for the improvement and expansion of the research on APE. First, considering the impact of climate change on crop growth and the negative environmental externalities faced by agricultural production mentioned in the introduction, it is necessary to incorporate climate change and resource and environmental constraints into the evaluation index system of APE measurement. Second, although ESDA can analyze the current situation of APE pattern and spatial change characteristics, it can only do that based on the spatial pattern in a specific year, and it is difficult to comprehensively reflect the changing trend and the transfer trajectory of APE. Third, the decline in exchange costs has led to the increasingly frequent spatial flow and interaction of agricultural production factors such as rural labor transfer and cross-area operation of machinery services, coupled with the similar climatic characteristics among neighboring regions, the correlation among neighboring regions and spillover effects of agricultural production is enhanced. Therefore, it is necessary to introduce spatial effects into the convergence test of APE.

In view of the above considerations, this paper incorporates the dual constraints of climate change and resource environment into the evaluation index system of APE based on the panel data of 30 provinces in mainland China from 1978 to 2018 to gain an in-depth and comprehensive understanding of the current level and changing trend of APE in China. Firstly, the super-SBM model was applied to measure the APE under the dual constraints.

Secondly, the imbalance of spatial transfer of APE was analyzed through the Kernel density estimation (KDE) and SDE-COG transfer model. Finally, the spatial correlation effect was introduced into the convergence test, and established a spatial econometric model to test the overall convergence and the convergence in different regions and different periods and explore the differentiation characteristics of APE.

3. Materials and Methods

3.1. Methods

3.1.1. Efficiency Measurement: Super-Efficiency SBM-Undesirable Model

Agricultural production processes are not only affected by climate change, but also have negative externalities to the environment through excessive inputs and inefficient use of chemicals such as fertilizers and pesticides. Usually, in the agricultural production process, the economic benefit is the desirable output, while the farmland environmental pollution caused by the excessive use of chemical products such as fertilizers, pesticides and agricultural films and other chemicals is the undesirable output, which mainly includes agricultural non-point source pollution and agricultural carbon emissions in this paper. The slacks-based measure (SBM) model, which considers undesirable outputs (SBM-undesirable model), is a non-radial, non-angle efficiency measurement model first proposed by Tone [34]. Compared with the traditional data envelopment model (DEA), the SBM model can effectively address the "crowding" or "slack" phenomenon of input factors caused by the radial and angular traditional DEA model. However, the SBM-undesirable model, like the traditional DEA model, has difficulty in further distinguishing the efficiency differences among efficient decision making units (DMUs) for DMUs with efficiency of 1. Based on the SBM-undesirable model, Tone further defined the super-efficiency SBM-undesirable model [35], which combines the advantages of the super-efficiency DEA model and the SBM-undesirable model, and can effectively further compare and evaluate the DMUs at the frontier.

Suppose there are n DMUs, each DMU includes input vector $X \in R^{m\times n} = (x_1, \cdots, x_n)$, desired output vector $Y^d \in R^{r_1\times n} = \left(y_1^d, \cdots, y_n^d\right)$, and undesirable output vector $Y^u \in R^{r_2\times n} = (y_1^u, \cdots, y_n^u)$, m, r_1, and r_2 are the elements in the input matrix, desired output matrix, and undesirable output matrix, respectively, where X, Y^d, Y^u are both greater than 0. Define the set of production possibilities (p) as: $P = \{(x, y^d, y^u) | x \geq X\lambda, y^d \leq Y^d\lambda, y^u \geq Y^u\lambda, \lambda \geq 0\}$, λ is the weight vector [36]. ρ is the value of agricultural production efficiency (APE).

The super-efficiency SBM-undesirable model is constructed as

$$Min\ \rho = \frac{\frac{1}{m}\sum_{i=1}^{m}(\bar{x}/x_{ik})}{\frac{1}{r_1+r_2}\left(\sum_{s=1}^{r_1}\overline{y^d}/y_{sk}^d + \sum_{q=1}^{r_2}\overline{y^u}/y_{qk}^u\right)} \tag{1}$$

$$\begin{cases} \bar{x} \geq \sum\limits_{j=1,\neq k}^{n} x_{ij}\lambda_j; \overline{y^d} \leq \sum\limits_{j=1,\neq k}^{n} y_{sj}^d\lambda_j; \overline{y^d} \geq \sum\limits_{j=1,\neq k}^{n} y_{qj}^d\lambda_j; \\ \bar{x} \geq x_k; \overline{y^d} \leq y_k^d; \overline{y^u} \geq y_k^u \\ \lambda_j \geq 0, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n, j \neq 0; \\ s = 1, 2, \cdots, r_1; q = 1, 2, \cdots, r_2; \end{cases} \tag{2}$$

3.1.2. Kernel Density Estimation (KDE)

Kernel Density Estimation (KDE) belongs to density mapping, which is essentially a process of surface interpolation through discrete sampling points, that is, through a smooth method, a continuous density curve is used instead of a histogram to better describe the distribution pattern of variables. It is more accurate and better smoothed than histogram estimation by virtue of its excellent statistical properties. Its specific basic principle is: KDE, as a non-parametric estimation method, can use continuous density curves to describe the distribution pattern of random variables. We set the density function of the random variable to be *f(x)*, and for the random variable X with n independent identically distributed observations, $x_1, x_2, \cdots, x_n$, respectively, x is their mean value. The estimate of the Kernel density function is

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K(\frac{x_i - x}{h}) \tag{3}$$

Among them, n is the number of study regions and h is the bandwidth.

K is a random kernel function, which is a weighting function or a smooth conversion function, including Gaussian (Normal) kernel, Epanechnikov kernel, Triangular kernel, Quartic kernel, and other types. It usually satisfies

$$\begin{cases} \lim\limits_{x\to\infty} K(x)\cdot x = 0 \\ K(x) \geq 0 \quad \int_{-\infty}^{+\infty} K(x)dx = 1 \\ \sup K(x) < +\infty \quad \int_{-\infty}^{+\infty} K^2(x)dx < +\infty \end{cases} \tag{4}$$

The choice of bandwidth determines the smoothness of the estimated density function. The larger the bandwidth, the smaller the variance of the KDE and the smoother the density function curve but the larger the estimated bias, and, conversely, the smaller the bandwidth, the less smooth the density function but the higher the estimated accuracy. Therefore, the optimal bandwidth must be chosen in a trade-off between the variance and bias of the kernel estimate so that the mean square error is minimized. At this time, the corresponding optimal window width $h = cN^{-0.2}$ (c is a constant) [37]. In this paper, the kernel density function of Gaussian normal-terminus distribution is used, and the window width is set to $h = 0.9SeN^{-0.2}$ ($c = 0.9Se$, Se is the standard deviation of observed values to the random variables)

3.1.3. Standard Deviational Ellipse-Center of Gravity Transfer Model

Standard deviational ellipse (SDE) is an effective method that can accurately reveal the overall characteristics of the spatial distribution of geographic elements [38,39]. It describes the spatial distribution characteristics of geographic elements and their spatiotemporal evolution process from a global and spatial perspective through a spatial ellipse that takes the center, long axis, short axis, and azimuth as basic parameters [40]. SDE takes the distribution COG of the geographical element as the center, i.e., mean center, the main trend direction of the element distribution as the azimuth (the angle of clockwise rotation of the long axis of the ellipse from due north), and the standard deviation of element in the X and Y directions as the ellipse axis to construct the spatial distribution ellipse of the geographical element. By the construction of the ellipse, SDE describes and elucidates the spatial distribution characteristics of the geographical element, such as centrality, direction, and spatial distribution pattern [41]. The center of the ellipse is the relative position of the spatial distribution of an economic phenomenon in two-dimensional space and is also the COG of spatial distribution. It can reflect the trajectory change and spatial transfer characteristics of the COG of an economic phenomenon in a certain region so that the development direction of the economic phenomenon can be understood more intuitively. The calculation formula of major parameters of the SDE-COG transfer model is:

$$X = \sum_{i=1}^{n} \omega_i x_i / \sum_{i=1}^{n} \omega_i,\ Y = \sum_{i=1}^{n} \omega_i y_i / \sum_{i=1}^{n} \omega_i \tag{5}$$

$$\sigma_x = \sqrt{\sum_{i=1}^{n} (\omega_i x_i^* \cos\theta - \omega_i y_i^* \sin\theta)^2 / \sum_{i=1}^{n} \omega_i^2},\ \sigma_y = \sqrt{\sum_{i=1}^{n} (\omega_i x_i^* \sin\theta - \omega_i y_i^* \cos\theta)^2 / \sum_{i=1}^{n} \omega_i^2} \tag{6}$$

$$\tan\theta = \left(\left(\sum_{i=1}^{n}\omega_i^2 x_i^{*2} - \sum_{i=1}^{n}\omega_i^2 y_i^{*2}\right) + \sqrt{\left(\sum_{i=1}^{n}\omega_i^2 x_i^{*2} - \sum_{i=1}^{n}\omega_i^2 y_i^{*2}\right)^2 - 4\sum_{i=1}^{n}\omega_i^2 x_i^{*2} y_i^{*2}}\right) / 2\sum_{i=1}^{n}\omega_i^2 x_i^{*} y_i^{*} \quad (7)$$

where (X, Y) is the coordinate of the COG of an economic phenomenon; (x_i, y_i) is the spatial coordinate of the study region; (x_i^*, y_i^*) is the coordinate of each region relative to the COG of the region; ω_i is the weight and, in this paper, the concentration of grain production; $\sigma_x \sigma_y$ are the standard deviations along the x axis and y axis, respectively; θ is the ellipse azimuth, which represents the angle formed by the clockwise rotation of the long axis of the ellipse from the due north direction. In addition, we will calculate COG and SDE under *ArcGIS* platform.

3.1.4. Spatial Convergence

This paper studies the convergence of APE changes under the dual constraints mainly by the β-convergence test. β-convergence of APE exists if the efficiency of the low APE region improves faster than that of the high APE region [27]. β-convergence can be divided into absolute β-convergence and conditional β-convergence. In the present study, absolute β-convergence assumes that different regions have the same resource endowments, production conditions, income levels, technological equipment, etc., and that APE in different regions will converge to the same steady-state as time evolves. In contrast, conditional β-convergence does not assume homogeneity and represents that APE in different regions will converge to their respective steady-state over time [42]. The traditional β-convergence only shows convergence characteristics of APE evolving over time, while in the convergence process, agricultural production in a region may be influenced by neighboring regions, thus potentially leading to biased convergence conclusions. Thus, this paper introduces spatial econometrics into β-convergence analysis and establishes a spatial β-convergence model to test the absolute and conditional β-convergence characteristics of APE in each province. The basic models of spatial econometrics include the spatial lag model (SLM) and the spatial error model (SEM). The optimal model needs to be selected by test. The specific models combined with β-convergence are

$$\text{SLM}: \ \ln(Y_{i,t+1}/Y_{i,t}) = \alpha + \rho W \ln(Y_{i,t+1}/Y_{i,t}) + \beta \ln Y_{i,t} + \theta \ln X_{i,t} + \varepsilon_{i,t} \quad (8)$$

$$\text{SEM}: \ \ln(Y_{i,t+1}/Y_{i,t}) = \alpha + \beta \ln Y_{i,t} + \theta \ln X_{i,t} + \varphi_{i,t}; \ \varphi_{i,t} = \rho W \varphi_{i,t} + \varepsilon_{i,t} \quad (9)$$

where θ is the estimated coefficient of each control variable $X_{i,t}$. The model is β-absolutely convergent when θ_k takes 0, and is β-conditionally convergent when θ_k does not take 0. $\ln(Y_{i,t+1}/Y_{i,t})$ denotes the logarithmic increase in agricultural productivity of the i-th region in year t. ρ is the spatial effect coefficient. W is the spatial weight matrix. Since it is difficult to portray the situation that two non-adjacent regions are still related in economic, social, and ecological fields with 0–1 adjacency weight, this paper adopts the geographical distance weight matrix W [43] constructed based on the inverse of the latitude and longitude distance of the geometric center of the region and normalizes it. β is the judgment coefficient of convergence. When $\beta < 0$, APE tends to converge; otherwise, it tends to diverge. $\beta = e^{-\eta T} - 1$ with η being the convergence rate, which has a positive correlation with β and T being the time span [44]. $\varepsilon_{i,t}$ is a random error term and satisfies $\varepsilon_{i,t} \sim i.i.d(0, \delta^2)$. $\varphi_{i,t}$ is a spatially autocorrelated error term.

In addition, the convergence of APE will be done in Stata.

3.2. Core Variables and Data Sources

3.2.1. Core Variables of APE under Dual Constraints

APE under dual constraints is to obtain the largest possible agricultural output with the least possible agricultural factor input and the least environmental cost under climate change. This paper focuses on agriculture in the narrowest sense, namely a plantation. The plantation is primarily an agricultural production sector that cultivates plant crops such as food crops, cash crops, and fodder crops. According to the availability of data and the consistency of statistical caliber, the input indicators of APE include traditional agricultural elements such as land, labor, mechanical power, irrigation, fertilizers, and pesticides [19,21,24], and climate indicators such as precipitation, temperature, sunshine hours are incorporated into the input factors. The output indicators include total agricultural output value and total grain production as desirable output, and agricultural non-point source pollution emissions and agricultural carbon emissions as undesirable output.

For undesirable output, agricultural non-point source pollution is estimated by the amount of fertilizer loss, pesticide residues, and agricultural film residues, where the pollutant indicators for fertilizer loss accounting are total nitrogen (TN) and total phosphorus (TP), the pollution units are three types of nitrogen fertilizer, phosphate fertilizer, and compound fertilizer, and the pollution unit emission coefficient is equal to the pollution production coefficient multiplied by the fertilizer loss rate, the TN pollution production coefficients of nitrogen fertilizer, phosphate fertilizer, and compound fertilizer (*n*-*p*-K nutrient ratio of 1:1:1) are 1, 0, and 0.33, and TP pollution production coefficients are 0, 0.44, and 0.15, respectively [45]. The coefficients of TN pollution production for *n*, *p*, and compound fertilizers (*n*-*p*-K nutrient ratio of 1:1:1) are 1, 0 and 0.33, respectively, and the loss rate of fertilizer in each region is referred to the study of Lai [46], and the sum of TN and TP are the amount of fertilizer use. The accounting formula for pesticide residues is pesticide use amount × pesticide ineffective utilization coefficient, and the accounting formula for agricultural film residues is agricultural film use amount × agricultural film residue coefficient, these two coefficients of pollution emissions refer to the study of Wu [47] and the "First National Pollution Census: Manual of Pesticide Loss Coefficient and Agricultural Film Residue Coefficient", and take into account the differences of regional cultivated land topography. Agricultural carbon emissions include six types of direct or indirect carbon emission sources, such as fertilizers, pesticides, agricultural films, agricultural diesel, irrigation power and water consumption, and tillage loss, etc. Emission coefficients are estimated with reference to relevant literature [16,48].

The constructed index system of APE under dual constraints is shown in Table 1.

Table 1. APE index system under dual constraints.

Indicators		Variables	Variable Description
Basic Input Elements	Land	Total crop sown area/khm^2	It reflects the actual area cultivated in agricultural production
	Labor	Agricultural practitioners/10^4 people	Primary industry employees × (total agricultural output value/total agricultural, forestry, animal husbandry and fishery output value)
	Mechanical power	Total power of agricultural machinery/10^4 kW	It is the sum of the power of various machines, including tillage machinery, irrigation and drainage machinery, harvesting machinery, etc.
	Irrigation water	Effective irrigated area/khm^2	Water for agriculture is mainly used for irrigation
	Fertilizer Pesticide Agricultural film Energy	Amount of fertilizer use/10^4 t (Purity) Amount of pesticide use/10^4 t Amount of agricultural film use/10^4 t Agricultural diesel use/10^4 t	Fertilizer, pesticide, agricultural film, diesel fuel, and other inputs are the main sources of pollution in the agricultural production process

Table 1. *Cont.*

Indicators		Variables	Variable Description
Climate Indicators	Precipitation	Average annual precipitation extracted based on GIS/mm	It is the depth of accumulation on the horizontal plane without evaporation, infiltration and loss
	Temperature	Average annual temperature extracted based on GIS/°C	It is the air temperature measured in the field under air circulation and not under direct sunlight
	Sunshine hours	Sunshine hours extracted based on GIS/h	It is the time of the day when the direct rays of the sun hit the ground
Desirable Output	Economic output	Total agricultural output value/billion yuan	Converted to 1978 constant prices based on CPI index to remove the effect of price changes
	Physical output	Grain yields/million tons	Total regional year-end grain production
Undesirable Output	Pollution emissions	Agricultural non-point source pollution emission/10^4 t	The total amount of fertilizer loss, pesticide residues and agricultural film residues
	Carbon emissions	Agricultural carbon emissions/10^4 t	Reference to related literature [16,48]

3.2.2. Data Sources

The research sample of this paper is 30 provinces (autonomous regions and municipalities directly under the central government) in mainland China, Tibet, and Hong Kong, Macao and Taiwan do not participate in the empirical study, and the time span is 1978–2018 since the reform and opening up. The data of variables involved in the paper were obtained from *China Rural Statistical Yearbook*, *China Agricultural Statistics*, *Agricultural Statistics of New China in the Past Fifty Years*, provincial and municipal statistical yearbooks and 60-year statistics, the data website of National Bureau of Statistics (data.stats.gov.cn accessed on 10 January 2022), and some missing data were made up by interpolation. Among them, the data of Chongqing before 1997 and Hainan before 1988 were obtained through *Chongqing Statistical Yearbook* and *Hainan Statistical Yearbook*, and adjusted the data of Sichuan and Guangdong for the corresponding years.

The data of climate indicators are obtained from the "China Surface Climate Data Annual Value Data Set" of the Meteorological Data Center of China Meteorological Administration (data.cma.cn accessed on 10 January 2022), which is a data set of annual values of climate information since 1951 for 613 basic benchmark ground meteorological observation stations and automatic stations in China, and statistics of the average value of each province over the years.

According to the division of the National Bureau of Statistics, this paper divides the country into four regions: eastern, central, western, and northeastern (eastern region includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan; central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei and Hunan; western region includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang; northeastern region includes Liaoning, Jilin and Heilongjiang).

In addition, the spatial coordinate system in this paper is Krasovsky_1940_Albers.

4. Results

4.1. The Measurement and Distribution Dynamics of APE in China

After measuring and calculating the APE of 30 provinces in China from 1978 to 2018 under the dual constraints of climate change and resource environment (hereafter referred to as under the dual constraints), the average values of each year were calculated in order to compare and analyze different regions (Figure 1). It can be seen that during 1978–2018, the evolution of APE under the dual constraints has the following characteristics: (1) The overall APE in China is at a low level, and there is still much room for efficiency improvement in agricultural production, which requires more efficient use of production factors such as mechanization and more adaptation of planting systems to climate change.

In terms of the change in different periods, due to the influence of early unsustainable production inputs and vulnerability caused by climate fluctuations, although APE shows a rising trend, the change process is in fluctuation, and the average APE is less than 0.8 in most years. The overall APE shows a trend of first declining and then rising, with the year 2000 as the dividing point; the fluctuation mainly occurs during 1978–2000. After 2000, APE shows a stable, rising trend and has exceeded 0.8 since 2012. (2) In terms of changes in different regions, the northeastern region has the highest efficiency. With the year 2000 as the dividing point, the ranking of APE during 1978–2000 is northeastern > western > eastern > central; the difference between regions roughly shows a trend of first narrowing, then widening, and then narrowing again. During 2000–2018, the APE ranking is northeastern> eastern> western> central (in most years). The ranking of the eastern region is rising, and the gap between the central and western regions and the eastern region is gradually narrowing.

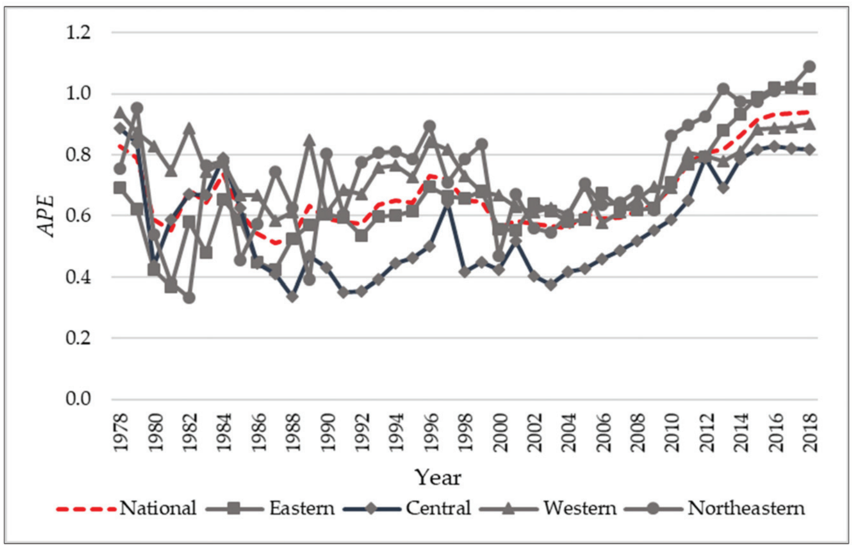

Figure 1. The trend of APE under dual constraints during 1978–2018.

To further explore the differences in APE clustering evolving over time among provinces, a non-parametric Kernel density function of Gaussian distribution [49] was used, and six years, 1978, 1986, 1994, 2002, 2010, and 2018, were selected as observation time points for Kernel density estimation to obtain the distribution status at different time points (Figure 2). The height and width of the peak reflect the degree of agglomeration and the magnitude of differences in each province, respectively, and the number of peaks reflects the degree of polarization [50]. APE under dual constraints shows an overall "bi-modal" distribution from left to right and does not show polarization. It generally shows an upward trend but also has fluctuations. With the year 2000 as the dividing point, during 1978–2000, the height of the right peak has experienced the process of "falling and rising," and the width first becomes large and then becomes small, indicating that APE showed a trend of fluctuations and the reduction in regional differences, consistent with the results of the aforementioned feature analysis. During 2000–2018, the height of the right peak increases and the width decreases, implying that APE stably improves and inter-regional difference gradually decreases. The overall APE under climate change shows a trend of first fluctuating and then stably increasing over time. Most provinces gradually change from "similar levels of high or low agglomeration" to high levels of agglomeration, and the gap among provinces in APE tends to narrow.

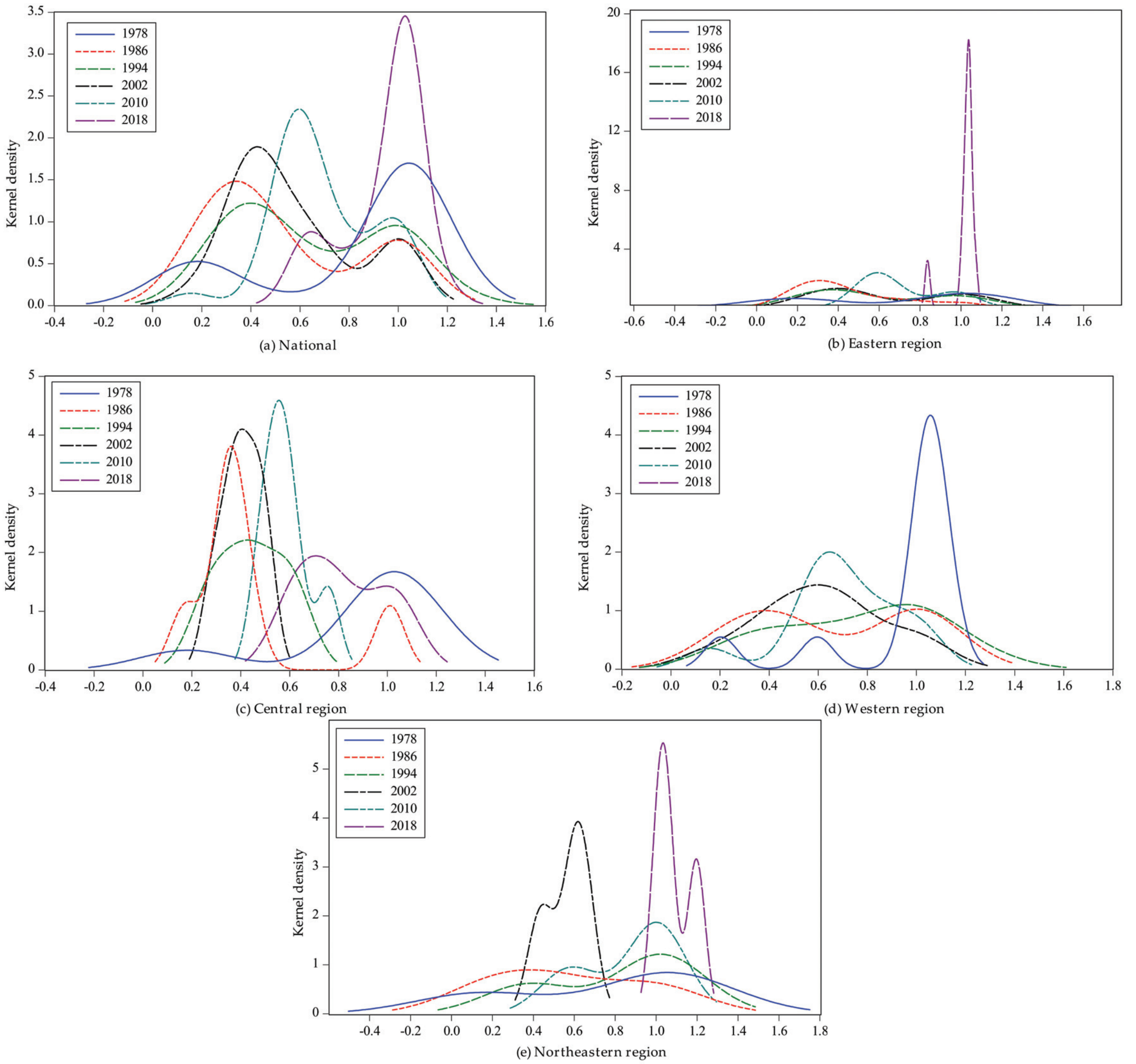

Figure 2. The KDE of APE under climate change during 1978–2018. (**a**) is the kernel density estimation at the national level; (**b**) is the kernel density estimation of the eastern region; (**c**) is the kernel density estimation of the central region; (**d**) is the kernel density estimation of the western region; (**e**) is the kernel density estimation of the northeastern region.

In the aspect of the evolutionary trends in the four regions, the distribution of APE in the eastern, central, western, and northeastern regions all show a rightward shift of the peak that first declines and then rises. The width of the peak first increases and then decreases. Since the reform and opening up, the APE of each region has shown an upward trend in fluctuation, and the differences within regions have first increased and then decreased. In addition to these changes, there are different evolutionary characteristics of APE among regions. The eastern region shows a significant trend from "bimodal to skew unimodal distribution," with the width of the peak continuously narrowing. In 2018, the right-skewed peak tends to occur and the left peak further narrows, indicating that while the APE in the eastern region is improving, the gap within regions is narrowing. APE in the central region shows the trend of "bimodal, unimodal, and bimodal distribution" with the peak width continuously narrowing. In the current bimodal distribution, the height and width of the peaks are equal, which means that APE in the central region does not show obvious polarization and the gap within the region is narrowing. APE in the western region shows the trend of "multimodal, bimodal, single, and bimodal distribution," with the peak height showing the trend of "high, low, and high," and the width gradually narrowing. The provinces in the western regions are mainly concentrated in the right peak, with less intra-regional differences. APE in the northeastern region shows the trend of "unimodal and bimodal distribution" with the height of the peak gradually increasing and the width gradually narrowing. Currently, the APE of all provinces in the northeastern region is above 1, and the differences within this region are small in spite of the bimodal distribution.

4.2. Characteristics of the Changes in the Spatiotemporal Patterns of APE Evolution

Based on the SDE-COG transfer model, the COG of APE was located, and the distance, direction, and SDE range of COG transfer between 1978 and 2018 under the dual constraints of climate change and resource environment were plotted to analyze the imbalance characteristics of COG spatial transfer (Figure 3). A total of nine time points was selected, i.e., 1978, 1983, 1988, 1993, 1998, 2003, 2008, 2013, and 2018, to specifically report the spatial distribution of the COG and SDE parameters of APE (Table 2).

The geographic coordinates of the COG of APE in China ranged from 111.459° E to 112.641° E and 33.478° N to 34.842° N, which was within Henan Province in all years, transferring approximately northeastwards from Nanyang City in 1978 to Pingdingshan City in 2018. Therefore, the APE in northern China increased significantly compared to southern China, though the path of COG transfer fluctuated. During the study period, the COG was within the city of Luoyang for most of the years before transferring to Pingdingshan City in 2018. The COG transferring path varied from northeastward (1978 to 1993) to southwestward (1993 to 2003), and then to southeastward (2003 to 2018)", showing an overall northeastward trend, i.e., shifting eastward in the east-west direction and northward in the north-south direction. In terms of the distance and speed, the northeastward COG transfer distance was 110.828 km, reaching an average annual speed of 22.166 km/a. The distance and speed of COG transfer between 1978 and 1993 were most significant at 142.156 km and 9.477 km/a, respectively. The distance and speed of COG transfer decreased between 1993 and 2003, with an overall southward transfer distance of 59.155 km and an average transfer speed of 5.916 km/a. Although the distance and speed of COG transfer increased between 2003 and 2018, the increases were relatively small, showing an eastward transfer distance of 91.609 km and an average speed of 6.544 km/a, respectively.

In terms of the changes in the elliptical shape, the major axis was extended from 1189.957 km in 1978 to 1202.703 km in 2018, while the minor axis was shortened from 1119.570 km in 1978 to 1016.121 km in 2018, and the mean shape index (minor axis/major axis) in 1978, 1993, 2003, and 2018 was 0.941, 0.805, 0.912, and 0.845, respectively. Assessing by periods, the mean shape index decreased from 0.941 to 0.805 between 1978 and 1993, increased from 0.805 to 0.912 between 1993 and 2003, and decreased again from 0.912 to 0.845 between 2003 and 2018. Thus, the mean shape index of the ellipse went through a series of downward, upward, and downward trends resembling an inverted *n* shape. However, the mean shape index was decreasing overall, and the ellipse resembled less and less of a circle. The north-south direction became the major axis and expanded, while the east-west direction contracted, indicating that APE tended to be imbalanced in the north-south and east-west directions, and the COG mainly transferred northward in the north-south direction. The azimuth angle of the ellipse varied slightly from 29.592° to 39.032° and showed a series of decreasing, increasing, and decreasing trends. The azimuth angle shifted 6.714° to the east between 1978 and 1993, 8.514° to the north between 1993 and 2003, and 6.596° to the north by east between 2003 and 2018. Overall, the spatial distribution of APE showed a northeast-southwest pattern, and the contraction of the minor axis in the east-west direction reflected the east by north trend in the north-south direction.

Table 2. Parameter changes of the COG and SDE of APE in China since 1978.

Year	COG Coordinates	Direction	Distance/km	Speed/(km/a)	Long Axis/km	Short Axis/km	Azimuth/°
1978	111.535° E, 33.585° N	-	-	-	1189.957	1119.570	37.332
1983	111.459° E, 33.478° N	Southwest	21.911	4.382	1268.881	1043.088	29.592
1988	111.856° E, 34.198° N	Northeast	88.485	17.697	1281.599	1066.620	32.887
1993	112.123° E, 34.842° N	Northeast	73.706	14.741	1294.073	1041.915	30.518
1998	111.591° E, 34.491° N	Southwest	55.443	11.089	1260.227	1122.895	35.804
2003	111.640° E, 34.372° N	Southeast	12.981	2.596	1196.798	1091.650	39.032
2008	112.135° E, 34.313° N	Southeast	43.612	8.722	1190.063	1052.301	35.479
2013	112.578° E, 34.679° N	Northeast	56.745	11.349	1201.527	1054.815	37.019
2018	112.641° E, 34.114° N	Southeast	64.091	12.818	1202.703	1016.121	32.436
	1978–2018	Northeast	110.828	22.166	-	-	-

Note: The parameters of COG and SDE over the years are shown in Appendix A.

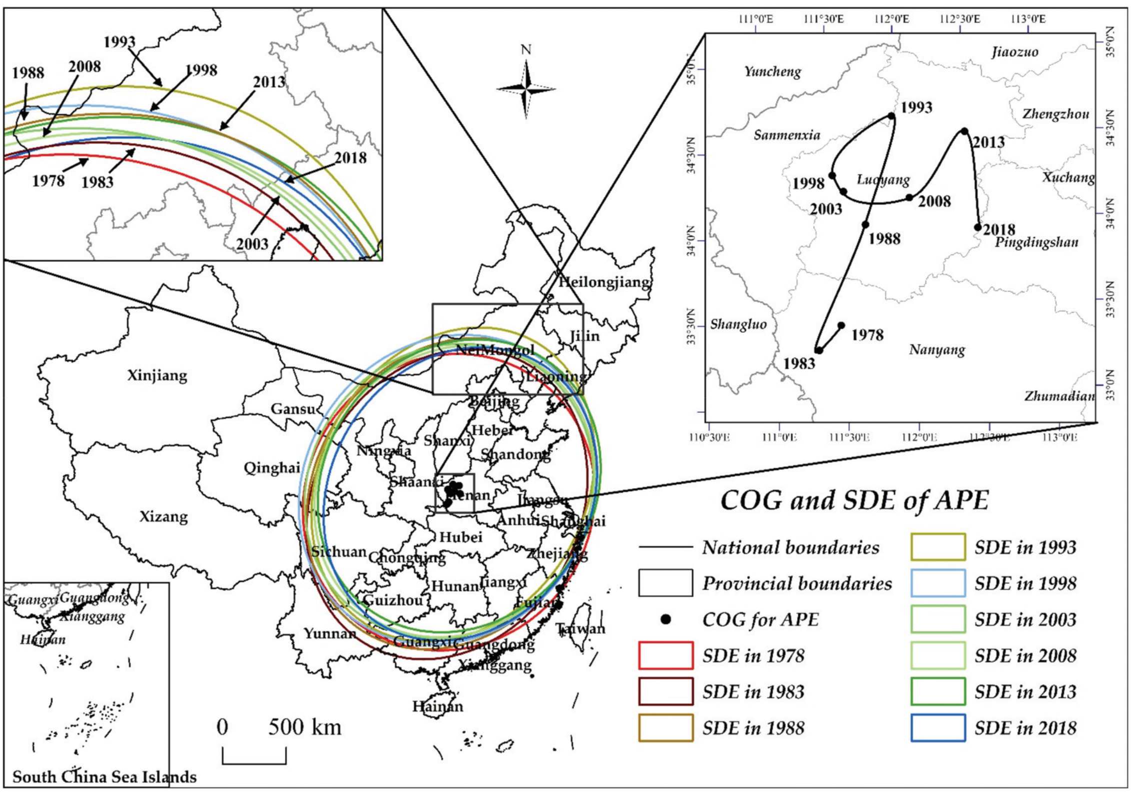

Figure 3. Changes of the COG and SDE of APE in China since 1978.

4.3. Spatial Convergence Test of APE

The β-convergence test with the spatial effect introduced into it is required to test the spatial correlation of APE, usually with Moran's I. Each Moran's I for APE from 1978 to 2018 was significantly positive (0.135 to 0.215), but mostly at the 5% or 10% level (Table 3). Thus, APE had a strong spatial correlation, i.e., there were mutual influences and correlations between agricultural production in neighboring regions.

Table 3. The Moran's I for APE since 1978.

Year	Moran's I	z-Value	*p*-Value	Year	Moran's I	z-Value	*p*-Value	Year	Moran's I	z-Value	*p*-Value
1978	0.190	1.646	0.100	1992	0.146	1.202	0.023	2006	0.137	1.528	0.063
1979	0.178	1.637	0.102	1993	0.141	1.214	0.055	2007	0.157	1.422	0.080
1980	0.187	1.881	0.060	1994	0.168	1.527	0.013	2008	0.158	1.413	0.082
1981	0.208	1.922	0.055	1995	0.136	1.054	0.029	2009	0.189	1.079	0.028
1982	0.205	1.880	0.060	1996	0.135	1.567	0.058	2010	0.205	1.225	0.022
1983	0.205	1.863	0.062	1997	0.135	1.012	0.031	2011	0.206	1.233	0.022
1984	0.197	1.900	0.057	1998	0.199	1.927	0.054	2012	0.210	1.253	0.021
1985	0.190	1.801	0.072	1999	0.168	1.506	0.013	2013	0.215	1.359	0.017
1986	0.181	1.667	0.095	2000	0.184	1.085	0.028	2014	0.194	1.100	0.027
1987	0.168	1.351	0.117	2001	0.169	1.344	0.095	2015	0.187	1.283	0.033
1988	0.214	1.656	0.051	2002	0.154	1.783	0.043	2016	0.185	1.281	0.041
1989	0.173	1.461	0.065	2003	0.139	1.519	0.064	2017	0.197	1.125	0.026
1990	0.178	1.481	0.063	2004	0.138	1.556	0.059	2018	0.186	1.279	0.035
1991	0.140	1.305	0.076	2005	0.136	1.574	0.057				

The convergence test requires the optimal spatial econometric model, which can be selected using the goodness-of-fit R^2, the Log-Likelihood (LogL), $Sigma^2$, the Akaike Information Criterion (AIC), and the Schwartz Criterion (SC) [51]. (1) The model with higher explanatory power was selected using AIC and SC, and lower AIC and SC values mean a higher explanatory power. (2) The goodness-of-fit of the model was determined based on LogL, R^2, and $Sigma^2$ statistics: higher values of LogL and R^2 and lower values of $Sigma^2$ mean better model fitness [52]. The study period was 1978 to 2018, which makes the research data long panel data. Elhorst pointed out that spatial panel models would be relatively more effective with fixed effects when the time was long enough [53]. With the Hausman test, SLM with fixed effects was finally selected as the main analytical model for the spatial convergence test. The test results showed that the spatial effect coefficient ρ was significantly greater than 0, indicating a significant spatial spillover effect of APE convergence under the dual constraints. Further discussions were conducted by reference to regions and time periods. The study area was divided into four major regions, eastern, central, western, and northeastern. The study period was divided into three parts based on the characteristics of APE GOC transfer mentioned above: the initial period from 1978 to 1993, the middle period from 1994 to 2003, and the late period from 2004 to 2018, with different timespans.

The absolute convergence coefficients at the national level and at regional and period levels were significantly smaller than 0 (Table 4), indicating significant spatial absolute β-convergence characteristics of APE under the dual constraints, i.e., a tendency for APE in different regions to converge to the same steady-state over time. Table 3 also presents the results of traditional absolute convergence at the national level without considering spatial effects. By comparison, the convergence rate of spatial absolute β-convergence (0.87%) is greater than that of traditional absolute β-convergence (0.76%), indicating that the spatial correlation between regions accelerates the convergence rate of APE. By region, the western region has the fastest convergence rate (1.31%), the central region has the second-fastest rate (1.00%), and the central and western regions have significantly faster rates than the eastern and northeastern regions, showing a significant latecomer catching-up effect. By time period, the convergence rate is fastest (7.86%) in the middle period (1994 to 2003) and slowest (2.14%) in the late period (2004 to 2018), indicating a stabilizing trend in APE convergence rate during the study period.

Table 4. Spatial β absolute convergence test of APE under the dual constraints of climate change and resource environment.

Variables	National Level		Regional Level				Period Level		
	Traditional	Spatial	Eastern	Central	Western	Northeastern	Initial	Middle	Late
lnape	−0.256 *** (−14.01)	−0.289 *** (−14.40)	−0.179 *** (−6.73)	−0.322 *** (−6.91)	−0.401 *** (−10.63)	−0.238 *** (−4.36)	−0.416 *** (−12.05)	−0.507 *** (−13.11)	−0.259 *** (−5.70)
C	−0.148 *** (−11.04)								
ρ		0.477 *** (13.86)	0.532 *** (8.32)	0.769 *** (5.17)	0.310 ** (3.40)	0.633 *** (7.21)	0.452 *** (8.73)	0.301 *** (4.08)	0.291 *** (3.94)
R^2	0.540	0.583	0.690	0.563	0.788	0.618	0.465	0.478	0.455
LogL		−69.432	−21.637	−32.054	27.765	9.229	−125.294	112.220	230.825
Convergence rate	0.76%	0.87%	0.51%	1.00%	1.31%	0.70%	3.59%	7.86%	2.14%

Note: those in parentheses are *z*-Values; *** and ** denote significance at the 1% and 5% levels, respectively.

The conditional convergence liberalizes the assumption condition of homogeneity, i.e., differences in economic growth, resource endowment, technological progress, and financial support across regions. In this paper, a total of five indicators, namely, regional economic development level, arable land endowment, multiple crop index, technological progress, and financial support to agriculture, are selected from macro and micro perspectives and added to the conditional convergence test model of APE to examine whether the differences among regions converge to their respective steady states over time. Of the five indicators, the economic development level was characterized by GDP per capita (pgdp); arable land endowment was characterized by the area of arable land owned per capita (area); the multiple crop index was calculated as the ratio of total sown area to the area of arable land (mci); the technological progress was characterized by total mechanical power per unit of labor (tech) [54]. The financial support to agriculture was characterized by the expenditure on agricultural, forestry, and water affairs as a share of GDP (fiscal). (The financial support expenditure for agriculture includes agricultural expenditure, forestry expenditure, water conservancy expenditure, poverty alleviation expenditure, and comprehensive agricultural development expenditure. In 2003, there was a change in the statistical subjects of financial revenue and expenditure, and in 2007, the new indicator of expenditure on agriculture, forestry, and water affairs was adopted uniformly. Although the statistical subject structure of this indicator has changed several times, the flow of funds to support agriculture has not. In order to maintain the statistical consistency, data were converted to the expenditure of agriculture, forestry, and water affairs.)

The conditional convergence coefficients at the national level and at regional and period levels were also significantly smaller than 0 (Table 5), indicating significant spatial conditional β-convergence characteristics of APE changes under the dual constraints, i.e., APE in different regions evolved over time and the gap between regions, although narrowing, would converge to their respective steady states, but not to the same steady state. Compared to the spatial absolute β-convergence, the R^2 and LogL for the spatial conditional β-convergence have a certain degree of improvement. Thus, spatial conditional β-convergence has a higher explanatory power compared to spatial absolute β-convergence in addition to characteristics similar to spatial absolute convergence.

(1) The introduction of spatial correlation accelerates the convergence rate of APE (1.12% > 0.82%) and shortens the convergence period to its own steady state.
(2) Among the different regions, the middle and western regions have the highest convergence rate (1.47% and 1.48%), which are relatively similar and greater than those in the eastern and northeastern regions.
(3) The APE convergence rates in different time periods have a phase change, showing a rise and then a decline overall with the highest convergence rate in the middle period (9.15%) and the lowest convergence rate in the late period, indicating that the APE convergence rate tends to stabilize.

Table 5. Spatial β conditional convergence test of APE under the dual constraints of climate change and resource environment.

Variables	National Level		Regional Level				Period Level		
	Traditional	Spatial	Eastern	Central	Western	Northeastern	Initial	Middle	Late
lnape	−0.275 *** (−7.49)	−0.354 *** (−9.24)	−0.282 *** (−6.20)	−0.436 *** (−3.87)	−0.438 *** (−6.90)	−0.400 *** (−4.54)	−0.452 *** (−8.82)	−0.561 *** (−5.12)	−0.416 *** (−6.46)
lnpgdp	0.033 *** (2.81)	0.032 ** (2.52)	0.019 * (1.65)	0.148 ** (2.19)	0.0167 (0.54)	0.078 (1.35)	−0.048 (−0.89)	−0.161 *** (−5.35)	0.049 (1.09)
lnarea	0.078 * (1.86)	0.080 * (1.82)	0.047 (0.74)	0.301 (1.04)	0.148 ** (2.39)	−0.480 *** (−3.26)	0.117 (0.84)	0.011 (0.21)	0.132 ** (2.24)
lnmci	−0.175 ** (−2.55)	−0.173 *** (−2.58)	−0.013 (−0.17)	0.152 (0.40)	−0.094 (−1.26)	−0.355 *** (−4.08)	−0.014 (−0.06)	−0.147 (−1.03)	0.012 (0.14)
lntech	0.021 (0.96)	0.023 (0.49)	0.109 ** (2.32)	−0.289 ** (−2.28)	−0.013 (−0.18)	0.037 (0.23)	0.201 (1.51)	−0.069 (−1.13)	0.003 (0.06)
lnfiscal	0.020 (1.40)	0.021 (1.06)	0.048 (1.55)	0.074 (1.07)	0.007 (0.38)	0.121 ** (2.24)	0.063 (0.94)	0.063 (1.40)	0.098 ** (2.35)
C	0.364 (0.99)								
ρ		0.357 *** (6.34)	0.501 *** (4.77)	0.678 *** (3.86)	0.281 ** (2.13)	0.590 *** (10.00)	0.373 *** (6.46)	0.106 *** (2.82)	0.139 *** (2.92)
R^2	0.462	0.695	0.497	0.513	0.714	0.675	0.488	0.466	0.565
LogL		−30.215	−10.112	−19.518	25.033	9.229	−124.674	126.699	210.524
Convergence rate	0.82%	1.12%	0.85%	1.47%	1.48%	1.31%	4.01%	9.15%	3.84%

Note: those in parentheses are *z*-Values; ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

5. Discussion and Policy Implications

At the early stage of reform and opening up, the APE of most provinces was clustered at a low level on the bimodal distribution due to the backward agricultural technology level. With the progress of reform and opening up and the continuous development of the agricultural economy, the APE in various provinces shows different degrees of improvement [16]. However, due to differences between provinces in terms of resource endowment and economic strength, the APE gap among provinces has begun to widen. Over time, the left peak of the low APE cluster gradually declines, while most provinces are within the right peak of the high APE cluster. Therefore, the APE gap is narrowing and gradually forming a near "peak-skewing" distribution spatiotemporal evolution pattern with "high-high and low-low APE clusters gradually disappearing." There are spatial imbalances in the improvement of APE [55]. Specifically, APE in the northeast was maintained at a high level, relying on the rich resource endowment, the climatic conditions, and the spread of agricultural mechanization services. APE improvement in the eastern region was steady thanks to the significant technological progress in the agricultural industry, the modernization of agriculture, the coordination of agricultural production with resources and the environment, and the adaptation to climate changes. The effects of topography and extreme climatic conditions were more profound in the central and western regions, leading to slow development of agricultural technology, low degree of agricultural mechanization, and a relatively cruder development of the agricultural economy [22]. Thus, their APE was relatively lagging behind that of the northeastern and eastern regions in the early stages. With the accelerated spatial flow of production factors, the inter-regional gap in agricultural technology has gradually narrowed, and the latecomer catching-up effect has led to a rapid APE increase in the central and western regions [56], gradually narrowing the gap with the eastern region.

Agricultural production is closely related to climate change, and resources such as water, soil, light, and heat are the necessary material and energy sources for crop growth. The uniqueness of natural endowments such as geographical environment and climatic characteristics of different regions makes the spatial distribution of resources such as water, soil, light, and heat to sustain agricultural production differ, and also determines the heterogeneous distribution of crop varieties, production methods, and cropping systems among regions, which leads to regional heterogeneity in APE, and different forms of combinations of the various production factor inputs will also yield different APE [57]. In addition, the volatility of climate change and extreme weather put agricultural production in an unstable natural environment, placing higher demands on agricultural production to actively respond and be green and sustainable [58]. At the micro level, agricultural production is an adaptive behavior formed by farmers in different regions based on local climatic characteristics over a long period of time. Based on the trade-off between their own cost inputs and expected benefits, farmers spontaneously choose adaptive strategies to cope with climate fluctuations in order to avoid the adverse effects brought by climate fluctuations, considering environmental constraints. Fluctuating changes in APE also imply an intensive use of production factors and more attention to whether the environmental resources of farmland are overexploited; climate change also affects the farmland environment, and rainfall runoff has an accelerating effect on the migration of agricultural pollution [59], thus, maintaining a balanced state of agricultural production, resource use, and climate change is beneficial. In addition, the irreversible nature of environmental damage caused by the use of certain inputs would cause continuous harm to soil fertility and the farmland environment, such as the unreasonable use of agricultural films, and the accumulation of agricultural film residues in the soil, which would destroy the soil structure. Therefore, we also need to pay attention to the recycling of waste resources and improve the recovery rate of residues in the agricultural production process.

The distance and speed of APE COG transfer showed the trend of increase, decrease, and slightly increase, with the overall transfer toward the northeast and a spatially unbalanced pattern from northeast to southwest. The SDE of APE covers most of the eastern, central, and western regions of China and gradually transfers northeastward while contracting, indicating that the spatial distribution pattern of APE gradually tends to cluster and contract. The provinces distributed inside the SDE are basically the main food-producing provinces. The northeastward COG transfer of APE indicated that the predominant and high APE region in China gradually shifted to the northeast. As a strategic base for national food security, the northeastern regions have higher APE than other regions due to their excellent natural base endowment and modern agricultural production conditions. With faster industrial structure upgrading, higher per capita income, and higher labor cost, the southern region has seen a decline in the comparative returns of agricultural production and has gradually ceased to undertake the main task of agricultural production.

Regions with higher APE in the current period tend to have a lower rate of improvement in the next period, while regions with lower APE in the current period tend to have a higher rate of improvement in the next period, which means that the provinces share a common long-run equilibrium convergence path [60]. The latecomer catching-up effect in low APE regions has led to a narrowing APE gap among regions, resulting in the convergence rate showing a decreasing distribution pattern from the central and western region to the northeastern and eastern regions. The progress of reform and opening up has brought about accelerated spatial flow of factors such as talent, technology, and capital, improved agricultural infrastructure, improved agricultural production conditions, and financial and policy support for the central and western region from the central and local governments. As a result, the APE gap between the provinces of the central and western region and those of the eastern and northeastern region have begun to narrow gradually. Faced with the limitation of resource utilization and the increase in food demand [61], the northeastern region has a fine resource endowment and agricultural production conditions so agricultural modernization is developing fast; it is an important crop production base in China, and the level of the farmland ecosystem is also high [62]. The fact that provinces in the eastern region are mostly grain consumption provinces, except Hebei and Shandong, means that the marginal effect of agricultural output through factor inputs and infrastructure improvement is decreasing, and the spatial convergence rate is slightly lower. The unbalanced distribution and spatial spillover effect of APE [63] has led to extensive spatial flows and interactions of agricultural factor inputs, agricultural technology applications, and information diffusion between geographically neighboring regions. As a result, the spatial effect has accelerated the convergence of APE.

In addition, the changes in the convergence rate of APE corresponded to the distance and speed of APE COG transfer. The COG transfer distance and speed were at their minimum in the middle period with the maximum convergence rate. In that time period, APE convergence accelerated to a certain steady-state, and the differences between regions tended to decrease, leading to no major APE COG transfer. In the initial and late periods, the convergence rates were relatively low, but the distance and speed of COG transfer were large, whereas the initial period showed the lowest convergence rate and the highest COG transfer speed. Since the reform and opening up, the market mechanism has undergone a gradual transformation from initial implementation to full implementation, and the production factors have also undergone the transformation to full flow. Regions with advantages in initial resource endowments and production conditions were able to release larger agricultural productivity and widen the gap with other regions, leading to the imbalanced development of agricultural production between regions and lower convergence rates. With the gradual narrowing of comparative advantage gaps between regions and the improvement of agricultural infrastructure, the APE gap between regions has been narrowing, and the convergence rate has been increasing. As more emphasis has been placed on quality, efficiency, and sustainability in agricultural production [64], the supply-side structural adjustment has slowed the convergence rate of APE, and its convergence trend may stabilize.

It should be noted that the establishment of spatial relationships in the test of spatial convergence in this paper relies on the geographic distance weight matrix, which has been able to better portray the spatial correlation of agricultural production between regions. However, the proximity of geographic distance does not mean the same spatial correlation, which also has a certain relationship with the economic scale of each region, this is the distance of the cooperative relationship in the economic sense. Therefore, in future research, the spatial relationship between regions will be further constructed by using the economic distance weight matrix.

Introducing climate change and environmental pollution into the APE measurement system and assessing them more objectively will help to understand the sustainability laws of agricultural production under the dual constraints, so as to respond to climate change more resiliently and with fewer negative externalities on resource utilization, and to explore more practices of agricultural sustainability and adaptation to climate change. The policy implications from this study are as follows:

Firstly, China's APE has a relatively large room for improvement, and the dual constraints of climate change and resource environment must be considered to promote agricultural production quality and efficiency. Investment in infrastructures such as agricultural meteorological monitoring services and agricultural environmental pollution prevention and management can be increased continuously to promote the structural reform of agriculture at the supply side. The technological progress in soil testing and fertilization technology, pesticide reduction, and resource utilization and conservation can be employed to further transform the agricultural development mode [65]. Emission reduction and control of agricultural non-point source pollution should be strengthened to continuously promote green production methods, eco-agriculture construction, clean agricultural production, and sustainable agricultural development.

Secondly, the northeastward COG transfer trend implied the continuous strengthening of agricultural production in the northeastern region, a strategic base for national food security. The main connotation of food security is to ensure the production of sufficient quantities of food and to maximize the stability of food supply capacity [66], which requires more efficient use of production resources, efforts to improve APE, and an active response to climate change. In addition to ensuring food security and food supply, the northeastern region should plan ahead by strengthening the monitoring of agricultural meteorological disasters and timely releasing of meteorological information to minimize the agricultural production losses caused by extreme meteorological disasters. In the meantime, the monitoring of resource waste and environmental pollution in the process of agricultural production should be strengthened, and the efforts of agricultural environmental regulation should be increased to achieve harmony between agricultural production and the ecological environment. These initiatives are equally applicable to other areas with low APE.

Thirdly, due to the inter-regional differences, spatial correlation, and convergence, governments in the regions should consider the dependence and differences with the agricultural production of neighboring regions while focusing on their own agricultural quality and efficiency improvements. The similarity between neighboring regions in terms of location conditions, resource endowment, and agricultural infrastructure, and the free flow of factors such as labor, capital, technology, and information require that neighboring regions should strengthen cooperation and exchange in agricultural production and establish cross-regional mechanisms for cooperation in agricultural production and ecological policies, and to do so in accordance with local conditions. Inter-regional agricultural production is hardly unique, and considering the inter-regional differences in APE, regions with higher APE should play the leading role and improve their exchanges with other regions in terms of management experience and technological progress. Regions with lower APE need to actively learn the agricultural development methods of neighboring regions with higher APE according to their own endowment conditions and upgrading strength, and the introduction of technology, talents, and capital should be strengthened to narrow the APE gap between regions. In view of the similar climatic characteristics and endowment conditions between neighboring regions, local governments should not only focus on improving their own quality and efficiency, but also seek a balanced point between agricultural production, climate change, and the resource environment through joint prevention and control, to achieve the win-win goal of improving APE and protecting the farmland ecological environment, and, ultimately, realize clean and efficient modern agricultural production. In addition, the patterns of APE changes in China could also shed light on agricultural production in other parts of the world.

6. Conclusions

Based on the long-period panel data for 30 provinces in mainland China from 1978 to 2018, this study re-estimated APE considering the dual constraints of climate change and resource environment. The spatiotemporal evolution and imbalanced spatial pattern of APE were analyzed using KDE, SDE, and COG transfer models. Then, the spatial convergence and divergence properties of APE were tested using spatial *β-convergence*. The main conclusions are as follows.

(1) Under the dual constraints, APE showed a stable upward trend with fluctuation (mainly between 1978 and 2000), but still at a low level overall with much room for improvement. Region-wise, the northeastern region had the highest APE and higher growth than the central and western regions. However, the gap was narrowing between the central and western regions and other regions. The APE evolution in China showed a bimodal distribution with a narrowing gap between the heights of the two peaks, i.e., no manifestation of polarization. The intra-regional differences widened and then narrowed, while the spatiotemporal evolution characteristics were different among different regions.

(2) Under the dual constraints, the COG of APE transferred to the northeast, and the transfer path was with fluctuations. In the east-west direction, the transfer was eastward, and in the north-south direction, the transfer was northward, showing a northeast to southwest spatial pattern overall. The distance and speed of COG transfer showed the trend of increase, decrease, and slight increase. The changes in the SDE of APE were similar to those of COG transfer. The ellipse gradually shifted to the northeast and resembled less and less of a circle. The major axis was in the north-south direction and expanded, the minor axis was in the east-west direction and contracted, and the ellipse covered a gradually decreasing area. The spatial

distribution of APE tended to be unbalanced in the east-west direction and tended to cluster in the north-south direction towards the east by north.

(3) Under the dual constraints, APE showed significant spatial convergence characteristics. The gap between regions was narrowing, and the trend of latecomer catching-up was significant in the low APE regions. The spatial effect accelerated the convergence rate of APE and shortened the convergence period of APE to its own steady-state. The convergence rates of different regions showed a decreasing distribution pattern from the central and western regions, the northeastern region, and the eastern region. The latecomer advantage of the central and western regions was significant, and the marginal decreasing effect reduced the convergence rate of the eastern and northeastern regions. The APE convergence rates in different time periods had a phase change, which corresponded to the distance and speed of COG transfer.

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Appendix A

Table A1. The parameters of COG and SDE of APE over the years.

Year	Longitude	Latitude	Long Axis /km	Short Axis /km	Azimuth /°	Year	Longitude	Latitude	Long Axis /km	Short Axis /km	Azimuth /°
1978	111.535° E	33.585° N	1189.957	1119.570	37.332	1999	112.391° E	34.509° N	1288.511	1049.231	30.325
1979	111.685° E	34.000° N	1277.166	1106.806	29.136	2000	111.213° E	33.852° N	1201.468	1103.839	19.163
1980	110.440° E	33.486° N	1269.357	1039.668	20.306	2001	111.925° E	34.325° N	1263.521	1072.065	29.244
1981	109.877° E	32.995° N	1143.208	1107.513	162.067	2002	111.737° E	34.371° N	1201.798	1105.617	35.226
1982	110.409° E	32.784° N	1052.511	1189.965	127.606	2003	111.640° E	34.372° N	1196.798	1091.650	39.032
1983	111.459° E	33.478° N	1268.881	1043.088	29.592	2004	111.637° E	34.309° N	1230.335	1104.477	33.034
1984	111.980° E	33.256° N	1119.422	1205.095	45.822	2005	111.879° E	34.309° N	1243.058	1042.393	29.978
1985	110.986° E	33.867° N	1137.822	1168.365	70.922	2006	112.410° E	34.444° N	1211.414	1049.260	29.597
1986	110.994° E	34.360° N	1158.674	1258.521	65.915	2007	112.274° E	34.163° N	1212.941	1031.826	28.170
1987	111.350° E	34.545° N	1351.720	1186.664	42.190	2008	112.135° E	34.313° N	1190.063	1052.301	35.479
1988	111.856° E	34.198° N	1281.600	1066.620	32.887	2009	111.731° E	34.522° N	1093.920	1158.506	50.044
1989	110.192° E	33.874° N	1109.052	1143.374	110.831	2010	112.278° E	34.982° N	1098.534	1215.464	48.381
1990	112.448° E	34.584° N	1330.760	1047.468	33.788	2011	112.269° E	34.480° N	1225.036	1070.668	29.626
1991	111.419° E	34.027° N	1266.883	1080.622	35.929	2012	112.247° E	34.212° N	1194.298	1064.534	35.238
1992	111.652° E	34.909° N	1337.862	1163.769	35.952	2013	112.578° E	34.679° N	1201.527	1054.815	37.020
1993	112.123° E	34.842° N	1294.073	1041.915	30.518	2014	112.500° E	34.454° N	1167.115	1048.558	36.218
1994	111.343° E	34.715° N	1286.685	1181.106	44.819	2015	112.466° E	34.140° N	1151.643	1034.807	31.474
1995	111.839° E	34.190° N	1285.051	1103.894	33.101	2016	112.547° E	34.133° N	1161.895	1025.265	29.622
1996	111.977° E	34.390° N	1291.400	1058.160	28.940	2017	112.594° E	34.124° N	1182.481	1020.793	31.263
1997	111.461° E	33.896° N	1217.814	1111.495	30.206	2018	112.641° E	34.114° N	1202.703	1016.121	32.436
1998	111.591° E	34.491° N	1260.227	1122.895	35.804						

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E-commerce Adoption and Technical Efficiency of Wheat Production in China

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Abstract: Improving technical efficiency (TE) is crucial for the sustainable growth of smallholder agriculture in developing countries. While there has been a large literature investigating the determinants of smallholders' agricultural technical efficiency, little is known about the effect of e-commerce on agriculture and crop production efficiency despite the growing importance of rural e-commerce in developing countries. This study, therefore, bridges the research gap by examining the impact of e-commerce adoption on TE using household survey data of wheat farmers in China. We employ the combination of propensity score matching (PSM) and a selectivity-corrected stochastic production frontier model to address the possible selection biases stemming from both observable and unobservable factors. We found that e-commerce adoption would lead to a 2.75 per cent increase in the technical efficiency of wheat production. Our study also complements the existing research of rural e-commerce, which mainly focuses on the benefits of e-commerce from the perspective of market opportunity and farmers' welfare.

Keywords: e-commerce; ICT; technical efficiency; stochastic production frontier; propensity score matching; selection bias

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1. Introduction

Enhancing agricultural productivity and technical efficiency is widely perceived as a key strategy for sustainable rural advancement in developing countries, especially in China, where smallholder farmers make up 99% of the nation's total agricultural producers [1]. Technical efficiency is the effectiveness with which a given set of inputs is used to produce an output, which is often measured by the ratio of farmers' observed output to the maximum realizable output given the existing inputs [2–5]. However, smallholder farmers usually face multiple complex production and marketing challenges that hinder the technical efficiency of their agricultural production. For example, the high transaction costs of accessing inputs and output markets, the unavailability of modern technologies, and the limitations of farmers' skillsets are among some of the key constraints [6–12]. These, in turn, constrain farmers' optimal decision-making strategies, not only for their initial production decisions but also for harvesting, storage, and marketing decisions. As a result, the technical efficiency for smallholder farmers is relatively low in developing countries [11,13], posing challenges to their sustainable development in modern agriculture.

Improving technical efficiency has long been of interest by policymakers and scholars. While the scholarly interest in the technical efficiency of agricultural production can be dated back to the 1970s [14], it was not until the 1990s that the technical efficiency of agricultural production became a popular empirical research topic among agricultural economists [15]. In recent years, there has been a renewed interest in this topic, and a large number of empirical studies have emerged to understand the factors affecting agricultural production's technical efficiency [16–18].

The related literature has identified a broad range of factors that potentially influence the technical efficiency and productivity of agricultural production. These factors include government R&D spending on agricultural research [7,9,19], agricultural extension services and technical training [20,21], institutional and market reform [22–24], land tenure security and the functioning of land rental [6,25,26], agricultural cooperatives [16,20,21,27], the reduction of input costs due to the improvement of markets and/or bargaining power [28,29], and off-farm employment and migration [28–30]. A growing number of recent studies focus on the role of Information and Communication Technologies (ICTs) in agricultural production and technical efficiency. Overall, the adoption of ICTs (e.g., mobile phones and Internet) is found to be positively correlated with the improvement of technical efficiency [12,31,32].

Despite the large and active literature exploring factors affecting the technical efficiency of agricultural and crop production, there exists a considerable gap in the literature. More specifically, we are not aware of any study that investigates the possible effect of e-commerce on the technical efficiency on agricultural and crop production. We define e-commerce adoption as the enablement of farmers to participate in online trade, including both selling and buying, as is consistent with previous studies [33–35]. Recent years have witnessed that (1) e-commerce has rapidly emerged in the developing world, and (2) e-commerce is an important type of ICT focusing on digital transactions and mechanization. We posit that the adoption of e-commerce can potentially affect smallholder farmers' production efficiency. By directly matching and connecting buyers and sellers (especially those living in rural regions), via the Internet, e-commerce reduces transaction costs and facilitates the exchange of goods, services, information, and knowledge. The process improves their ability to access markets while greatly reducing the transaction costs [36,37], and thus may lead to potential changes in agricultural production and technical efficiency. Nevertheless, to the best of our knowledge, such potential is yet to be explored.

Therefore, we aim to fill the research gap by empirically exploring the impact of e-commerce adoption on the technical efficiency of crop production. Our research contributes to the existing literature in three ways: Firstly, we are the very first study to provide quantitative evidence of the impact of e-commerce on the technical efficiency of agricultural production. This is important, given that e-commerce is quicker than ever in changing rural societies and agriculture [38–40]. Secondly, our study further extends the existing literature exploring the roles of e-commerce in rural economic development. The existing research on rural e-commerce is typically based on cases or limited data from small sample surveys [36,39,41–43]. Of the few quantitative studies, most have delved into the impact of e-commerce adoption on farmers' welfare and household income growth, and few have investigated its effect on agricultural production [33,44,45]. Thirdly, we employ an empirical method that corrects for self-selectivity biases arising from both observable and unobservable factors. Specifically, we use the propensity score matching method to address the selection bias arising from the observed factors and the selectivity-corrected stochastic frontier approach developed by Green to address the selection bias arising from unobservable factors [19,20,46].

Our study focuses on the wheat crop because (1) China is the biggest wheat producer in the world, and (2) its productivity is relatively low. According to FAOSTAT, wheat yield in China was 5.48 tons/hectare in 2017, ranking only 20th globally. It is documented that there exists a considerable gap between the actual yield and the yield potential in China's wheat production [47,48]. Enhancing wheat's technical efficiency and productivity is, therefore, essential to ensure both food security and farmers' welfare. Using a micro dataset from rural households in top-tier wheat-producing provinces in China, we found that the adoption of e-commerce would increase the technical efficiency by approximately 2.75 per cent, which is in line with previous studies on ICTs.

This paper is organized as follows: Section 2 briefly recounts the background of China's rural e-commerce and introduces the background-based data collection procedure, followed by Section 3, the estimation strategy where we briefly introduce selectivity-corrected SPF model combined with propensity score matching. Section 4 reports the descriptive and empirical results with the discussion of relevant findings, and, finally, Section 5 concludes the article with policy implications and discusses the limitations and future research directions.

2. Background and Data Collection

2.1. Rapid Emergence of Rural E-commerce in China

Rural e-commerce in China has undergone a rapid development in the past decade. Overall, the value of rural online retail sales has increased from USD 27.99 billion in 2014 to USD 278.25 billion in 2020, accounting for 15.2% of the total national online retail sales, with a year-on-year growth exceeding 30% for six consecutive years since 2015. The total value of online agri-product retail sales topped USD 61.81 billion in 2019, with a year-on-year growth of 27%, which is 10.5% higher than the average growth rate of national online retail sales [49]. The rapid development of rural e-commerce in the past decades has been gaining increasing recognition internationally for its potential in promoting the rural economy in developing countries [40]. Over the years, the government has steadily funded the construction of Information and Communication Technologies (ICTs) infrastructures in the rural regions, which has provided a solid ground for e-commerce development. Consequently, the netizen population is booming, and the trade values of e-commerce in agri-sectors have multiplied in the past decade [50].

Major ICT companies in China, such as Alibaba, Tencent, and Jingdong, have provided abundant business opportunities and employment for rural residents. Through e-commerce, millions of farmers do business online regardless of their remote residency [39,51], which has innovated the agricultural supply chain [34,52] and improved rural societies in various facets [38,53,54]. Naturally, it has attracted increasing scholarly attention worldwide, as China is not alone when it comes to rural e-commerce development. Around the world, an inspiring phenomenon has occurred in developing countries such as India, Vietnam, and Kenya, where rural e-commerce is used to promote local rural societies and agriculture [55–58]. The experience China has to offer is needed more than ever, as it is potentially beneficial to other developing countries.

Taobao village is a typical phenomenon fostered by China's rapid rural e-commerce growth [43,51,54]. It is an administrative village with a total annual e-commerce trade value exceeding USD 1.56 million (CNY 10.00 million). To be considered as a Taobao village, a village also needs to fulfil one of the two following requirements: (1) the village has at least 100 operational e-commerce adopters; or (2) 10% of the total households in a village are e-commerce adopters [59]. Regarding the above qualitative and quantitative requirements, it is clear that Taobao Village, which reaches some scale in the number of online sales and stores, is an aggregation of e-commercial sellers in rural areas. The number of Taobao villages has drastically increased from only 3 in 2009 to over 5425 in 2020, multiplied over a thousand-fold in a single decade. Together, these Taobao villages have achieved a combined annual online retail sales of over USD 157.12 billion (CNY one trillion), creating over 28 million jobs [59].

2.2. E-commerce and Technical Efficiency

The rapid emergence of rural e-commerce not only changed the way rural residents conduct business but is also likely to have impacts on smallholder farmers' production decisions and efficiency. The adoption of e-commerce by rural farmers may improve the technical efficiency of crop production for several possible reasons. First, e-commerce may improve farmers' productivity, as conducting business online incentivize farmers to learn and utilize ICTs. This process enables them to better infuse new and better technologies and is widely observed to be positively associated with productivity and efficiency growth [12,31,60]. Second, e-commerce may lower the costs of farmers in acquiring different inputs (e.g., fertilizers, and pesticides). Adopting e-commerce enables farmers to access online input markets (where prices are usually lower than those of traditional markets because of the lower costs associated with online transactions), with a corresponding direct impact on farm revenue and overall performance [61–64]. Third, e-commerce may facilitate the efficient use of labour. While e-commerce significantly reduces transaction costs, less labour is needed to conduct the transaction as sellers (farmers) and buyers (customers) are matched online. It helps reallocate labour within a rural household in a more efficient way [54,65,66]. Fourth, e-commerce may help farmers to better adjust their production strategy. As e-commerce can directly match buyers and sellers online, it enables farmers to quickly and timely capture the changes of markets and adjust their production strategy to suit the demand [37,38]. It is also widely observed that e-commerce adopters have a higher income than their non-adopter counterparts [33,35,64]. A higher income may alleviate the credit constraint, which is also a key barrier to efficiency improvement [67,68].

For these reasons, e-commerce adoption may ultimately affect farmers' production behaviours on how to invest and utilize different inputs as well as their productivity, and thus the potential of enhancing the technical efficiency of crop production.

3. Materials and Methods

3.1. Data Collection

Based on the distribution of Taobao villages, we collected the data using a multistage sampling procedure. Between April and July 2018, we conducted a comprehensive survey of rural households in China. In the first stage, we selected three provinces that are famous for their rural e-commerce development, namely Jiangsu, Shandong, and Zhejiang. These three provinces have the most Taobao Villages in China. For example, Zhejiang province has 1573 Taobao villages in 2019, whereas Jiangsu has 615 and Shandong 450. When combined, these three provinces account for over 61.21% of Taobao villages nationwide [59]. In the second stage, we chose one county within each selected province, which included Cao county in Shandong, Shuyang county in Jiangsu, and Lin'an county in Zhejiang. These counties were among the very first adopters of rural e-commerce in China, and are widely perceived as the most representative with regard to rural e-commerce. In the third stage, we randomly selected 8 Taobao villages and 8 non-Taobao villages from each selected county. In each Taobao village, we randomly interviewed 10 households that operate e-commerce businesses and 10 households that do not as a control group. In each non-Taobao village, we randomly interviewed about 20 households, regardless of whether they operated an e-commerce business. Given that our aim was to study the effect of rural e-commerce on the technical efficiency of wheat production, we naturally limited our sample to wheat producers. As a result, we obtained a sample size of 371 wheat producers, among which 105 were e-commerce adopters and 266 non-adopters.

We followed the relevant literature to carefully select the variables used in the study [35,36,69]. Specifically, e-commerce adoption was defined as a dummy variable that equals 1 if a rural household participated in e-commerce business in 2017, and 0 otherwise [33,35]. The questionnaire was adjusted and modified multiple times during several pre-tests to better suit the academic needs and reflect reality. The final version of the questionnaire included various household characteristics (e.g., cultivated land size, household size), household head characteristics (e.g., age, gender, education level), agricultural production variables (e.g., seedling, fertilizers, pesticides, and labour), and other related variables (e.g., household's access to the Internet).

We trained our numerators carefully to better carry out the structured surveys. The necessary ethical procedures were strictly followed during the entire survey to ensure our respondents' confidentiality and data privity. All surveys were conducted on a face-to-face basis with either the household head or, on the rare occasions when he/she was absent, another household member who had a good knowledge of the production and market decisions of the household. Cross-sectional data of the year 2017 were employed in our study, as it was the year before the interview and farmers recalled the situation quite well.

3.2. Empirical Specification

There are two common practices when estimating the technical efficiency of crop production: non-parametric methodologies such as data envelope analysis (DEA) [70] and parametric methodologies such as the stochastic production frontier (SPF) [12,21,31]. In this study, we employ the SPF model for the following reasons: first, we are interested in capturing the production effect of various inputs on wheat output. This requires the model to be parametric, which is in stark contrast to the non-parametric DEA. Second, random errors are crucial in our calculation, as the efficiency of wheat production is sensible to not only inefficiency terms but also random errors (e.g., unpredictable conditions like weather). This can be addressed by the SPF that assumes a random error, while DEA does not. Therefore, our study is based on the SPF method.

The objective of this study is to investigate the impact of e-commerce adoption on technical efficiency, evidenced by smallholder wheat farmers in China. As analysed above, farmers self-identify as either e-commerce adopters or non-adopters, which has caused a potential selectivity bias. Learning from the previous literature, we took into account such bias and employed the selectivity-corrected stochastic production frontier (SPF) model, combined with propensity score matching (PSM), to address the issue [18–20,46].

3.2.1. Stochastic Production Frontier Model (SPF)

As the farmers in our sample are exclusively either e-commerce adopters or non-adopters, following the initial SPF proposed by Aigner, Lovell, and Schmidt [71], the SPF model is specified as follows:

$$Y_i = f(Z_i, E_i) + e_i,\ with\ e_i = v_i - \mu_i \tag{1}$$

where Y_i is the wheat output of the farmer i; Z_i is a vector of variables representing different inputs (e.g., fertilizers, pesticides); E_i is the binary variable that depicts the e-commerce adoption status of farmers (1 = e-commerce adopters; 0 = non-adopters); e_i is an error term, which is composed of $v_i \sim N\left(0, \sigma_v^2\right)$, an asymmetric stochastic term capturing statistical noise, and $\mu_i \sim N^+\left(0, \sigma_v^2\right)$, a half-normal stochastic term that accounts for inefficiency in wheat production.

We then proceeded to estimate the production function based on the likelihood ratio test. The Cobb–Douglas function is used, as it is in line with the test and fits the nature of wheat production. Following Anang [72], we estimated the production frontier as follows:

$$ln(Y_i) = \beta_0 + \sum_{j=1}^{6} \beta_j lnZ + \varphi_i M_i + w_i \tag{2}$$

where ln represents a natural logarithm; Y_i represents the wheat output of the i-th farmer; Z_i denotes a vector of production input variables. In particular, the output variable is defined as the gross revenue from production per mu (1 mu = 1/15 ha). Inputs are aggregated into five major categories including expenditure on seedlings, fertilizers, pesticides, family labours, and hired labours; β_j and φ_i are parameters to be estimated; and w_i is an uncorrelated random error that has a normal distribution.

We then calculate the technical efficiency score of wheat [19,72].

$$TE_i^E = \frac{Y_i}{Y_{i*}} = \frac{Y_i}{e^{f(z_i,\beta)+v_i}} \tag{3}$$

where TE_i^E represents the TE score of farmer i growing wheat, Y_i is the actual wheat output, Y_{i*} is the maximum output possible when all inputs Z_i were used in the most efficient ways. As indicated in Equation (3), the efficiency of the i-th farmer is 1 when the error term is 0. That is, if e-commerce adopters can obtain a higher wheat output (Y_i) given existing inputs (Z_i), they may have a higher technical efficiency score than non-adopters.

3.2.2. Addressing Selection Bias

Based on the utility maximization framework, we depicted farmers' choices to adopt e-commerce or not in a binary sample selection model as follows:

$$E_i^* = \alpha X_i + \varepsilon_i,\ where\ E_i = \begin{cases} 1,\ if\ U_i^e - U_i^{e*} > 0 \\ 0,\ otherwise \end{cases} \tag{4}$$

where E_i represents a binary variable that equals 1 for e-commerce adopters and 0 for non-adopters; X_i refers to the set of explanatory variables which affect farmers' decision to adopt e-commerce (e.g., internet accessibility, various household characteristics); α is the set of estimated parameters; ε_i is the error term; U_i^e represents the expected utility farmer *i* adopting e-commerce, whereas U_i^{e*} *is* the expected utility farmer *i* not adopting e-commerce. It is obvious that a farmer *i* only adopts e-commerce when the expected utility gain $U_i^e - U_i^{e*}$ is positive.

As farmers identify themselves as being either e-commerce adopters or non-adopters, some of the factors determining adoption in e-commerce are likely to influence efficiency as well. Such is the presence of selection bias, which is caused by both observed (e.g., age, education of household head) and unobserved factors (e.g., farmer's openness to new technologies) simultaneously.

Learning from similar literature [18,19,73], we introduced propensity score matching (PSM) to control bias stemming from observed factors. PSM enabled us to match farmers who adopted e-commerce and those who did not on observed characteristics. In the PSM estimation framework, Equation (4) can be estimated using a binary choice model (a Logit model in this study) to generate a propensity score for each farmer in the sample. Depending on the propensity scores, the PSM approach matches e-commerce adopters and non-adopters who are similar in observed characteristics X_i to address the potential selectivity effects arising from observable factors. In the selection of matching techniques, we learned from the past literature and employed the nearest-neighbour matching technique, as it is a commonly used method to efficiently reduce bias from observed factors [74–76]. We matched every adopter with four neighbours with a calliper of 0.01. We also allowed for a replacement so as to reduce the omission of sample sizes. The technique generated 344 matched samples in total, with 90 e-commerce adopters and 254 non-adopters. Overall, each adopter had two to three non-adopters in comparison.

To control bias stemming from unobserved factors, we learned from Greene and implemented a selectivity-corrected SPF model [46]. This model assumes that the unobserved factors in the selection equation are correlated with the error term in the stochastic frontier model. It is, therefore, a significant improvement over Heckman's self-selection specification for the linear regression model [77]. Specifically, this model has the following error structure:

$$\begin{aligned} \mu_i = \left|\sigma_\mu U_i\right| &= \sigma_\mu |U_i|,\ where\ U_i \sim N(0,1) \\ v_i = \left|\sigma_v V_i\right| &= \sigma_v V_i,\ where\ V_i \sim N(0,1) \\ (\mu_i, v_i) &\sim N_2\left[(0,1), \left(1, \rho_{\mu,v}\sigma_v, \sigma_v^2\right)\right] \end{aligned} \tag{5}$$

As shown in Equation (5), the error term in Equation (1) is correlated with that in Equation (4), which lays out the basic assumption of the selectivity-corrected SPF model. It is to be noted that the correlation coefficient between the two error terms of Equation (1) and Equation (4), namely $\rho_{\mu,v}$, represent the possible selection bias from unobserved factors [19,46]. That is, an insignificant $\rho_{\mu,v}$ would suggest that there exists no selection bias stemming from unobserved factors. We then proceeded to estimate the parameters of the selectivity-corrected SPF model following Greene by using a conventional gradient-based Broyden–Fletcher–Goldfarb-Shanno (BFGs) method and used the BHHH estimator to obtain the asymptotic standard errors [46].

3.2.3. Different Production Frontiers for E-commerce Adopters and Non-Adopters

The calculation of Equation (3) relies on the underlying assumption that all farmers have access to the same technology and share the same production frontier. However, with access to the internet and various online services, including training programmes for new technologies, e-commerce adopters may grow wheat with a different production frontier than that of non-adopters. In light of this, we need to identify whether the SPF estimation should be run for the whole sample or if separate frontiers are necessary for e-commerce adopters and non-adopters [19]. This can be achieved by a likelihood ratio test between the two groups of farmers [75]. Specifically, the estimated likelihood ratio (LR) can be estimated as follows:

$$LR = -2\big(lnL_p - (lnL_m + lnL_{nm})\big) \quad (6)$$

where lnL_p, lnL_m, and lnL_{nm} represent the log-likelihood function values obtained from the SPF model for the pooled sample, two separate SPFs models for e-commerce adopters and non-adopters, respectively. The null hypothesis is that the two groups have the same technology in wheat production. If such hypothesis is rejected, we need to respectively estimate the parameters for two groups of wheat farmers as they have different production frontiers [46], expressed as follows:

E-commerce adopters:

$$ln(Y_i) \ = \eta_0 + \sum_{j=1}^{6} \eta_j lnX + (1-\phi)\varphi_i\rho_i + \tau_i \quad (7)$$

Non-adopters:

$$ln(Y_i) \ = \xi_0 + \sum_{j=1}^{6} \xi_j lnX + (1-\phi)\varsigma_i\rho_i + \omega_i \quad (8)$$

where Y_i and X_i are defined as previously; ρ_i refers to the selectivity-correction term, which is calculated based on the propensity scores matching as mentioned above; η_0 and ξ_0 are constant terms; φ_i, ς_i, η_j, and ξ_j are parameters to be estimated; τ_i and ω_i are random errors.

We can, therefore, calculate the technical efficiency scores following these steps. First, we estimated a pooled SPF estimation that includes a dummy variable representing e-commerce adoption. Second, we estimated two separate SPF models, one for e-commerce adopters and another for non-adopters. Third, we performed a likelihood ratio test to examine if there were technical differences. Forth, where such differences were present, we respectively estimated the two production frontiers for both adopters and non-adopters. And fifth, we calculated the technical efficiency scores for both adopters and non-adopters, using matched and unmatched samples, respectively, and drew conclusions therefrom.

4. Results

4.1. Descriptive Results

We present descriptive statistics for the variables in Table 1. Following the previous literature exploring the causes and impacts of e-commerce, we modelled the sample selection equation (i.e., determinants of rural e-commerce adoption) as a function of both household heads' characteristics (e.g., age, gender, education level, health status) and household characteristics (e.g., household size, cultivated land size, the availability of high-speed internet and mobile phones) [33,35,36]. For the stochastic production frontier function, we modelled the wheat output per unit of land as a function of the four main categories of inputs (e.g., labour, seedlings, fertilizers, and pesticides) [60,78]. Land was not necessary because the dependent variable was wheat production per unit of land (i.e., yield) instead of the total wheat production of the household. A detailed description of the selected variables is presented in Table 1.

Table 1. Variable definition and summaries.

Variables	Descriptions	Mean (S.D.)
	Variables used in sample selection equations	
E-commerce	1 if household operates an online e-commerce business, 0 otherwise	0.28
Age	Age of household head in years	45.96 (12.37)
Gender	1 if household head is male, 0 otherwise	0.98 (0.15)
Education	Total years of education received of the household head	7.63 (3.51)
Health	Self-reported health status of household head, ranging from 1 = very bad to 5 = very well	4.52 (0.99)
Cadre	1 if household head is a village cadre, 0 otherwise	0.08 (0.28)
Household Size	Number of residents in the household	4.60 (1.61)
Access to Internet	1 if household has access to high-speed internet, 0 otherwise	0.73 (0.45)
Land Size	Cultivated land size of household in hectares	0.61 (2.48)
Phone	Numbers of mobile phones owned by household	3.08 (1.39)
	Variables used in production frontier models	
Output	The yield of wheat output (100 kg per hectare)	67.05 (13.35)
Seedlings	Expenditure on seedlings (100 USD per hectare)	0.40 (0.10)
Fertilizers	Expenditure on fertilizers (100 USD per hectare)	0.88 (0.28)
Pesticides	Expenditure on pesticides (100 USD per hectare)	0.20 (0.11)
Family Labour	Numbers of family labour input (days per hectare)	302.40 (272.40)
Hired Labour	Expenditure on hired labours (100 USD per hectare)	0.60 (0.20)

We present the mean differences of inputs and output variables used to estimate the production frontier models in Table 2. We express both the inputs and output variables in natural logarithms, as this is the functional form in the estimation of the Cobb–Douglas stochastic production frontier model [19,79]. To correct issues of zero values for certain input variables (e.g., some farmers do not hire labour in their smallholder production), we followed the literature and employed a dummy variable technique [80]. As shown below, the wheat yield of e-commerce adopters was generally higher than that of non-adopters. Several input variables, including seedlings, fertilizers, and pesticides, also exhibited differences between these two groups. While the information on the level of output and input reported in the descriptive table is informative, the higher yield of adopters compared to non-adopters does not necessarily mean that the productivity or technical efficiency is higher for adopters than non-adopters because yield is affected by input use. We will need to rely on the econometrics analysis to separate the effects of e-commerce on technical efficiency from other confounding effects, including the input effects and selection effects caused by unobservables, which is the focus of the next section.

Table 2. Mean differences of variables used in the SPF models.

Variables	Adopters	Non-Adopters	Diff.
Wheat Output (ln)	5.39 (0.02)	5.34 (0.02)	0.05 *
Seedlings (ln)	3.46 (0.03)	3.55 (0.02)	−0.09 **
Fertilizers (ln)	4.22 (0.05)	4.30 (0.02)	−0.09 *
Pesticides (ln)	2.73 (0.10)	2.71 (0.05)	0.18 *
Hired Labour (ln)	3.84 (0.05)	3.91 (0.03)	−0.07
Family Labour (ln)	1.78 (0.11)	1.74 (0.07)	0.04
Sample size	266	105	371

Standard errors are presented in parentheses. ** $p < 0.05$; * $p < 0.1$.

4.2. Empirical Results

4.2.1. Matching

As discussed above, we used propensity score matching to control selection bias stemming from observed factors [74–76]. A four-nearest-neighbour replaceable matching with a calliper of 0.01 is employed in our study. In doing so, we first estimate a logit model to identify factors affecting farmers' e-commerce adoption, and the results are reported in Table 3.

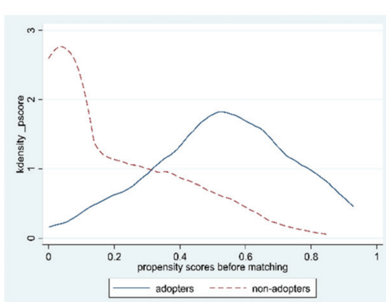
Table 3. Factors concerning e-commerce adoption using Logit regression.

Variables	Unmatched	Matched
Age	−0.084 *** (0.016)	−0.046 *** (0.009)
Gender	−3.102 ** (1.297)	−1.636 ** (0.681)
Education	0.124 ** (0.050)	0.077 ** (0.028)
Health	0.221 (0.213)	0.116 (0.117)
Cadre	−0.695 (0.655)	−0.487 (0.376)
Household Size	0.050 (0.129)	0.046 (0.074)
Access to Internet	3.374 *** (1.049)	1.559 *** (0.403)
Land Size	−0.025 (0.028)	−0.017 (0.019)
Phone	0.420 *** (0.152)	0.231 * (0.084)
Constant	−0.428 (2.128)	−0.155 (1.153)
Sample size	371	344

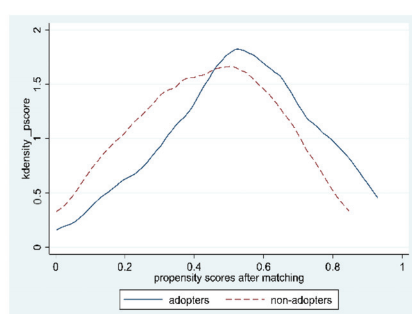
Standard errors are presented in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

There are several interesting findings regarding what drives farmers' willingness to e-commerce adoption (Table 3). For example, age, gender, and education level of the household head are important factors, as these are found to be significantly correlated with the farmer's decision to adopt e-commerce. Generally, a younger, male household head with a longer education is more likely to participate in e-commerce. Moreover, the local ICT infrastructure is very important, as households' access to the high-speed internet and mobile phones are also crucial factors. When combined, these results yield, as they reveal what factors affect the adoption of e-commerce, and this not only resonates with the existing literature [33,35] but also yields important insights for both scholars and policymakers.

A key assumption underlying the validity of PSM is the balance of matching variables between the treated and the control group after the matching [81,82]. We therefore employed a balancing test to check how the matching process fulfilled the balancing objective. The results of the balancing test are given in Table 4 and Figure 1.



(**a**)



(**b**)

Figure 1. Propensity scores before (**a**) and after (**b**) matching.

Table 4. Mean difference of variables used in the sample selection.

Variables		Mean		Bias(%)	Reduced Bias(%)	*t*-Test	
		Adopters	Non-Adopters			Statistic	*p*-Value
Age	Unmatched	41.48	53.31	−106.2	86.1	−9.18	0.000
	Matched	42.16	43.81	−14.8		−1.05	0.294
Gender	Unmatched	0.97	0.98	−3.8	100.0	−0.34	0.735
	Matched	1.00	1.00	0.0		-	-
Education	Unmatched	9.02	7.08	59.5	96.7	4.95	0.000
	Matched	8.72	8.79	−2.0		−0.16	0.871
Health	Unmatched	4.85	4.38	54.3	98.8	4.22	0.000
	Matched	4.84	4.84	0.6		0.06	0.955
Cadre	Unmatched	0.03	0.10	−25.0	78.1	−1.99	0.047
	Matched	0.04	0.03	5.5		0.49	0.626
Household Size	Unmatched	4.97	4.45	33.9	57.6	2.85	0.005
	Matched	4.94	5.17	−14.4		−1.09	0.277
Access to Internet	Unmatched	0.99	0.62	106.4	97.8	7.80	0.000
	Matched	0.99	0.98	2.4		0.45	0.651
Land Size	Unmatched	0.33	0.72	−18.7	94.2	−1.36	0.176
	Matched	0.33	0.35	−1.1		−0.61	0.541
Phone	Unmatched	3.49	2.92	40.9	36.7	3.57	0.000
	Matched	3.37	3.72	−25.9		−1.82	0.070

As seen in Table 4, the matching has significantly improved the balance of variables between e-commerce adopters and non-adopters. The differences between major variables are mostly reduced to 10 per cent, indicating a fitting matching that accomplishes the balancing condition of the covariates [83]. Furthermore, while the mean difference between the treatment and control groups is statistically significant at 1% for seven variables before matching, all the variables are insignificant except for the head's health, which is significant at 10% after matching, suggesting that the quality of matching is high. Figure 1 presents in a more direct way the density of the common support region between adopters and non-adopters before and after matching. Panel (a) shows a large common support of propensity scores between the adopters and non-adopters. Except at the end of the right tail (score > 0.9), there are overlapping scores between adopters and non-adopters. The large common support region is another criterion for matching quality. Panel (b) shows the propensity scores for the treatment and control groups based on the matched sample. It is not surprising that the common support covers the entire region of the propensity scores and that the score distributions are almost the same between the adopters and non-adopters. With a satisfactory matching quality, we estimate Greene's selectivity-correction term using the calculated propensity scores and apply it in the stochastic frontier model [46].

4.2.2. Production Frontier Estimates

We employed the Cobb–Douglas stochastic frontiers using the inputs and output variables that are measured by the natural logarithm [46,72]. In doing so, we first performed a likelihood ratio test to examine if the technology differences between e-commerce adopters and non-adopters were significant [19]. This test was estimated based on Equation (6), which resulted in a likelihood ratio test statistic of 65.32 ($p = 0.000$). Therefore, we proceeded to separately estimate the frontiers for each group, as this would provide us with more accurate results. Based on Equations (7) and (8), we conducted the maximum likelihood estimates of the conventional and selectivity-corrected SPF using the matched samples and present the results in Table 5. We also present the results based on the unmatched samples in Table A1 for comparison.

Table 5. Parameter estimates for both the conventional and selectivity-corrected SPF models for matched samples.

Variables	Conventional SPF			Selectivity-Corrected SPF		
	Pooled	Adopters	Non-Adopters	Pooled	Adopters	Non-Adopters
E-commerce	0.630 *** (0.183)			0.803 *** (0.157)		
Seedlings (ln)	0.074 ** (0.242)	0.049 ** (0.256)	0.079 * (0.315)	0.063 ** (0.158)	0.050 ** (0.174)	0.070 * (0.374)
Fertilizers (ln)	0.052 * (0.189)	0.047 ** (0.134)	0.054 * (0.168)	0.050 ** (0.243)	0.037 ** (0.452)	0.059 * (0.217)
Pesticides (ln)	0.127 * (0.097)	0.112 ** (0.182)	0.135 (0.247)	0.176 * (0.109)	0.134 (0.168)	0.225 * (0.173)
Hired Labour (ln)	0.020 (0.068)	0.019 (0.030)	0.023 * (0.047)	0.023 (0.092)	0.020 (0.009)	0.028 (0.057)
Family Labour (ln)	0.061 (0.069)	0.083 (0.136)	0.052 * (0.162)	0.063 (0.031)	0.057 (0.124)	0.088 (0.063)
Constant	5.988 *** (0.156)	6.125 *** (0.187)	6.367 ** (0.321)	6.268 ** (0.261)	6.326 *** (0.339)	6.466 *** (0.331)
Log Likelihood	205.536	128.424	123.725	207.557	133.793	124.462
$\sigma(v)$	0.278 ***	0.265 ***	0.213 *	0.247 ***	0.246 ***	0.231 *
$\sigma(\mu)$	0.312 ***	0.332 ***	0.298 **	0.336 **	0.305 **	0.341 *
λ	8.874 ***	9.171 ***	7.253 *	8.613 **	8.972 **	8.423 *
Selectivity correction term (ρ)				−0.303 *** (0.088)	−0.273 *** (0.057)	−0.053 * (0.057)
Sample size	344	90	254	344	90	254

Standard errors are presented in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

The fact that the selectivity correction term (ρ) in both selectivity-corrected SPF models is significant indicates the presence of selection bias in the adoption of e-commerce. The conventional SPF model is, therefore, biased in the estimation. The selectivity-corrected SPF model with PSM in this study is justified [18–20,46]. However, for comparison reasons, we report the results from both the conventional and selectivity-corrected SPF models.

As seen in Table 5, the coefficient for the e-commerce adoption is positive and statistically significant in both the conventional and the selectivity-corrected SPF models based on all pooled samples. Our findings that the adoption of e-commerce has a positive and significant effect on wheat yield are in line with existing studies about the impact of ICTs on agricultural production and technical efficiency [12,31,60]. Regarding the traditional production inputs, we find that seedlings, fertilizers, and pesticides all contribute positively to wheat yield, as the coefficients of these three variables are positive and significant (albeit less consistent for pesticide) across both SPF models in all groups of samples. These three factors have the potential of contributing to higher agricultural production, since the adoption of e-commerce reduces the input costs for seedlings and fertilizers as indicated in Table 2. It is interesting to note that the labour inputs are not statistically significant in all the regressions, a result that is in line with other studies based on household survey data [27]. It suggests that labour is not a constraint for wheat farmers, which may be explained by the fact that rural labour in developing countries is usually surplus, whereas its marginal effect is low.

4.2.3. Technical Efficiency Scores

Based on the SPF models estimated above, we calculated the TE scores of wheat farmers from both the conventional and selectivity-corrected SPF models using matched samples, and present the results in Table 6. For a more comprehensive analysis, we also present the results using unmatched samples in Table A2.

Table 6. Technical efficiency levels.

	Pooled	Adopters	Non-Adopters	Diff.
Matched samples				
Conventional SPF (Pooled)	0.80 (0.07)	0.80 (0.00)	0.79 (0.01)	0.009
Conventional SPF (Separated)		0.79 (0.00)	0.77 (0.00)	0.021 ***
Selectivity-corrected SPF (Separated)		0.82 (0.00)	0.80 (0.00)	0.022 ***

Standard errors are presented in parentheses. *** $p < 0.01$.

When estimating using pooled samples, there are no significant differences between the TE scores of adopters and non-adopters. However, a previous analysis has demonstrated the existence of different technology and production frontiers for adopters and non-adopters, which suggests that we should estimate the SFP using separated samples. In doing so, we show that the TE scores of e-commerce adopters range from 0.79 to 0.82, and from 0.75 to 0.80 for non-adopters. Significant differences are observed regardless of the SPF specification and sample selection. To further address the selection bias, the estimates of the selectivity-corrected SPF models using matched samples were presented. This showed that the TE score of e-commerce adopters was about 0.82, and 0.80 for non-adopters. On average, e-commerce adopters and non-adopters could increase production by 18 per cent and 20 per cent using their current input quantities. The adoption of e-commerce increased the TE score by approximately 2.75 per cent.

Our results agree with previous studies on ICTs and TE improvement. For example, Zheng et al. discovered that internet adoption improves TE for banana farmers by 3.4 per cent [12], while Kelemu demonstrated that mobile phones improve TE for wheat farmers by 7 per cent [60]. In association with these studies, our findings reaffirm that the adoption of ICTs may improve TE for smallholder farmers. It is easily noted that in all separate models, e-commerce adopters have a higher level of TE score compared with that of non-adopters, and there exists a significant efficiency gap. The findings further confirm that e-commerce adopters and non-adopters perform differently in terms of technology adoption.

We also present the distribution of technical efficiency scores estimated by a selectivity-corrected SPF model for matched samples in Figure 2. A similar graph for unmatched samples is presented in Figure A1. Jointly, these two figures suggest a significant difference between the TE scores of e-commerce adopters and non-adopters. For example, about 70 per cent of adopters have a TE score between 0.71 and 0.90 when estimated using unmatched samples. This ratio increases to about 80 per cent when using matched samples, and similar increments occur with non-adopters. Altogether, they indicate that the technical efficiency level of adopters was higher than that of their counterparts in the median-high level, where their percentage of farmers was also larger. Hence, we provide a piece of evidence that the adoption of e-commerce does improve technical efficiency.

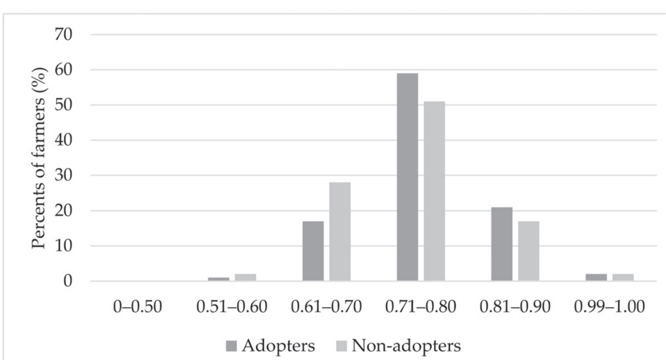


Figure 2. Efficiency level estimated by a selectivity-corrected SPF model for the matched samples.

5. Conclusions

Improving the technical efficiency of smallholder farmers is crucial for food security and rural development all across the world. While there are certain constraints to achieving this goal, recent years of ICT development and e-commerce adoption are generating new potentials. Although the world has witnessed the rapid development of rural e-commerce, little attention has been paid to understanding how e-commerce affects the technical efficiency of crop production for smallholder farmers. To bridge the research gap, this paper uses data collected from wheat farmers in China to estimate the impact of e-commerce adoption on crop technical efficiency. A matched group of e-commerce adopters and non-adopters is determined using a propensity score matching technique to address biases stemming from observed variables, whereas the selectivity-corrected stochastic frontier model is used to control bias stemming from unobservable factors.

The results reaffirm the presence of selection bias and justify the technique employed in this paper. An estimation from separate stochastic production frontiers reveals that technical efficiency is consistently higher for e-commerce adopters than that of their counterparts. Specifically, technical efficiency ranges from 0.79 to 0.82 for e-commerce adopters and from 0.75 to 0.80 for non-adopters depending on how biases were controlled. The differences between the two groups are coherently significant. After controlling for the selection bias stemming from both observable and unobservable factors, the average technical efficiencies for e-commerce adopters and non-adopters are found to be 0.82 and 0.80, respectively. The adoption of e-commerce improves 2.75 per cent of technical efficiency in wheat production.

There are several policy implications deriving from our results. Firstly, the finding of a positive relationship between e-commerce adoption and the technical efficiency of smallholder wheat farmers suggests that policymakers and administrative entities should put forth policy incentives to encourage smallholder farmers to adopt e-commerce for an increment in agricultural productivity. For example, government and extension services could provide farmers with training programmes to enhance farmers' understanding of the necessity and mechanism of e-commerce. Secondly, the finding that the farmers with higher education levels are more likely to adopt e-commerce indicates the importance of promoting education in rural societies, and hence the call for policy incentives for smallholder farmers to take longer, more intensive education. Thirdly, the finding that gender is crucial in the adoption of e-commerce, with a disproportionate favour for the male household head, has shown the importance to promote gender equality in rural development, as females should not be neglected in the process of technological inclusion and the benefits therein. Policymakers should use incentives to encourage more women to actively participate in the adoption of e-commerce as well as other ICTs. Finally, studies have shown that the ICT-related infrastructure, like communication networks, logistic systems, and high-speed internet construction play an important role in e-commerce development [33,35,69]. Our finding that e-commerce adoption improves wheat farmers' production efficiency offers additional support to government investment in rural infrastructure to encourage the development of e-commerce.

Nevertheless, there are certain limits in our study that require further scholarly attention. While our findings have provided some evidence that farmers' adoption of e-commerce is beneficial to the improvement of technical efficiency and crop production, we did not specify different models of rural e-commerce, which may be an important factor driving farmers' willingness to adopt e-commerce. Moreover, the data we employ are cross-sectional due to various limitations in data collection, mainly because the development of Chinese rural e-commerce was so fast in the past years and no existing large dataset had considered relevant variables beforehand. The unavailability of panel data is the main drive for the implementation of different methodologies. With the increasing scholarly attention on rural e-commerce, the availability of panel data is expected in the near future, and a more robust analysis will be in order.

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

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to interviewees' privacy protection.

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Appendix A

Table A1. Parameter estimates for both the conventional and selectivity-corrected SPF models for unmatched samples.

Variables	Conventional SPF			Selectivity-Corrected SPF		
	Pooled	Adopters	Non-Adopters	Pooled	Adopters	Non-Adopters
E-commerce	0.619 ***			0.821 ***		
	(0.165)			(0.154)		
Seedlings (ln)	0.067 *	0.045 **	0.082 *	0.057 **	0.047 **	0.068 **
	(0.216)	(0.278)	(0.315)	(0.186)	(0.168)	(0.352)
Fertilizers (ln)	0.058 *	0.049 **	0.065 *	0.049 **	0.038 *	0.057
	(0.188)	(0.330)	(0.212)	(0.254)	(0.425)	(0.214)
Pesticides (ln)	0.134 *	0.106 *	0.145	0.188 *	0.112	0.214 *
	(0.091)	(0.122)	(0.275)	(0.107)	(0.180)	(0.142)
Hired Labour (ln)	0.017	0.016	0.022 *	0.024	0.018	0.037
	(0.064)	(0.029)	(0.033)	(0.086)	(0.008)	(0.023)
Family Labour (ln)	0.058	0.088	0.048 *	0.078	0.056	0.104
	(0.066)	(0.109)	(0.124)	(0.082)	(0.126)	(0.036)
Constant	6.359 ***	6.983 ***	7.036 ***	6.832 ***	7.017 ***	7.264 ***
	(0.136)	(0.207)	(0.330)	(0.210)	(0.259)	(0.325)
Log Likelihood	232.406	136.322	125.625	227.323	124.438	109.436
$\sigma(v)$	0.241 ***	0.277 ***	0.203 *	0.234 ***	0.265 ***	0.267 **
$\sigma(\mu)$	0.336 ***	0.378 ***	0.302 *	0.302 ***	0.307 **	0.312 *
λ	8.109 ***	9.159 ***	7.287 *	8.242 ***	8.738 ***	7.963 *
Selectivity correction term (ρ)				−0.296 ***	−0.207 ***	−0.036 *
				(0.068)	(0.053)	(0.071)
Sample size	371	105	266	371	105	266

Standard errors are presented in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

Table A2. Technical efficiency levels for unmatched samples.

	Pooled	Adopters	Non-Adopters	Diff.
Unmatched samples				
Conventional SPF (Pooled)	0.80 (0.07)	0.80 (0.00)	0.79 (0.01)	0.008
Conventional SPF (Separated)		0.78 (0.00)	0.75 (0.00)	0.038 ***
Selectivity-corrected SPF (Separated)		0.79 (0.00)	0.76 (0.01)	0.027 ***

Standard errors are presented in parentheses. *** $p < 0.01$.

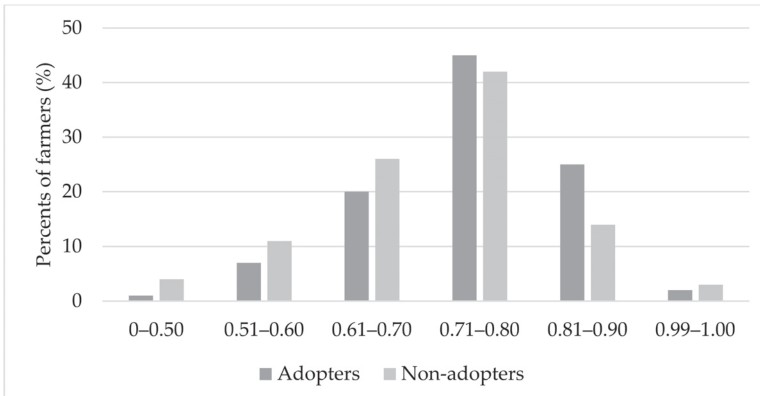

Figure A1. Efficiency levels estimated by selectivity-corrected SPF for the unmatched samples.

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Consumers' Benefit—Risk Perception on Pesticides and Food Safety—A Survey in Greece

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Abstract: Pesticides are widely used to protect agricultural products from pests and diseases. Although a strict regulatory framework exists in the EU, concerns about pesticide residues in food are retained among consumers. This study represents the first large sample (N = 1846) attempt to identify the main predictors influencing Greek consumers' attitude concerning the benefits—risks ratio of pesticide use. After a principal components analysis and a bivariate logistic regression were performed, it was found that Greek consumers express high concerns from pesticide residues in food regarding their loved ones and their own health. At the same time, however, they recognize to a significant extent beneficial contributions of the use of pesticides to food security and the national economy, as well. Several significant predictors of consumer's attitude towards benefit—risks perception of pesticide use was identified, concerning personal values, pesticide user status, gender, confidence in controlling and certification procedures, and received information. Our results suggest that efforts for risk communication are needed to address food safety issues targeting the general public.

Keywords: consumer's attitudes; pesticide residues; risk-benefit ratio; principal components analysis; logistic regression; cluster analysis

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1. Introduction

Pesticides are used in many areas of agriculture to improve yield and product quality [1]. The positive outcomes of the rational use of pesticides have been extensively reviewed by Cooper & Dobson (2007) [2], who pointed out that pesticides make our lives better, provided they are regulated and used in such a way that the benefits significantly outweigh the risks. The most featured contribution of pesticide use is the reduction of food losses due to crop pests and diseases [3–5], especially in developing countries where pre- and post-harvest losses have an impact on poverty and malnutrition [6,7].

The public health risks from dietary exposure to pesticide residues is highly controversial because the significance of their presence in the diet is difficult to evaluate [1,8]. Most of the studies related to the human health effects of pesticides deal with occupational exposure [9]. Nevertheless, concerns have been expressed about the potential negative effects of pesticides on the health of the general population via dietary exposure. Several studies have shown the neurotoxic [10] and cytotoxic effects [11] of pesticides and their activity in gene mutation, chromosomal damage, and DNA damage effects [12]. Population studies have revealed possible links between exposure to pesticides and severe health effects, including cardiovascular disease, negative effects on the male reproductive system and nervous system, dementia, a potential increased risk for non-Hodgkin's lymphoma [13], as well as a possible role in colorectal carcinoma etiology [14]. There is also suggestive evidence for pesticides increasing Parkinson's disease risk [15]. It has been shown that the dietary intake of pesticides represents the major source of exposure in urban/suburban young children and a great concern has been raised about the children's health because of their susceptibility to possible neurologic and neurodevelopmental effects [16–19]. Bourguet and Guillemaud (2016) [20] have argued that the cost of pesticide use has outreached the benefits. However, concern has been expressed that few of the health effects that have been associated with pesticides can be classified as causal [9]. In addition, concerns have been raised about the simultaneous presence of multiple pesticide residues in food [11,21]. However, Hernández and Lacasaña (2017) [22] concluded that synergisms at dietary exposure levels are rather rare and cannot be predicted quantitatively based on the toxicity of the mixture components. After the recently published retrospective cumulative risk assessments of dietary exposure to residues in 2014, 2015, and 2016 of pesticides that have acute effects on the nervous system [23] and chronic effects on the thyroid [24], the European Food Safety Authority has concluded that, with varying degrees of certainty, cumulative dietary exposure does not reach the threshold for regulatory consideration for all the European population groups examined. After all, research on the health benefits of fruit and vegetable consumption has demonstrated that they significantly outweigh the pesticide residues' estimated risks [25].

There is, therefore, still high uncertainty about the health effects of pesticides in research, and reliable information about pesticides and health can scarcely reach lay people [10]. Additionally, the role of pesticides in sustainable food production is barely discussed with the public [26]. Consequently, the ratio of risks versus the benefits of pesticide use will continue to be a matter of public concern, and the consumers' perceived risks will deviate from the estimations of Regulatory Authorities based on facts [2,27,28] and following specific risk assessment procedures [29]. It is, therefore, inevitable that pesticide residues in food generate high levels of perceived risks [30,31].

Perceived risk is a function of subjective uncertainty perceived by the consumer. Consumer risk perception tends to give greater weight to the perceived potential severity of unhealthy food than the probability of exposure [28]. It has been shown that consumers perceive relatively high risks associated with the consumption of conventionally grown agricultural produce, particularly pesticide-related risks [32]. Besides, health benefits are among the most important factors motivating the purchase of organic food products [33].

Yeung and Morris (2001) [28] stated that chemical hazards tend to be rated relatively high on the "unknown" factor because people view these as unnatural and unfamiliar. People very often attribute high risks to food products if they have less knowledge of chemical or technological processes. Individuals perceive greater control over biological food risks than chemical/technical risks [34]. The tolerance of risk is positively correlated with the perceived benefit; the bigger the benefit, the greater the willingness to take risk [28]. Perceived control and benefit perceptions are negatively associated with food safety risk perception. On the contrary, consumers who prefer natural food and those who are more concerned about their food perceive more food safety risks [35].

Risk perception and purchase behavior are causally linked: the former is an important explanatory variable of the latter. Some consumers are willing to pay marginally higher prices for quality assurance and, hence, reduced risk in food, especially during periods of safety concern [28]. Many studies have previously investigated the consumers' willingness to pay for pesticide-free products. It has been shown to be influenced by factors such as female gender, younger age, shopping at health food stores, as well as concern about pesticides, health, and sustainability issues [36–39].

Trust of the stakeholders [40] and the official Authorities and confidence in the safety of the food supply are significant predictors of the consumers' food safety risk perceptions [32,34]. In modern industrialized societies, people outside of the food production chain rely on institutional actors to protect the safety of their food, although the effect of trust on food risk concerns varies substantially across European countries [34]. Government agencies seem to lack credibility among consumers, and consumer confidence in the adequacy of government regulations on pesticide use has decreased dramatically [32,34,41]. Han et al. (2020) [42] have found that the monitoring of pesticide residues and control procedures significantly reduce people's negative perceptions of food safety. It has been suggested that risk communication efforts designed to educate consumers about food safety issues need to further include issues related to the credibility of regulatory procedures and information sources [32], as well as appropriate information dissemination systems, to bridge the gaps between regulators and the general public [42].

Harris et al. (2001) [43] stated that the perception of the risk of pesticide residues by consumers has always been affected by emotional input, which is something that possibly accounts for any exaggeration upon new information [9]. Risk perception of food is most commonly affected by cognitive processing of information provided by third parties and deliberations related to the individual's condition [44].

The media play a critical role in risk communication [45]. Effective risk communication should contain information on the nature of the risk and the benefits, uncertainties in risk management, and risk management options [46]. The consumers' attitudes and risk perceptions towards food safety are influenced by the media [34,47]. Risk amplification by the media has been thoroughly discussed in the literature [45]. Massive media coverage is more likely to heighten the perception of risk and demand for action to alleviate the perceived risk [28]. Food risks are often covered by the media according to factors that are more suited to the criteria for making the news than to the way in which experts rank food risks [48]. According to Kehagia & Chrysochou (2007) [49], Greek media are sensitive in uncovering a great deal of information about food hazards to the public. They concluded that the media coverage of food hazards considering pesticide residues in food were characterized by alarming content with a tendency to exaggerate the potential risk. On the contrary, exposure to media has been associated with better knowledge on the regulatory aspects of pesticides and, consequently, lower reported levels of perceived risks [50].

Consumer attitudes towards food safety differentiate according to sociodemographic factors [51]. Gender is a good predictor of risk perception. Females seem to perceive more food safety risks than males. Marriage status also increases the likelihood of concern [34,52,53]. The effect of children on food risk concerns may be significant [52] but not always [34,53]. Young, well-educated, and female urban residents perceived greater risks to food safety than other groups [42]. As education increases, respondents report significantly fewer concerns about biological risks, but greater concerns about chemical/technical risks [34].

Several previous studies have recorded the attitudes and perceptions of Greek consumers regarding the willingness to pay more money to buy safer food from brands that provide information. Karagianni et al. (2003) [54] have shown that consumers in Greece consider the absence of pesticide residues from the fruits and vegetables they purchase as a very important parameter. Females, as well as those who had knowledge of the HACCP certification system were more concerned about chemical residues. A high willingness to purchase certified fruits and vegetables has also been demonstrated [55]. Tsakiridou et al. (2006; 2008) [56,57] have shown that Greek consumers who are interested in chemical residues in food express a greater willingness to buy organically produced products. In addition,, it has been shown that both attitudes toward consuming safer food and the presence of traceability affect Greek consumers' willingness to buy certified food [58–61], with labeling acquiring special significance as a means of helping consumers assess the quality of food products [61–63]. Information is an important risk reliever. Consumers wish to acquire more information if there are uncertain outcomes for purchasing decisions, and product traceability has been a key issue in this respect [28].

Making the EU food supply chain "from farm to fork" more sustainable is at the heart of the European Green Deal. One of the main purposes of this fundamental shift in the EU food and agriculture policy is the targeted 50% reduction in the use and risk of chemical pesticides by 2030 [64,65]. As criticism regarding the strategy is not lacking concerning agricultural production, competitiveness and social welfare [66], there is a need for additional information on the general public's perceptions regarding pesticide use. The present work aimed to improve our knowledge about the Greek consumers' beliefs, the predictor variables associated with personal attitudes and views, as well as socioeconomic characteristics that might influence them, addressing the question of the ratio between the benefits of pesticides versus their potential risks. In this area, information on the general public's perceptions is scarce. In this respect, the research in this paper was undertaken aiming to answer the following research questions:

RQ1: What are the Greek consumers' views towards the issue of whether the benefits of pesticide use outweigh their potential risks;

RQ2: What sociodemographic and attitude variables predict the Greek consumers' personal views towards the benefits versus the potential risks ratio of pesticide use.

2. Materials and Methods

The study was conducted through a web-based survey. The data collection was facilitated using a questionnaire posted on the Google Forms platform (https://www.google.com/forms/ (accessed on 31 March 2021). The survey questionnaire was sent via email, through Viber and Facebook's Messenger applications to approximately 9100 recipients, while it was also disseminated by articles in online news fora and magazines. Through the duration of the survey, 1846 completed questionnaires were obtained, which indicates a survey response rate estimated at 20%. The purpose of this survey was exploratory in nature, since no prior study was conducted using a large, nationwide sample to inquire about the Greek general population's attitudes towards the research questions.

The survey, undertaken between 6th March and 31st March 2021, aimed to investigate the beliefs, perceptions, and feelings of the general consumers' audience on pesticides, pesticide residues, and food safety in Greece. The questionnaire was designed based on previous consumer opinion studies on food safety [36,41,50,58]. It included 5-point Likert-scale closed questions regarding the participants' perceptions or attitudes. The response levels for the Likert scale were: 1 = totally disagree, 2 = partly disagree, 3 = neither disagree/nor agree, 4 = partly agree, 5 = totally agree, or, 1 = never, 2 = rarely, 3 = occasionally, 4 = frequently, and 5 = habitually, depending on the case. The questionnaire was divided into two sections: (a) sociodemographic data and (b) respondents' views. The personal views questions related to the participants' beliefs regarding statements on the positive contributions of pesticides to food production and the national economy, the pesticide proper application, and the necessity of their use. The questions also related to their views and concerns regarding plant food safety and consumer health, pesticide residue official control, food traceability, and certification issues, as well as specific diet habits. In addition, they related to their worries regarding their own health and other people's. Finally, questions regarding the participants' information sources were included. The specific items of the questionnaire are presented in Appendix A, Table A2.

In order to describe the characteristics of the sample and to present the results of the survey, the data collected from the questionnaires were initially subjected to descriptive statistical analysis. The median was used as the appropriate central tendency measure to present and interpret the results of the questionnaire, following Skarpa and Garoufallou (2021) [67]. The non-parametric Kruskal–Wallis test was performed to test differences in the ordinal variables.

A principal components analysis (PCA) was performed to identify the underlying information structure contained in the original interrelated variables and to summarize it into a smaller set of composite variables. An eigenvalue criterion greater than 1 was used as a cut-off point for the number of principal components (PC) retained. After oblique (promax) rotation was performed, the rotated loadings (eigenvectors) portrayed a much more simplified PC-loading pattern with each variable loading (correlating) substantially only to a single PC. In the final analysis, only variables with loadings > 0.6 were retained. The appropriateness of PCA was tested performing the Kaiser–Meyer–Olkin (KMO) test, which takes values ranging from 0 to 1, as a measure of sampling adequacy, and the

Bartlets's test of sphericity, a significant result of which indicates that at least some pairwise correlations among variables are not equal to 0 [68].

The McDonald's ω reliability coefficient of internal consistency for the scale variables [69] loading on a single PC was calculated and reported. In order to get a single measure of each PC, variables loading on a single PC were combined using composite scores for further analysis [68].

Binary logistic regression was performed to identify any potential predictors concerning the participants' views about the overall benefits of pesticides upon their risks, as the dependent variable. Sociodemographic variables and PCs retained from the PCA were involved as possible predictors in the model. Odds ratios (OR) and 95% confidence intervals (CI) were calculated and presented. The Wald test of statistical significance for each of the independent variables in the model was performed. Finally, performance metrics such as specificity and sensitivity, which presents the proportions of true-negative and true-positive observations predicted by the model, respectively, along with AUC (area under the ROC curve portraying the trade-off between true positive rate versus false positive rate) which is an overall test of predictive accuracy and indicates the amount of discrimination between true-positive and false-positive values of the estimated model, were calculated and presented. A large AUC (>0.5–1) indicates better model fit [68].

For the purpose of performing logistic regression analysis, variables of participants' views were split into two levels with a binary outcome: "in favor" = 1, after grouping together the Likert response levels "partly agree" and "totally agree," and "not in favor" = 0, after grouping the Likert response levels "totally disagree," "partly disagree," and "neither disagree/nor agree," following Skarpa & Garoufallou (2021) [67].

A non-hierarchical k-means cluster analysis was performed in order to proceed with the partition of participants into groups based on similarity for a set of user selected characteristics. The aim was to determine structures that adequately summarize the data in order to identify groups of consumers with similar attitudes towards pesticide use. The analysis was based on the PC's that had been previously retained from PCA as clustering variables that related to consumer's perceptions [44]. To further characterize the clusters and to investigate any significant differences between the clusters, the Chi-squared test of association and Mann-Whitney U tests were conducted for variables with nominal and ordinal outcomes, respectively.

The analyses were carried out using the open-source statistical analysis software "Jamovi 2.0.0" using the R programming language [70].

3. Results

3.1. Characteristics of Survey Participants

A total of 1846 participants replied to the questionnaire, from all Greek Regions. The target population under investigation is defined as consumers of plant food, aged 18 to over 65 years old, and residents of both urban and rural areas from all over Greece (Continental and the Islands). In Appendix A, Table A1, the sociodemographic characteristics of the survey participants are presented. Both genders were represented adequately (females 48.5%), as well as all age groups. Most subjects (45.1%) were living in southern Greece, with 26.6% in Central and 29.3% in Northern Greece. For the purpose of the analyses, the age groups were reduced to three, following Miles et al. (2004) [53], and the distribution of the participants among the three main age groups included 22.5% who were ages 18–34, 58.1% who were ages 35–54, and 19.4% who were ages $\geq$ 55 years old. The vast majority of participants had at least a high school educational level and were mainly civil servants (44.1%), private employees (18.6%), self-employed persons (12.1%), university students (11.7%), and farmers (5.3%). Additionally, several individual habits were recorded concerning free personal time, smoking, sports habits, and vegetarian attitude (Appendix A, Table A1).

Participants were offered a sub-set of questions regarding their specific consuming habits in recent years. The frequency distribution of the responses is presented in Table 1. Participants tended to hold positive attitudes towards eating fruits and vegetables. Specifically, data analysis showed that, in central tendency terms of the distribution of replies, respondents frequently consumed "*Fruits and vegetables*" and followed the "*Traditional Greek cuisine*" (median 4, IQR 1). On the contrary, they seemed to rarely consume "*Organic*" (median 2, IQR 1) or "*Produced-by-themselves, fruits and vegetables*" on the central tendency level (median 2, IQR 3). Finally, respondents declared that they occasionally consumed "*Products of certified origin*" (after Protected Designation of Origin or Protected Geographical Indication certification) (median 3, IQR 2). These specific consuming habits, among other sociodemographic factors, along with principal components retained from the PCA have been taken into account below in a binary logistic regression analysis in order to investigate the presence of predictors of participants' willingness to accept the perceived benefits of pesticides over their perceived potential risks.

Table 1. Special consumption habit of the respondents (N = 1846).

Consumption Habits	Median (IQR) [(1)]		Frequent to Habitual Consumption
I consume fruits and vegetables	4 (1)	"Frequently"	79.5%
I follow the traditional Greek (Mediterranean) cuisine	4 (1)	"Frequently"	80.6%
I consume organic fruits and vegetables	2 (1)	"Rarely"	20.9%
I consume products of certified origin (PDO, PGI)	3 (2)	"Occasionally"	34.2%
I consume products of my own cultivation	2 (3)	"Rarely"	26.2%

3.2. The Participants' Views towards the Benefits versus Risks of Pesticide Use Research Question

The frequency distribution of participants' replies to the question under investigation, concerning their views about whether or not the benefits of pesticides outweigh their potential risks (*RQ1*), was obtained as follows: Totally disagree (med. = 1): N = 283 (15.33%); disagree (med. = 2): N = 463 (25.08%); neither disagree/nor agree (med. = 3): N = 269 (14.57%); agree (med. = 4): N = 634 (34.35%); totally agree (med. = 5): N = 197 (10.67%). The median of the replies' distribution is equal to 3 (IQR: 2), which implies neither disagreement, nor agreement to the statement in central tendency terms. Nevertheless, a significantly higher proportion of unfavorable responses were found, tested against the null hypothesis that the two categories are equally likely (p = 0.50). After splitting the response rates into two levels with a binary outcome, i.e., "*in favor*" and "*not in favor*", a binomial proportion test was applied. The proportion of "not in favor" replies was 0.550 (CI: 0.527–0.573), N = 1015 and the corresponding proportion of "in favor" responses was 0.450 (CI: 0.427–0.473), N = 831 ($p < 0.01$).

3.3. The Variables Predicting the Participants' Attitudes towards the Benefits versus Risks of Pesticide Use Research Question

In order to investigate the sociodemographic and ideological variables that could possibly be found as significant predictors of the Greek consumers' views towards the benefits versus the potential risks ratio of pesticide use (*RQ2*), a principal components and a logistic regression analyses were performed.

3.3.1. Principal Components Underlying the Participants' Attitudes

A principal components analysis was performed to identify the structure of relationships among variables of the original data. Twenty -ive original variables were analyzed having loadings greater than 0.6. Seven principal components (PC) were retained applying the eigenvalue criterion, having substantial amounts of common variance, and considered appropriate to adequately represent the underlying structure in the data (Appendix A, Table A2). The explained cumulative variance was 61.7%. Reliability coefficients (McDonald's ω) varied between 0.634 and 0.865. All PC's had sum of the squares loadings (eigenvalues) greater than 1.0. Both Bartlett's test of sphericity ($p < 0.001$) and the KMO Measure of Sampling Adequacy (0.829) suggested suitability of the correlation matrix for a principal components analysis.

The first PC summarizes variables representing "*Specialized information sources*" (SINF) used by participants to get informed about pesticides, consists of four variables explaining 18.757% of variance. Official websites, public bodies newsletters, scientific journals and agronomists as information sources were variables mostly correlating to the first PC. After analyzing the median scores of the respondents' replies to the variables loading in SINF, it was obvious that "*Agronomist*" (med.: 4; IQR 2) is the most frequent specialized provider of information on pesticides. Participants views on pesticides' contribution to the national income and to increased food production, as well as on the statements that pesticides' proper application ensures the user, or the consumer, were variables that were loading to the second PC. Accordingly, this is associated with "Perceived contributions of pesticides" (CONTR) and explains 11.377% of the variance. The printed and electronic Press as well as television and radio as sources of information on pesticides were variables loading to the third PC, namely "General information sources on pesticides" (GINF), that explains 8.438% of the variance. The participants' views on statements related to the safety of food of plant origin, the consumer's safety from the consumption of fruits and vegetables, as well as the pesticide residues official controlling procedures, all were correlated to the forth PC. This is labeled as "*Confidence in plant food safety*" (SAFE) and explains 7.175% of the variance.

The existence of labeling and traceability information that accompanies the food, and the safety of certified and integrated farming management food products were variables loading to the fifth PC. This is labeled as "*Confidence in food certification procedures*" (CERT) and explains 6.232% of variance. The sixth PC consisted of variables representing "*Perceived threats of pesticides*" (THR), which explains 5.598% of the variance. Participants' attitudes about their health status related to pesticides, worries about their health from pesticide residues in food, and feeling insecure about the health of their own people, were all loading in THR. Finally, "*Special plant food consuming habit*" (CONS) related to the Greek (Mediterranean) cuisine adoption, as well as fruits and vegetables consumption are loading to the CONS, which explains 4.078% of the variance.

The relationship among the seven PCs is summarized in Figure 1. Perceived threats (THR) load in the opposite direction in the horizontal axis and is negatively correlated with perceived pesticides' contributions (CONTR) and consumers' confidence in plant food safety (SAFE). It is also essentially orthogonal to specialized information sources (SINF) and confidence in food certification procedures, (CERT) which implies a negative relationship.

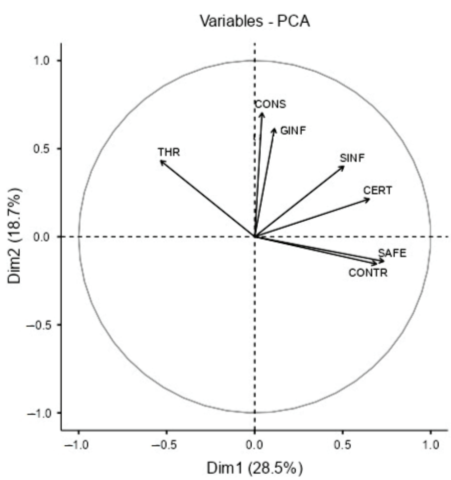

Figure 1. Principal components analysis graph depicting the relationship among PCs. SINF: Specialized information sources; CONTR: Perceived pesticides' contributions; GINF: General information sources; SAFE: Confidence in plant food safety; CERT: Confidence in food certification procedures; THR: Perceived pesticides' threats; CONS: Special plant food consumer habits.

3.3.2. The Existence of Predictive Variables of Participants' Attitudes–Logistic Regression Model

A binary logistic regression analysis was performed to identify the existence of any variables predictive of the participants' attitude concerning the use of pesticides. Specifically, the question about participants' views on the statement that "*there are more benefits from pesticide use against the risks*" is considered as the dependent variable. A preliminary logistic regression analysis using a stepwise method revealed that no sociodemographic variables significantly contributed to the model (the Wald test result was not significant), except for the "gender" and the "habit of using pesticides" variables (data not shown). Along this line, it was chosen to present a binary logistic regression analysis using an enter method concerning the "*gender*", the "*habit of using pesticides*", as well as the seven principal components previously retained from the PCA as possible predictors in the model.

The performance measures of the model, specificity (% of cases correctly predicted as not having the outcome) and sensitivity (% of cases that had the outcome correctly predicted) are 81.3% and 74.7%, respectively. The overall predictive accuracy of the model as measured by the AUC value (area under the ROC curve) is 0.855, which is considered very good for the model fit (Appendix A, Table A3).

The regression coefficients for "Specialized information sources" (b = 0.176; $p = 0.012$), "Perceived pesticides' contributions" (b = 1.343; $p < 0.001$), "General information sources on pesticides" (b = 0.156; $p < 0.012$), "Confidence in plant food safety" (b = 0.339; $p < 0.001$), "Confidence in plant food certification procedures" (b = 0.143; $p = 0.038$), "Users of pesticides" (b = 0.745; $p < 0.001$), and "Male gender" (b = 0.489; $p < 0.001$) are positive and statistically significant. This indicates that the probability of respondents intending to accept the benefits of using pesticides against their potential adverse effects was higher for those who were informed about pesticides most frequently by "Specialized" or "General information sources" those who declared a higher intensity of views regarding "Perceived pesticides' contributions", and showed greater "Confidence in plant food safety" and "Confidence in plant food certification procedures" followed by those who were "Users of pesticides" and, finally, "Males".

According to the odds ratios, the odds of a participant considering that the pesticide use poses "more benefits than risks" change by a factor of 3.83 (95% CI: 3.21–4.57) with each unit increment in their propensity towards "*Perceived pesticides' contributions*", 1.71 (95% CI: 1.30–2.25) towards "*Using of pesticides*", 1.49 (95% CI: 1.16–1.91) if they are "*Males*", 1.40 (95% CI: 1.22–1.61) towards "*Confidence in plant food safety*", 1.19 (95% CI: 1.04–1.47) with each unit increment in their frequency to get informed about pesticides by "*Specialized information sources*", 1.17 (95% CI: 1.03–1.32) by "*General information sources*", and finally, 1.15 (95% CI: 1.01–1.32) towards "*Confidence in plant food certification procedures*".

The regression coefficient for "*Perceived pesticides' threats*" and "*Southern Greece geographic region*" are negative and statistically significant (−0.286; $p < 0.001$ and −0.302; $p = 0.039$, respectively), indicating that respondents with a high perceived threats of pesticides and Southern Greece residents are less likely to accept the benefits of pesticides against their potential adverse effects. The odds ratio for these predictors indicates that the odds of a respondent viewing that there are "*more benefits than risks*" from pesticide use changes by a factor of 0.752 with unit change towards "*Perceived pesticides' threats*". Additionally, it changes by a factor of 0.739 for residence in Southern Greece. A prominent difference among Greek geographic regions was that participants who were residents in Southern Greece expressed significantly higher intensity of perceived threats, compared to Central and Northern Greece counterparts, after performing the Kruskal–Wallis test (df = 2; W = 3.777; $p = 0.021$ and df = 2; W = 4.885; $p = 0.002$, respectively).

Respondents' declarations on "*Special plant food consumption habit*" did not constitute a significant predictor of their views on the statement that there are "more benefits than risks" from pesticide use (Wald test, $p = 0.969$); therefore, this component is not supported in the model.

3.4. Cluster Analysis of the Respondents

The cluster analysis was based on the principal components relating to consumer's perceptions that were retained from the PCA. A two-cluster solution was obtained for further analysis. To characterize the participants' perceptions regarding pesticide use among Clusters, the Mann-Whitney U test was performed (Table 2). Cluster 1 (N = 812) was labeled as "*Supporters of pesticide benefits over the threats*" as it was comprised of participants with greater intensity of views towards perceived pesticides' contributions ($p < 0.001$), with a higher frequency of being informed about pesticides by specialized information sources ($p < 0.001$) and expressing greater confidence in plant food safety ($p < 0.001$). Cluster 2 (N = 1034) consists of participants with a greater intensity of the perceived threat of pesticides ($p < 0.001$), with a lower frequency of being informed about pesticides ($p < 0.001$) and expressing lower confidence in plant food safety ($p < 0.001$). For this reason, Cluster 2 was labeled "*Non-supporters of pesticide benefits over the threats*". The sociodemographic profile of the clusters was made using the Chi-squared test of association as shown in Table 3. Cluster 1 is characterized by a greater proportion of male respondents ($p < 0.001$) and pesticide users ($p < 0.001$) compared to Cluster 2. Furthermore, farmers, retired, and self-employed persons are represented with significantly higher proportions in Cluster 1. On the contrary, significantly greater proportions of females ($p < 0.001$), civil servants, private employees, unemployed persons, and university students ($p < 0.001$), as well as urban residents ($p = 0.017$) are classified in Cluster 2. Participants' special plant-food consuming habit, residential geographical regions, age, and educational level did not differ significantly between the Clusters.

Table 2. Median values of perceptions on pesticides and information sources attributes according to clusters of respondents concerting benefits—threats of pesticides.

	Cluster 1 (N = 812)	Cluster 2 (N = 1034)	Mann-Whitney U Test
	"Supporters"	"Non-Supporters"	
PRINCIPAL COMPONENTS	MEDIAN (IQR) *	MEDIAN (IQR)	
PC 1: Specialized information sources on pesticides	4 (2) ^{a}	3 (2) ^{b}	W = 189,516; $p < 0.001$
PC 2: Perceived pesticides' contributions	5 (1) ^{a}	4 (1) ^{b}	W = 148,057; $p < 0.001$
PC 3: General information sources on pesticides	3 (1) ^{a}	2 (2) ^{b}	W = 381,959; $p < 0.001$
PC 4: Confidence in plant food safety	4 (0) ^{a}	3 (1) ^{b}	W = 112,711; $p < 0.001$
PC 5: Confidence in plant food certification procedures	4 (1) ^{a}	4 (1) ^{b}	W = 183,623; $p < 0.001$
PC 6: Perceived pesticides' threats	3 (2) ^{b}	4 (2) ^{a}	W = 204,718; $p < 0.001$
PC 7: Special plant food consumption habits	4 (1)	4 (1)	W = 410,625; $p = 0.419$

*: Median values as a central tendency measure of the participants' replies distribution of each principal component between clusters and in brackets the interquartile range as a variability measure. ^{a,b}: Partitioning of principal components' median values among clusters followed by different letter differs statistically significantly at 0.001 level.

Table 3. Sociodemographic characterization of the two obtained clusters of respondents.

NOMINAL VARIABLES		Cluster 1 (N = 812) "Supporters"	Cluster 2 (N = 1034) "Non-Supporters"	Chi-Squared Test
GENDER	Female	35.4%	64.6%	$X^2 = 52.4$; df = 1; $p < 0.001$
	Male	52.1%	47.9%	
AGE	18–34	41.4%	58.6%	$X^2 = 3.54$; df = 2; $p = 0.170$
	35–54	43.6%	56.4%	
	≥55	48.0%	52.0%	
POPULATION	Less than 10,000 inhabitants	48.7%	51.3%	$X^2 = 5.70$; df = 1; $p = 0.017$
	More than 10,000 inhabitants	42.4%	57.6%	
REGION	Northern Greece	43.9%	56.1%	$X^2 = 0.105$; df = 2; $p = 0.949$
	Central Greece	44.6%	55.4%	
	Southern Greece	43.7%	56.3%	
I USE PESTICIDES	No	30.2%	69.8%	$X^2 = 193$; df = 1; $p < 0.001$
	Yes	62.6%	37.4%	
PROFESSION	Civil servants	40.2%	59.8%	$X^2 = 40.4$; df = 6; $p < 0.001$
	Farmers	63.3%	36.7%	
	Private employees	43.3%	56.7%	
	Retired	55.0%	45.0%	
	Self-employed	54.9%	45.1%	
	Unemployed	32.4%	67.6%	
	University students	39.1%	60.9%	
EDUCATION	Secondary education	41.4%	58.6%	$X^2 = 1.57$; df = 1; $p = 0.211$
	Higher education	44.8%	55.2%	

4. Discussion

This study investigated the attitudes and perceptions of Greek consumers in respect to the balance between the benefits and risks of pesticide use. According to our knowledge, no previous study has attempted to elucidate the consumers' views on pesticide use in Greece and, moreover, this is the first large-sample survey conducted regarding the Greek consumers' attitudes towards this issue. The subjects used in this survey came from all Greek Regions, were residents of urban and rural areas, and belonged equally to both genders. All age groups were adequately represented, ranging from 18 to over 65 years old. On a central tendency basis, participants were regular agricultural food consumers, frequently consuming fruits and vegetables, following the traditional Greek cuisine. They occasionally consumed certified agricultural food products and rarely consumed organically or self-produced fruits and vegetables.

Data analysis, using the median of participants' responses as the central tendency measure, revealed neither disagreement, nor agreement to the statement under consideration, i.e., whether or not the benefits of using pesticides outweigh the potential risks. Nevertheless, a significantly higher proportion of unfavorable responses were found. Approximately 55% of the respondents to the survey of the present study seem not to be supportive of a statement implying the predominance of benefits over the potential risks from the pesticide use. This outcome was expected once the findings of the previous Special Eurobarometer survey, concerning the food safety in the EU, were taken into account. Greek consumers ranked pesticide residues as the most important food safety concern, followed by animal diseases and veterinary pharmaceutical residues in the meat [41].

In the overall regression model, the general hypothesis that perceptions, personal concerns, and views about several procedures and sociodemographic characteristics help to explain consumers' attitudes on pesticide use was confirmed. According to the results, there is evidence that the participants supported the statement that "there are more benefits of pesticide use than their potential risks" if they were in favor of the beneficial contributions of pesticide use and they were professional or amateur users of pesticides. A similarly positive response was recorded if the participants were males and expressed more intense confidence in plant food safety and control procedures, were informed about pesticides by specialized or general information sources, and, finally, showed confidence in plant food certification procedures. Perceived threats about pesticide use was a significant predictor that negatively influenced the respondents' attitude regarding the pesticides' benefits versus their potential threats ratio.

The stronger positive predictor of the consumer's attitude towards pesticides seem to be the perceived pesticide contributions. They can be analyzed into the constituent variables of pesticides' contribution to the national income, their necessity to ensure crop production and food security, and the belief that the user and the consumer can be safeguarded through the proper application of pesticides. In central tendency terms, respondents in the survey agreed with all the above elements. Perceived pesticide contributions seem to influence the judgments of participants in favor of the statement that pesticide benefits outweigh their potential threats. Our results are in line with Dunlap & Beus (1992) [71], who have reported that the perception of the necessity of pesticide use was the most important predictor of public views on pesticides. Attempts to explain such outcomes have been made through the concepts of cognitive consistency. People are possessed by a strong desire for consistency in their beliefs. This is about the consistency between a comparatively stable affective or evaluative orientation toward an issue and the individual's views about how this relates to other issues of affective significance. Issues that are favored are usually considered to serve the value background, to have characteristics that are favorable, grouped with other attractive topics, and stand out from the unattractive ones [72]. Previous studies have shown the existence of a strong inverse interdependence between risk and benefit judgments. Alhakami & Slovic (1994) [73] have shown that issues towards which people had positive attitudes were viewed as having high benefit and low risks and vice versa. Ueland et al. (2012) [44] stated that if there is a greater benefit associated with a product, more risk can be accepted. Accordingly, Dunlap and Beus (1992) [71] have found that those who considered pesticides essential did not perceive a high risk, suggesting that they were more likely to consider the use of pesticides acceptable. In our results, this negative relationship that has been previously described between perceived risks and benefits is clearly indicated in the PCA graph, where the perceived threats point in the opposite direction than the perceived pesticide contributions.

The status of a pesticide user, whether for professional or amateur reasons, particularly affects the participants' positions and views on pesticides. While most of the participants were not users of pesticides (57.3%), neither for professional nor amateur reasons, this is the strongest positive predictor variable after the perceived pesticide contributions. This result confirms Coppin et al. (2002) [74] who also found that the pesticide-use variable was a significant predictor of acceptability of pesticide use. This could be explained by Huang (1993) [75] who reported that personal use of pesticides has a significant impact in reducing consumers' fear about pesticide residues on food and the balance between the benefits and risks associated with them. It seems that familiarity with an issue reduces the feelings of uncertainty and increases perceived control, which lays the basis for the consumer to be more appreciative of the beneficial aspects of the issue [44,75]. It should be noted that no significant influence was recorded from the population of the place of residence variable (i.e., urban/rural areas). Pesticide users acting as professional or amateur farmers may have also experienced the importance of pesticide use in successful crop production directly associated with food security at a community level. This is in line with Coppin et al. (2002) [74], who stated that for pesticide perceptions, personal experience is more important than residence status.

Male gender also has a significant impact on consumer views, causing a positive effect on the acceptance of pesticide use benefits against their potential negative effects. The finding of a positive and significant male gender effect is consistent with previous studies that have shown that females have a higher risk perception than males with respect to chemical residues [51,54,71,75,76].

Perceived plant food safety and confidence in pesticide residues control procedures positively affects the respondents' attitude. This outcome is related to the constituent perceptions that food of plant origin is generally safe, and that plant food produced in Greece is as safe as in other EU States. Respondents agreed to both aforementioned statements. Two additional variables were associated with the above predictor, namely, that the consumer is generally not at risk from the consumption of fruit and vegetables and that plant food is routinely tested for pesticides residues. These results depict the importance of control procedures and effective implementation of pesticide and food safety regulations. At the central tendency level, neutrality was recorded to both statements among participants. The results of previous Special Eurobarometer survey have shown that a 28% of Greek consumers agree that official Authorities and EU keep them safe from food risks, just below the EU28 average [41]. This implies the need for further involvement of food safety Authorities in the communication of the risk associated to pesticide use to the Greek public. Given the inherent difficulty of such an endeavor due to difference in risk perception between experts and lay people [44,77], the challenging and decisive role that official bodies are called upon to play is realized.

Our results depicted that information plays an important role in consumer's perceived views on pesticide use. Being informed about pesticides by either specialized or general information sources is a significant predictor of the participants' positive predisposition to the benefits of pesticide use over any potential adverse effects. Among specialized information sources, agronomists seem to be the most frequent source for obtaining information on pesticides. This outcome is explained by the fact that in Greece, the legislation on pesticides requires that certain conditions of scientific background are met, so a natural or legal person is allowed to be actively involved in the trade of pesticides [78]. Nonetheless, information sources on pesticides such as official websites, public bodies, newsletters, and scientific journals were more strongly associated with the principal component of specialized information sources in the PCA. General information sources (i.e., electronic press, television-radio, press and social media) were also positive predictors of the consumer's views on pesticides. In central tendency terms, respondents declared that they occasionally chose electronic press as a source of information on pesticides, while they rarely used television-radio, press, or social media.

Huang (1993) [75] has stated that consumers have the tendency to reverse the accepted hierarchy of risks from food, perhaps due to misinformation or lack of knowledge. Koch et al. (2017) [50] reported that unawareness of legal maximum residue limits was associated with increased levels of concern about pesticide residues in food. Our results depicted the key role of information related to pesticide use, particularly from specialized sources, communicating either risk assessment or the strict regulatory framework governing the trade and use of pesticides. More specifically, after participants' clustering, a significantly lower frequency of being informed about pesticides has been found among non-supporters than supporters of pesticide use benefits versus threats. This could imply a limited level of knowledge about pesticides, with possible implications to consumer's perceived threats, in line with Webster et al. (2010) [79], who reported that the public often ranks higher a food safety issue based on a lack of available knowledge.

An interesting principal component that has emerged from the results of the present study, with positive predictive influence on consumer's perceptions on pesticides, is the confidence in plant food certification procedures. This trust stems from the importance of traceability for consumers and information provision by plant-food labeling, along with the sense of safety that certification promotes, especially of integrated farming management certified products. Participants generally agreed to all above variables. The results are supportive of previous research showing the importance that certification, information provision, and labeling play to Greek consumers in order to assess the quality of food they buy [54–58,60–62]. Ueland et al. (2012) [44] commented that the lack of consumers' own control can be substituted by control exercised of trusted bodies. Benefits are more easily perceived when products come from trusted sources or with messages from trusted sources.

Perceived risk is the primary determiner of the risk adjustment ratings [80]. The participants' perceived threats of pesticide use negatively influence their views and perceptions on pesticide benefits over their potential risks, which is in accordance with Huang's (1993) [75] findings. Perceived threats are associated with the concern that their health has been affected, feeling insecure for the health of their loved ones, and expression of worries for their health from the pesticide residues. Participants particularly agreed with the two last statements. This outcome implies that pesticide residues in food is an issue of concern for Greek consumers, linked directly to their health. This is in line with the previous Special Eurobarometer survey reports [41]. It has been shown that individuals perceive greater control over biological food risks than chemical/technical risks [34]. Attempts to explain the high ranking of risk perceptions of pesticide residues have been made by Dickson-Spillmann et al. (2011) [76], who reported that consumers are dose–response insensitive, which, in turn, lead to higher risk perceptions of contaminants. This aspect has been also linked by Koch et al. (2017) [50] to the lack of knowledge of the regulatory framework and the presence of legal limits of residues in food, while in the same line, the presence of a discrepancy between expert and lay views of chemical risks has been reported [81]. This may explain the negative relationship that occurs in the PCA graph between perceived threats and consumers' confidence in plant food safety and food certification procedures.

The Southern Greek geographic region seems to be a significant negative predictor of respondents' views on pesticide benefits over their potential risks. This outcome should be expected due to higher perceived threats that participants of Southern Greek origin have expressed, compared to respondents from Central and Northern Greece. This result might be explained according to the findings of Hohl & Gaskell (2008) [31], who reported that food risk perception is strongly associated with generalized risk sensitivity. Additionally, the fact that environmental groups and the media often play a watchdog role as Meagher (2019) [34] states, may help explain this association with heightened concerns; research is needed to confirm this hypothesis.

The influence of a special plant-food consuming habit of the participants, which was associated with consumption of fruits and vegetables, following the traditional Greek cuisine, consumption of organically produced and of certified origin (PDA, PGI) agricultural products was not of significance concerning participants' views on pesticides. This may be attributed to the fact that there were no significant differences found in special plant-food consuming habit between the two distinct clusters of participants. In a similar way, several other socioeconomic variables were not found to influence the respondents' views on pesticides, such as education level, urban or rural areas of residence, the presence of minor children in the family, the availability of leisure time, smoking, vegetarian habits, physical activities, and profession.

Two distinct consumer groups were identified regarding participants' perceptions on pesticide benefits versus their potential risks. In the first group, supporters of pesticide benefits over their potential threats have been classified. Consumers who fit this profile received information mainly from specialized and general sources of information, are in favor of pesticide use contributions, express confidence in plant-food safety and controlling procedures, are primarily males, farmers, self-employed persons, retired, and pesticide users. In the second group, non-supporters of the pesticide use benefits over the risks statement have been categorized. Consumers in this category get less frequently informed about pesticides, express lower confidence in plant-food safety, declare more intense perceived threats, are primarily females, mostly inhabitants of urban areas, largely are not users of pesticides, civil servants, private employees, unemployed persons, and university students.

Several limitations should be taken into account concerning our study. First, our results were obtained through web survey disseminated by email, Messenger, and Viber applications, hence, anyone unfamiliar with communication technology was inevitably excluded. These individuals might have a low educational level or belong to older age groups. Second, the data were collected from self-reporting opinions with no means of checking their veracity. Third, the sample was collected from all over Greece, however, it may not be representative in several aspects of the Greek population (i.e., education, occupation, age group >65 years etc.). Fourth, although information sources were investigated, the study did not address other possible sources of information on pesticides like friends and family, peers, other internet content, bloggers, influencers, participation in collectives, consumer associations, activist organizations, etc., which constitute a proposal that future studies should further explore these issues.

5. Conclusions

Overall, this study represents a first attempt to identify the main predictors influencing Greek consumers' attitude concerning the balance between the benefits and risks of pesticide use. It was found that Greek consumers express high concerns about pesticide residues in food for their loved ones and their own health. At the same time, however, they recognize to a significant extent the beneficial contributions of the use of pesticides for food security and the national economy as well. The PCA analysis has identified several significant predictors of consumer's attitude towards benefit—risks perception of pesticide use, personal values, user status, gender, confidence in controlling and certification procedures, and received information. Knowing the perception of the public regarding the pesticide-use risks in food is essential to design clear and transparent risk communication strategies, which should consider, in addition to scientific information, the subjective aspects that affect risk perception. Our results suggest several implications concerning the undertaking of initiatives by competent authorities in the organization of general public training programs on food safety risks literacy to facilitate a better understanding of the information received by the public and reassure consumers on the safety of the plant-food supplying chain from farm to fork. Our results demonstrate that efforts for risk communication should be structured to address food safety issues, pesticide regulation, and residue control procedures targeting the general public via particularly general information sources, aiming at a broader audience. For such a purpose, the cultivation of a stronger connection between journalists and scientists, as well as more active involvement of official bodies are necessary to avoid the unfair provocation of dread and anxiety in the public. In addition, greater visibility to the wider public via specialized and general information sources of the work of the food safety authorities is considered equally important. Furthermore, it is suggested that there is a need more active involvement in the communication of the certification and traceability benefits of plant food to be taken over by stakeholders, especially the farmers' associations, should they gain consumers' confidence.

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Appendix A

Table A1. Sociodemographic characteristics of the respondents (N = 1846).

Demographic Variables		Frequency	Percentage
Gender	Female	896	48.5%
	Male	950	51.5%
Age	18–24	220	11.9%
	25–34	195	10.6%
	35–44	404	21.9%
	45–54	669	36.2%
	55–64	304	16.5%
	≥65	54	2.9%
Education level	Less than high school	31	1.7%
	High school–Technical education	397	21.5%
	Bachelor's degree	727	39.4%
	Master's degree	565	30.6%
	Doctoral degree	126	6.8%
Geographic area	Northern Greece	540	29.3%
	Central Greece	473	26.6%
	Southern Greece	833	45.1%
Population of place of residence	Less than 10,000 inhabitants	468	25.4%
	More than 10,000 inhabitants	1378	74.6%
Minor children in the family	No	1027	55.6%
	Yes	819	44.4%
Ample leisure time	No	735	39.8%
	Yes	1111	60.2%
Smoking	No	1404	76.1%
	Yes	442	23.9%
Vegetarians by conviction	No	1722	93.3%
	Yes	124	6.7%
Physical activities	Never	243	13.2%
	Occasionally	1207	65.4%
	Systematically	396	21.4%
Pesticides users either professional or amateur	No	1058	57.3%
	Yes	788	42.7%
Profession	Civil servants	814	44.1%
	Private employees	344	18.6%
	Self-employed	224	12.1%
	Farmers	98	5.3%
	Unemployed	71	3.9%
	University students	215	11.7%
	Retired	80	4.3%

Table A2. Results of the principal component analysis.

Original Variables (5-Point Likert Scale Statements)	Median (1)	IQR (2)	Principal Components							Uniqueness (3)
			SINF	CONTR	GINF	SAFE	CERT	THR	CONS	
			Specialized Information Sources	Perceived Pesticides' Contributions	General Information Sources	Confidence in Plant Food Safety	Confidence in Food Certification Procedures	Perceived Pesticides' Threats	Special Plant Food Consumer Habits	
I get informed about pesticides by Official Websites	3	2	0.910							0.188
Public Bodies Newsletters	3	2	0.861							0.261
Scientific Journals	3	2	0.852							0.269
Agronomist	4	3	0.709							0.431
Pesticides contribute to the increase in national income	4	1		0.805						0.410
Pesticides contribute to increased food production	4	1		0.788						0.441
The use of pesticides is inevitable	4	2		0.700						0.476
Pesticides's proper application secures the user	4	2		0.695						0.424
Pesticides's proper application secures the consumer	4	2		0.649						0.413
I get informed about pesticides by Electronic Press	3	2			0.789					0.287
Television-Radio	2	2			0.788					0.356
Press	2	2			0.741					0.375
Social Media	2	2			0.724					0.474
Food of plant origin is generally safe	4	2				0.787				0.432
Plant food produced in Greece is as safe as other EU States	4	1				0.750				0.445
The consumer is generally not at risk from the consumption of fruit and vegetables	3	2				0.750				0.351
Food of plant origin is tested for pesticides residues	3	2				0.663				0.450
The existence of labeling (traceability) reassures me	4	1					0.856			0.276
Certified products are safe	4	1					0.838			0.303
Integrated farming management products are safe	4	1					0.805			0.316
I think my health has been affected	3	1						0.810		0.289
I feel insecure about the health of my own people	4	2						0.783		0.427
I'm worried about my safety from pesticides residues in food	5	1						0.782		0.345
I consume fruits and vegetables	4	1							0.775	0.408
I follow the traditional Greek (Mediterranean) cuisine	4	1							0.768	0.433
I consume products of certified origin (PDO, PGI)	3	2							0.604	0.563
I consume organic fruits and vegetables	2	1							0.572	0.511
Sum of the squared loadings			5.064	3,072	2,278	1,937	1,683	1,512	1,101	
Scale reliability (McDonald's ω)			0.865	0.799	0.777	0.795	0.747	0.720	0.634	
Explained variance %			18.757	11.377	8.438	7.175	6.232	5.598	4.078	
Cumulative variance %			18.757	30.134	38.572	45.747	51.980	57.578	61.656	
Bartlett's Test of Sphericity	$\chi^2 = 16{,}358$; df = 351; $p < 0.001$									
KMO Measure of Sampling Adequacy test	0.829									

(1): Median values of the distribution of participants' replies to the 5-point Likert scale questions (1 = never to 5 = habitually, or 1 = totally disagree to 5 = totally agree, whatever applicable). (2): Interquartile range. (3): Proportion of variance that is "unique" to the variable and not explained by the PC's. Uniqueness is equal to 1—Communality. The lower the Uniqueness the greater the relevance of the variable in the PC model. *Note*: "promax" rotation was used, variable loadings > 0.6 and Uniqueness < 0.6 were selected.

Table A3. Results of binomial logistic regression analysis.

Model Coefficients—Dependent Statement: ***The Benefits of Pesticide Use Outweigh Their Potential Risks***									
		95% Confidence Interval		**Wald Test**				**95% Confidence Interval**	
Predictor	**Estimate, b**	**Lower**	**Upper**	**SE**	**Z**	***p***	**Odds ratio**	**Lower**	**Upper**
Intercept	−0.669	−0.920	−0.418	0.128	−5.222	<0.001	0.512	0.399	0.658
SINF—"*Specialized information sources*"	0.176	0.038	0.313	0.070	2.502	0.012	1.192	1.039	1.368
CONTR—"*Perceived pesticides' contributions*"	1.343	1.166	1.520	0.090	14.873	<0.001	3.829	3.208	4.570
GINF—"*General information sources on pesticides*"	0.156	0.034	0.279	0.062	2.502	0.012	1.169	1.034	1.321
SAFE—"*Confidence in plant food safety*"	0.339	0.200	0.478	0.071	4.772	<0.001	1.404	1.221	1.613
CERT—"*Confidence in plant food certification procedures*"	0.143	0.008	0.277	0.069	2.074	0.038	1.153	1.008	1.320
THR—"*Perceived pesticides' threats*"	−0.286	−0.418	−0.153	0.067	−4.232	<0.001	0.752	0.658	0.858
CONS—"*Special plant food consumption habits*"	−0.002	−0.127	0.122	0.063	−0.039	0.969	0.998	0.881	1.130
Users of pesticides	0.534	0.259	0.809	0.140	3.803	<0.001	1.706	1.295	2.246
Male gender	0.397	0.148	0.646	0.127	3.125	0.002	1.488	1.160	1.908
Southern Greece geographic region	−0.302	−0.590	−0.015	0.147	−2.060	0.039	0.739	0.555	0.985
Predictive measures: AUC = 0.855; Sensitivity = 0.747; Specificity = 0.813									

Note: Estimates represent the log odds of "The benefits of pesticide use are more than their potential risks = 1" vs. "The benefits of pesticide use are more than their potential risks = 0".

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agriculture

Perspective

Digital Technology-and-Services-Driven Sustainable Transformation of Agriculture: Cases of China and the EU

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Abstract: China's sustainable development goals and carbon neutrality targets cannot be achieved without revolutionary transitions of the agricultural sector. The rapid development of digital technologies is believed to play a huge role in this revolution. The ongoing prevention and control of COVID-19 has greatly boosted the penetration of digital technology services in all areas of society, and sustainable transformation driven by digital technologies and services is rapidly becoming an area of innovation and research. Studies have shown that the rapid advancement of digitalization is also accompanied by a series of new governance challenges and problems: (1) unclear strategic orientation and inadequate policy and regulatory responses; (2) various stakeholders have not formed a sustainable community of interest; (3) information explosion is accompanied by information fragmentation and digital divide between countries and populations within countries. Meanwhile, current research has focused more on the role of digital services in urban governance and industrial development and lacks systematic research on its role in sustainable agricultural and rural development. To address the realities faced by different stakeholders in the process of digital transformation of agriculture, this paper aims to propose an inclusive analytical framework based on the meta-governance theory to identify and analyze the demand, supply, actor networks, and incentives in the digital technology-and-services-driven sustainable agricultural transformation, starting from the goals and connotations of sustainable agricultural and rural transformation and the interactions among different stakeholders in governing information flows. This analytical framework is further applied to analyze the cases of China and the EU. Although China and the EU represent different development phases and policy contexts, the framework is valid for capturing the characteristics of information flows and actor networks along the flows. It is concluded that a common information platform based on the stakeholder network would benefit all stakeholders, help reach common framing of issues, and maintain a dynamic exchange of information. Depending on the country context, different types of stakeholders may play different roles in creating, supervising, and maintaining such platforms. Digital infrastructures/products as hardware and farmers digital capacity as 'software' are the two wings for digital sustainable transformation. Innovative incentives from different countries may inspire each other. In any case, farmers' actual farming behavior changes should be an important criterion for evaluating the effects and effectiveness of digital transition governance.

Keywords: digital technology; meta-governance theory; agriculture; SDGs; stakeholders; information flow

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1. Introduction

1.1. Digital Empowerment for Sustainable Agricultural Transformation

The contemporary agricultural development model faces multiple economic and environmental challenges [1]. Although chemical agriculture has increased grain production and ensured the absolute security of China's food rations in the near and medium to long term [2–4], it has also led to many agricultural areas presenting increasingly serious ecological and environmental problems such as declining groundwater levels and soil fertility and increased pollution from agricultural processes [5–7]. The sustainable development of the agricultural sector is one of the keys to achieving the Sustainable Development Goals (SDGs) [8,9], SDG 1, 2, 6, 8, 12, 13, 14, and 15 in particular. Improving the performance of the SDGs related to agriculture contributes to achieving the region's commitment to economic transformation and improving the wellbeing of the region [10,11] and the carbon neutrality that China pledged.

Digital technology and services offer new opportunities for sustainable transformation of the agricultural sector [12,13]. Digital technologies, represented by 5G, the Internet of Things (IoT), and cloud computing have been increasingly integrated into all aspects of agricultural development as a focus of future technological development that can improve efficiency and sustainability [14–18]. Digital technology and services can reduce environmental pollution and ensure the safety of agricultural products. Digital technology and services enable the development of agricultural databases, dynamically maintain the balance between crop growth needs and agricultural production inputs, regulate the interaction between soil, cultivation management patterns, and climate, achieve resource conservation and environmental friendliness, and contribute to carbon neutrality [19,20]. In addition, digital regulation and intelligent sorting build digital grading standards for agricultural products, provide the technical conditions for strict product certification and labeling systems, raise consumer concerns about social and environmental sustainability, and promote sustainable agricultural development [21,22]. Thus, many believed that digital agriculture would deliver a step change in efficiency, productivity, and sustainability at the farm level and across the value chain [23,24].

1.2. Digital Agricultural Transformation around the World

Given the merits of digital technologies, to ensure that agriculture meets the needs of the world's future population, the world's leading economies are accelerating the development of digital agricultural transformation [25]. The United States is vigorously promoting the spread of 5G technology in agriculture, with $9 billion planned to be invested in 5G for rural America over the next decade [26]. The UK's agricultural information technology project was started earlier, and agriculture faces the problems of smaller arable land areas, larger individual farms, and a small agricultural workforce, and they are currently working on a comprehensive 5G rural testbed project [27]. Japan has introduced a series of policies to promote agricultural informatization and intelligence since 1993 due to its small and aged agricultural workforce. The Japanese government is promoting Cross-ministerial Strategic Innovation Promotion Program (SIP) and building a WAGRI in phases to connect various data sources and services to promote cooperation between different actors in the agricultural sector [28]. India is a typical agricultural country, with a large agricultural workforce, but the development of agricultural information technology has been slow. In 2015, it proposed a "Digital India" strategy to establish 250,000 village-level public service centers to solve the problem of indiscriminate access for rural residents, while actively developing e-commerce for agricultural products [27]. Since 2013, the Common Agriculture Policy (CAP) has issued a series of regulations to promote sustainability and innovation in agriculture, supporting the digital transformation of European Union (EU) agriculture and rural areas, and 24 EU countries also agreed to cooperate on digital agriculture in 2019 [29]. Since its introduction in the 1990s, China's agricultural informatization has seen rapid development of information technologies such as mobile internet, cloud computing, big data, and the IoT, providing a good foundation and realistic conditions for the development of digital technology and services in agriculture [30].

The promotion of digital technology and services is an inevitable trend in the development of agricultural modernization, the basis for the development of digital agriculture, and an important means of intelligent agriculture [31]. Countries are experimenting with the application of digital technology in agriculture, but the following problems have been widely observed [32]: (1) policies and legislations lag behind the development of digital technology and services [30,33]; (2) developmental goals and interests of stakeholders may conflict with each other; (3) lack of inclusive and meta-governance of information flows; (4) uneven access to infrastructure and information between urban and rural populations, making it difficult for farmers to fully engage with digital transformation; (5) lack of effective incentives and regulations for market mechanism to play a full role; (6) farmers' perspectives on digital technologies and services are under studied [17,34,35].

1.3. Research Objectives

To accelerate the sustainable transformation of agriculture with the aid of digital technology and services, an analytical framework that enables a systematic and comprehensive identification of needs and problems is needed. Therefore, in response to the above-mentioned issues, this study aims to address the following questions: (1) What are government policies and programs that promote the adoption of digital technologies in the agriculture and food sectors? How are the factors influencing technology adoption by different stakeholders considered in policy process? (2) What are the perceived changes, challenges, and uncertainties facing the sustainable transformation of agriculture? (3) What needs be reformed and reinvented among different stakeholders in governing information flows?

To answer the questions above, from an integrated and interdisciplinary perspective [36], we aim to develop an inclusive analytical framework based on the meta-governance theory [37], which is helpful for capturing the complexity of digitalization, the dynamic interactions between stakeholders and their networks, the relevance of policy contexts in which these networks operate, and the leverages for changes. This analytical framework was then applied to analyze the cases of China and the EU, where multi-level governance exist and meta-governance is needed [29,33].

2. Analyzing Digitalized Transformation of Agriculture

2.1. Defining Digital Technologies and Services

In this study, digital technology and services refer to the application of digital technology for the digital industrialization of agriculture by various subjects with a certain level of affordability, education, and institutional support, on the basis of hardware with network coverage, internet access, electricity supply, and mobile terminals [25].

Digital technology and services are divided into two types: data and services. In this paper, data is classified according to Scown's classification of policies and practices for sustainable agricultural land systems [38], and services refer to those such as agricultural digital technology promotion, agricultural production and marketing solutions, environmental monitoring and management, advice on agriculture-related laws and regulations, and farming technologies and know-hows. The ultimate goal of digital technology and services is to realize the sustainable development of agriculture.

Digitalization-driven transformation of agriculture goes beyond agriculture as a sector and farmers as rural population. It requires integration of hardware and software, rural and urban, and collaboration of governments, businesses, and societal actors.

2.2. The Relevance of Meta-Governance Theory

The complexity of digitalized transformation means that there is a need to consider how different stakeholders should cooperate at various stages of the information flow [37]. The difficulty lies in the multiplicity of subjects and the complex structure of this process. There are often conflicts of interests, unclear obligations, negotiation-based rule-making, and dynamics of technology development [37,39–41]. Thus, digitalized agricultural transformation is a typical meta-issue.

Meta-governance is one of the representative theories of pluralistic cooperation, which can effectively address the complexity of sustainability governance [37]. "Meta-governance", also known as "governance of governance", is a higher-level approach to the integration of hierarchical, market, and network governance models, organizing and coordinating the governance mechanisms of government, market, and society. It has the advantage of anchoring different governance models in broader contexts in which the role of meta-governor can be discussed [41–44].

Meta-governance has three important attributes: firstly, it is a multiplicity of subjects, i.e., there are many actors such as government, enterprises and the public; secondly, it is a complex structural relationship, i.e., there are strong and weak structural relationships between subjects, which are not fully unified; thirdly, it has a "governor who governs", similar to the relationship of "peer elders", which enables government, market, and society to work together efficiently by creating a situation of coordination among multiple actors in information flow [37,39–41,45]. These three attributes make it flexible and powerful for addressing the realities of digital technology and services in agricultural transformation. (Table S1).

2.3. Analytical Framework from Meta-Governance Perspective

The meta-governance theory provides a new space of governance in which all the three types of actors (governments, market participants, and societal actors) are presented, and the functions of potential meta-governor are analyzed (Figure 1). All these actors and their networks are engaged in the generation, collection, analysis, disclosure and application, and impact of information flows. Depending on the characteristics of specific data and information, the capabilities and resources they possess, the interactions within and between different networks, and the policy and market contexts in which they operate, each of these actors can be potential suppliers, users, supervisors, or meta-governors [46–48]. To be more specific, in this analytical framework, governments include central and local governments, market participants refer to businesses and services, societal actors include farmers, farmers' organizations, social organizations, associations, research institutions, and media. It must be stressed that both the information flows as a result of digitalization and the institutional contexts in which actors networks operate are dynamic. Factors such as policy and institutional changes and technological advances can either constrain or enable digitalization. The effects and effectiveness of the meta-governance also depend on its ability to adapt to changes.

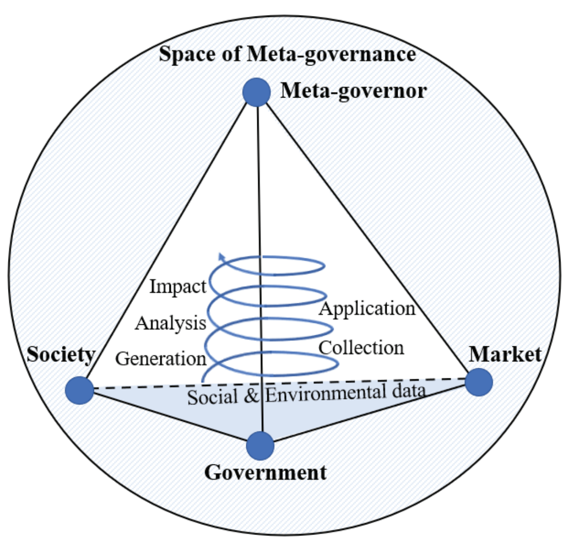

Figure 1. Meta-governance-based analytical framework for digitalization-driven agriculture transformation.

3. Case of China and the EU

Case studies on China and the EU serve two purposes: to test the relevance of the established analytical framework and to generate knowledge on the digitalization-driven agricultural transformation in China and the EU. Guided with the analytical framework, China and the EU are compared with regard to policy context, stakeholders involved, governments and governance modes, and roles of market actors and societal actors.

Both China and the EU have experimented with government-led digital technology service platforms. The EU set up Farm Sustainability Tool (FaST) based on the CAP to provide agricultural, environmental, and administrative simplification to farmers, EU member state payment agencies, farm advisors, and researchers through a user-friendly experience [49]. China's digital technology facilities are at a rapid stage of penetration, with provinces and cities setting up information platforms for farmers to connect farmers, farmer organizations, enterprises, consumers, and government departments through an online platform and offline outlets [13,17].

3.1. Policy Evolution

China and EU provide important experiences to draw from for validating the analytical framework in this study. However, as their initial platforms were not set up with the explicit goal of achieving sustainable transformation of agriculture, it is necessary to dig deeper into the evolution of their policy context. There are certain similarities and differences in the evolution of policies in China and the EU. For similarities, a top-down governance model can be observed in both cases. A central-local data sharing system exists in China and Europe. The Chinese central government has been continuously improving the top-level design of China's agricultural digital development. A three-in-one policy framework of "speed-breadth-quality" for agricultural digital technology has been formed [30]. In comparison, the EU's effort to establish inter-regional agricultural databases when the EU's CAP has changed the EU's original development model of promoting economic growth in agriculture [50].

For differences, in terms of policy starting points, the EU has been calling for the establishment of an agricultural database since 1992 through the reform measures of the CAP, well before China's initiative in 2015 [29]. In terms of policy objectives, China's digital agriculture development is designed to increase yields and incomes, agricultural modernization, and rural revitalization, with the transformation focusing on the means of production and technological development rather than on laborers. The EU's development is underpinned by the goal of farmers' income and rural development. In terms of the policy process, China has issued policies at a fast pace, with seven relevant documents issued in just four years from 2015–2019, especially in 2017, when the Ministry of Agriculture issued the Implementation Opinions on Promoting the Development of Big Data in Agriculture and Rural Areas, calling for the establishment of a global agricultural data center by 2025. In contrast, EU policies have been slower to advance, requiring a great deal of time to justify each policy as it progresses (Table S2).

3.2. Multiple Stakeholders in Agricultural Digital Transformation

In theory, all stakeholders can be potential providers and users of data and information. Different stakeholders have diverse roles and functions that can expand the application scenarios and technological innovations of digital technology services and promote sustainable transformation in agriculture. The role of stakeholders is mainly reflected in the flow of information. In China and the EU, for example, the government is able to standardize information standards, promote information sharing, integrate resources from all parties, and establish support platforms in the process of information collection. In the process of analysis and use, the government makes scientific decisions based on agricultural information. The diversity of social actors leads to the differentiation of different actors. Farmers and farmers' organizations upload data in the process of information collection, improve efficiency in the process of information use, and promote professionalization of labor and functionalization of decision-making. Scientific research institutions develop key technologies and supervise research data in the process of information collection. In the process of analysis, they establish analytical models to support government management and deepen research and provide development ideas. Social organizations and the media convey the needs of multiple parties in the process of information analysis, breaking the problem of information silos of various subjects. Market players integrate data and provide value solutions in the process of information analysis, ultimately realizing the mining of agricultural value and expanding business models.

We therefore need meta-governance theory to build an institutional framework for collaborative development and develop appropriate incentive mechanisms based on the needs of different subjects, to provide research support funding to improve farmers' returns, to promote market development and change government management, and to promote project incubation and implementation to achieve collaboration. Achieving sustainable development relies on the cooperation of government, markets, and farmers to build an innovation ecosystem that takes into account the drivers of different actors. Due to the complex linkages between different actors, sustainable agricultural development can only be achieved if they develop together [24,46,50] (Table S3).

3.3. Cases Studies

3.3.1. Government

China

Hierarchical decision making is particularly important in the Chinese governance model, in which central government provides top-level design and coordinates between different regions, while local governments are responsible for implementation and innovation. As a core part of the hierarchical governance model, the central government provides legal safeguards and oversees the process of the sustainable transformation of agriculture in a polycentric governance system, supporting and coordinating sustainable agricultural development [46]. However, the barriers to the property rights system for the flow of various resources and information in rural areas lead to poor information flow and prevent effective interaction between various stakeholders [51]. Besides, consultations generally take place only between governments, and it is difficult for other stakeholders to participate in the process [52]. As a result, it is difficult for the government to obtain a rapid response from the market and society to promote new technologies [41]. This dilemma is present in the diffusion of digital agricultural technology services [53]. On the other hand, the implementation of new governance models in China is generally based on local policy experiments with special central government interventions, relying on entrepreneurship, adaptation, and learning facilitated [40]. There are huge disparities in the economic development, natural conditions, and resource endowments of different regions in China. In order to facilitate information supply and demand coordination, local governments need to understand local agricultural production and farmers' needs [51]. Government departments therefore need to reconcile the top-level design of the transformation process of digital technology services with the different needs of local practice. The existence of a unified top-level design and local differences makes central and local coordination extremely important [30].

The government needs to build information communication channels with different stakeholders. For the promotion of digital technology and services among farmers in information collection, the central government should establish a unified system and channel, such as the "Information Platform for Farmers", in the hope of aggregating agricultural information to meet farmers' needs and the government's decision-making needs. For local governments, on the one hand, they need to implement the policies of the central government; on the other hand, they need to carry out innovative practices based on local information resource endowment and learning ability. In this way, the government's ability to recruit is a central element in the formation of information flow [53]. Currently, differences in digital technology endowment in terms of information investment, information equipment, and information capacity in different regions of China have resulted in huge disparities in the application of digital technology in agriculture across regions [54]. For example, the digital agriculture and rural development in Zhejiang province's counties is leading the country, with a development level twice as high as the national average, but there are still some provinces in slow digital transformation [55].

In information processing and analysis, China's agricultural science and technology innovation system consists of an agricultural research system, an agricultural technology extension system, and an agricultural science and technology intermediary organization, developed from the top down and categorized as part of the government. In the past 20 years, the number of funding inputs, topics, scientific papers, publications, and agricultural knowledge and innovation achievements in the field of agricultural science and technology have all been on the rise [56]. Research institutions also apply for a large number of variety rights and agriculture-related patents, and the index of intellectual property creation is much higher than that of corporate institutions [57].

The EU

In 1962, the EU fixed its agricultural policy with the CAP through comprehensive planning, design, and coordination of various stakeholders, and it has ensured the viability and effectiveness of the policy through continuous adjustments over six decades. After three rounds of major reforms, the CAP has progressively emphasized the wisdom, flexibility, and diversification of agricultural development on the basis of ensuring food security, and it has integrated rural development such as environmental protection, climate action, and agricultural competitiveness into the policy planning of the CAP [29,58]. The present data-driven agriculture governance system of EU can be characterized as hybrid regarding governance [59]. It has been undergoing a shift from formal, hierarchical policymaking to more open and inclusive modes of governance involving actors within the government, market, and civil society at multiple levels [60]. Government and other stakeholders seem to have played quite an active and beneficial role in meta-governance to resolve conflicts due to its perceived neutrality relatively [61].

The EU government is currently at the stage where information flows are generated and collected, but the division of responsibilities between the different levels is unclear. In the information flow, Eurostat and the farm accountancy data network (FADN) collect agricultural information by means of questionnaires in cooperation with third parties; the Agricultural Council is responsible for the analysis and processing of agricultural information, the formation of global guidance, and the regulation of markets, and the Agricultural Council is also responsible for publishing relevant information. Although the full responsibility of the EU agricultural information process is clear, its multi-level governance model coupled with market-oriented reforms, the disappearance of coordinating bodies, and the limited scope for the exercise of laws in different regions have led to a high degree of complexity and heterogeneity in the operation of the institutions [62].

3.3.2. Market Actors

China

The market actors, with the main goal of profit making, play important roles in promoting rural informatization and stimulating economic growth in digital agriculture. Santoso divided the agriculture information system into nine parts and focused on farmers and production activity [21]. Liu combined China's existing information technology promotion platforms, and they can be divided into nine categories based on enterprise function points: agricultural technology, machinery, technology, tools, services, trade, policy, loans, and land transactions [63]. On top of improving the hardware of digital technology, market players focus on cultivating the soft power of farmers to accept and use digital technology. In 2020, Alibaba worked with more than 100 counties nationwide to help train 133,200 farmers and nurture 100,000 new farmer anchors [64]. In 2021, Alibaba established the "Rural Talent

Revitalization" course program through its "Taobao Education" platform to provide free digital technology training courses to farmers [65].

In terms of information collection, the main way for market players to obtain information is to establish a partnership with the government. In addition, some of the more technologically powerful companies have begun to experiment with alternative ways of collecting agricultural data. Jing Dong, another Chinese e-commerce giant, applies digital technology to build modern agricultural bases and provide comprehensive solutions, while Alibaba Cloud uses the IoT to build digital origin warehouses and dock production and marketing processes [56,57].

In terms of information processing and analysis, market players integrate data from the agricultural production chain with China's national conditions, propose more optimal solutions for the production and marketing of agricultural products with the help of statistics, model building, visualization, and intelligent analysis, promote the effective interface between digital technology and agricultural production and operation, promote the deep integration of modern information technology with various fields and links in agriculture and rural areas, develop digital productivity to improve the quality, efficiency, and competitiveness of agriculture, activate the endogenous power of rural development, and increase market potential [13,66].

In terms of information impact, the e-commerce platform provided by commercial entities has played a huge role in the development of rural e-commerce by farmers. However, 95.4% of the 474 high-quality "e-commerce villages" are located in China's six developed coastal provinces, which cannot realize the "synergy sharing" and "mutual benefit" that digital technology services should provide. "The information divide is getting deeper and deeper" [54].

The EU

Since the 1990s, the EU's private stakeholders have played important analytical and influential roles along the information flow. In 2017, 474 and 157 counterpart consultancies in 51 and 42 private institutions in Italy and Germany, respectively [67,68], which create digital agricultural solutions through a supply chain management model, connecting directly with producers and providing services across the agricultural industry chain from cultivation to marketing through hardware systems such as monitoring base stations, remote visualization equipment, central control, and supporting software support such as management modules, early warning modules, and cloud-based management. By developing new agricultural technologies, technology companies are characterized as market style in meta-governance, and they improve agricultural production efficiency and reduce operating costs, allowing agriculture to shift from crude and inefficient to a sustainable development model. By establishing partnerships with governments or working with producers and operators to obtain data, market players obtain useful information from data, analyze it in depth, and use it to effectively predict or guide decisions [9,69].

For the promotion of the agricultural transformation of digital technology services, in terms of information generation and collection, market players are usually driven by material interests to develop a software package to obtain information from farmers through a business-company model, and an example would be Vital Fields, of Estonia. As a farm management tool, Vital Fields allows growers to record data, import maps, obtain help with compliance reporting, benchmark reports, and more. The software enables farmers to make a process of applying for European Union subsidies more efficient and automated. In terms of information analysis and application, the EU market players consist of technology and commercial companies, often working in partnership with governments and research institutions to form an independent platform. Food Valley NL, for example, is an independent platform for innovation and transformation of global food systems. Food Valley sets up a smart data system that contains all relevant and up-to-date data and knowledge, trends, and developments. It also lists the stakeholders in the food system (from investors to entrepreneurs). However, the multitude of market players has led to an increasingly competitive environment for service organizations to offer a diversified range of services, affecting the cost of access to IT services for farmers [62,70].

3.3.3. Society Actors

China

At present, the construction and development of agricultural digital technology services are increasingly tending towards real-time application, host-client integration, and overall co-biosis [6]. A large number of agricultural workers and managers are both users and makers of big data [9,71], but China has to overcome a number of barriers for digital agriculture and rural development. Overall, the level of digital agricultural and rural development in counties nationwide in 2019 reached only 36% [55], with only 23.6% of agricultural production digitized. The average age of China's agricultural production and operation personnel is on the aged side. Their overall education level is low: 91.7% of agricultural production and operation personnel have only received education at junior high school or below in 2020, and more than half of them have only received primary school education or below [72]. China's universal Internet infrastructure has achieved 309 million Internet users in rural China and an Internet penetration rate of 55.9% in rural areas [73]. There are already realistic conditions for improving farmers' ability to use digital technology, and there is an urgent need to improve farmers' ability to use IT in the digital transformation of agriculture.

Different stakeholders are trying to connect with farmers. The central government expects to use "Information Platform for Farmers" as a carrier to extend information technology projects to every administrative village in China. However, in practice, the role of "Information Platform for Farmers" is not significant. The "Information Platform for Farmers" is generally dedicated to providing technical training to farmers (e.g., cell phone use, access to data resources, agricultural technology training) and establishing e-commerce platforms for farmers. Three years after the establishment of "Information Platform for Farmers", 48% of the respondents had hardly heard of it. In addition, only 14.5% of Information Platform for Farmers is currently profitable, while 85.5% is not profitable or losing money [74]. This is mainly due to the fact that the training courses are not designed to focus on the "applied training" that farmers are interested in. In addition, the Information Platform for Farmers is not operating well, and it is difficult to get farmers interested in their training content [75]. Market players are also trying to motivate farmers for information training. Only 13,146 farmers participated in the same type of free course offered by the aforementioned "Alibaba" company [65]. This is similar to the dilemma governments face when promoting other types of agricultural technologies—the potential gap between technology supply and technology demand makes "recruitment" difficult [53].

The EU

The societal actors in the EU are mainly farmers, various farmers' organizations as well as social organizations, and the media. The main role of farmers' organizations is to act as a bridge between government and farmers and as guarantors of their common interests. On the one hand, farmers' organizations can transmit information to all their members via the Internet, association publications, and telephone calls, and on the other hand they are also the concrete implementing bodies for strategic guidance at national or regional levels, often actively advising the state. For example, in Austria, Belgium, Denmark, Finland, France, Lithuania, Portugal, Slovenia, Spain, and Sweden, farmers' organizations are the main providers of STI services to the public [67]. Farmer cooperatives can organize farmers to learn digital technologies, improve their scientific, technological, and business management skills and enhance their innovation, democratic awareness, and cooperative spirit. Due to the different levels of knowledge and education of farmers in different countries, farmers and farmers' organizations have different levels of acceptance of digital technology services [25].

For the diffusion of digital technology services, the role of farmers has also changed from being direct payers of services for help to being collectors of information in terms of information generation and collection [70]. The main reason for this is that the EU average knowledge level of farmers is among the world leaders, with 63.8% of 15–64-year-olds having a high school education or higher in 2020 [76]. The involvement of non-governmental organizations (NGOs) can also help to overcome the last-mile barrier to the application of data technology by fully understanding the needs, capacities, and concerns of farmers' practices, often considered to be the second-most reliable source of environmental information after scientific institutions [47]. In terms of information analysis and application, a large number of agricultural workers and managers are users of big data [9,71]. Farmers rely on agricultural information platforms, where farmers can upload, store, and analyze data to monitor weather changes, crop health, soil quality, and irrigation levels [35]. In terms of information influence, the media can enhance information exchange between different subjects, update farmers' knowledge and concepts, and improve their ability to receive and feedback information [68]. As a result, the media promote the development of the agricultural economy, the process of agricultural industrialization and the restructuring of the agricultural economy, and the development of markets such as agricultural e-commerce. Media operations are the most used and central tool in the field of agricultural information analysis and dissemination, publicity, and brand communication in recent years [30,77].

4. Discussion

China and the EU are accelerating the development of the digital agricultural transformation [25]. The government-led, market-led, and socially engaged synergistic promotion mechanism for the construction of digital agriculture and rural areas has gradually come into play, and a co-construction pattern of active input from enterprises and extensive participation by farmers and new agricultural business entities is taking shape.

4.1. Government as Meta-Governor in Digitalized Agricultural Transformation

Big data in agriculture is an inevitable trend in agricultural modernization, the basis for the development of digital agriculture, and an important means of intelligent agriculture. For the government, it should integrate the information system, emphasize demand orientation, adapt to local conditions and continuously improve the service capacity for ordinary farmers. The government should focus on public production service organizations to play a leading role in providing agricultural production services that are highly professional and technical and closely related to product quality and safety, and they should continuously improve the supply body of digital technology promotion services, integrate existing data platforms, promote government-enterprise cooperation and regional cooperation, create an integrated digital agriculture platform, build an integrated system of production, marketing, and protection, and improve the efficiency of digital technology application. The government, as a "meta-governor," needs to be involved in identifying common social goals and intervening with criteria other than purchasing power, which is a challenge for the government.

China is in the early stages of a sustainable transformation of its agriculture. The government still has a strong leading role in the development of digital agriculture. Chinese government is enabling the rapid development of China's agricultural information infrastructure, but, on the other hand, the government-led top-down governance model has been less successful in transforming into the meta-governance model needed for digital agriculture development. Some scholars argue that the existing governance model of the Chinese government is a continuation of sectional governance and does not belong to meta-governance [41], while others argue that it is a manifestation of "primus inter pares" and that the government is a responsible body that governs by "indirect-soft" means rather than a power body whose main mode is "command-and-control". For a country such as China with a strong hierarchical governance style, when the government acts as a "meta-manager", it may be necessary to clarify the boundaries of the government's role, focus on the needs of the real beneficiaries of digital agricultural technology services, and energize the market and grid governance styles [40]. The Chinese government conducts policy experiments under a hierarchical system, and farmers still behave passively in the flow of agricultural information, lacking the awareness and ability to collect, process, and apply information. However, due to the aforementioned weaknesses in China, the capacity building of farmers will be prioritized in future [66]. Sustainable transformation of agriculture cannot be realized without the changes of farmers [78].

The digital transformation of agriculture in the EU has gone through three phases of development and has already achieved some success. Nowadays, the role of government seems to be rather flexible and pragmatic and responsive to expectations associated with a certain governance style. One example is the Finnish forest data ecosystem. To build a data platform, the Finnish Forest center (FFC), a public body that operates under the steering of the ministry of agriculture and forestry, gathers data either by purchasing it from the private sector, from the general public, or from private-sector players via crowdsourcing solutions. Legitimacy of data-sharing activities was enforced. Furthermore, they provided a portal, which connects owners with relevant third parties, including providers of forestry services. The Finnish Forest policy program for integrated spatial planning argues explicitly in favor of more cooperation between government and citizens. Instruments to link different parts of government and stakeholders from different sectors rely on cooperation and trust, not on hierarchy [79]. Another example is from the Netherlands. As the second largest exporter of agricultural products worldwide, the 'National Proeftuin Precisielandbouw' (NPPL) (National Experimental Garden for Precision Farming) project has been launched in the Netherlands. In this project, experts from Wageningen University support farmers and gardeners in the application of various methods, such as location-dependent weed control and precision fertilization. The objectives are better harvests and a lower environmental impact from agriculture, and these strategies promote network governance under government guidance. In order to address the new challenges posed by climate change and the new pandemic for the development of European agriculture and to promote sustainable agricultural development, the EU has launched the "from Farm to Fork Strategy" and the "Biodiversity strategy for 2030" as the supplement of CAP, which enhance the competitiveness and resilience in response to the food crisis [34].

4.2. Engaging Non-Governmental Stakeholders Participation

Scientific research institutions need to promote the scientific research and innovation of digital technology in agriculture-related fields. Scientific research institutions should summarize and analyze the data and information generated in practice, build models, and construct risk prevention and control mechanisms in the agricultural sector. They should promote the application of big data in conjunction with relevant scientific research in the agricultural field and target and strengthen applied development research on the integrated application of data technology and technologies to assist decision-making, providing new methods and ideas for government decision-making and the development of agriculture-related enterprises.

Farmers are both the users and the makers of big data, and the impact of digital technology services on farmers' behavior is comprehensive and far-reaching. Not only does it provide a new data base in terms of farmer behavior and other aspects (leading to a more rational and optimal allocation of agricultural resources), a gradual reduction in environmental pollution, a better agricultural service system, and rapid development of the agricultural economy, but it can also change farmers' thinking and consciousness and establish the concept of sustainable agricultural development [25,80]. Meta-governance should promote information technology awareness and training to enhance information awareness, promote professionalism, and attract young farmers; different forms of self-organizations will also play an important role in engaging farmers.

For the market players, based on market demand, dig deeper into the value of demand and promote the effective docking of technology and agricultural production. Market players need to dig deeper into the value base of investment in the agricultural industry, promote the informatization of agricultural social service organizations, identify solutions to improve the efficiency of agricultural production by integrating data from the agricultural production chain, and promote the effective interface between digital technology and agricultural production and operation with the help of statistics, model building, and visual intelligent analysis. Market players use the new generation of digital technology to carry out the whole process of agricultural production, operation, and marketing supervision services and obtain stable investment returns to achieve their own business sustainability and social responsibility [13]. Therefore, there is a need to create a friendlier ecology of agricultural data technology services by a clear return on investment, creating enough business opportunities for them to drive solutions to technical challenges in agricultural practices [81].

In China, other stakeholders cannot be directly involved in the sustainable transformation of agriculture. Although most Chinese research institutions have tried or are providing data consultation or corresponding technical services to farmers in the process of transforming their achievements, the results are not effective. The main reasons for this include the lack of a professional service intermediary team adapted to the market mechanism, insufficient reliance on and importance attached to agricultural science and technology achievements by the stakeholders analyzed in this paper, and the inadequate design of the policy and regulatory system [82]. The media, NGOs, and farmer organizations' lack mechanisms for cooperation between different actors to participate in the digital transformation of agriculture in a sustainable or effective way [35,77]. To summarize the above, the Chinese government, with a tradition of a hierarchical governance style, moving towards more network governance seems to encounter serious obstacles with authorities.

The EU has a longer top-level design and now has some practical experience. FaST, the Copernicus, and ISA^2 provide technical support, will help EU farmers, member state paying agencies, farm advisors, and developers of digital solutions improve their respective capabilities across a host of agricultural, environmental, and sustainability-focused activities [49]. For farmers, the FaST platform helps to improve cropping management models, simplify day-to-day management, and improve economic efficiency while achieving environmental protection, in addition to facilitating communication between farmers and between farmers and other institutions about their own cropping history and overall European cropping programs. For the relevant EU institutions, the FaST platform helps to enable environmental monitoring of agricultural land, to increase two-way communication with farmers, to computerize agriculture, to simplify workflows, to develop relevant standards, and to build economies of scale. For researchers and farmer organizations, the FaST platform enables the provision of basic data and direct communication with farmers to deliver services. For policy makers, the FaST platform enables rapid retrieval of agricultural data, which helps analyze the current state of agricultural development and thus informs policy formulation. For NGOs, the FaST platform can help NGOs to connect with farmers or government agencies to reach collaboration and improve environmental action. For commercial service providers, the open-source nature of the FaST platform accepts value-added services provided by commercial service providers to farmers and helps to open up the smallholder market segment. In addition, some EU countries are also working on similar technologies for their own national contexts. In the future, in order to further promote the role of digital technologies in sustainable agricultural development, the EU needs to further promote the coverage of hardware facilities and increase the accessibility of digital technologies [83].

5. Conclusions

Digitalization is a means, not a goal. With increasing institutionalization of sustainability in policy making on agricultural development, digitalization is also increasingly being re-orientated to serve sustainable agricultural and rural transitions in both China and the EU. The EU represents a pioneer in the field of digitalized agricultural transition, while

China takes the advantage of late comer and is making a frog leap. The "fourth agricultural revolution" is on the way [84].

Digitalized agricultural transition also represents a typical case for meta-governance. Multiple goals, diverse stakeholders, conflicts of interest, uncertainties, and risks all contribute to digital politics. Without an effective meta-governor, rules of the game would not be made and followed automatically. Although market players are often the most innovative in technological development and marketing, and farmers as important end users define the success, it is the responsibilities of the government to initiate and facilitate the policy making and provide important public services. Having said this, it must be stressed that the roles of other non-governmental actors need be differentiated at different stages of information flows. The analytical framework proposed in this study recognizes the meta-issue nature of digitalization and emphasizes the importance of meta-governor. Tested in the case of China and the EU, this framework is proven inclusive and flexible to capture a holistic view and to identify similarities and differences in different countries. Future research needs to go further to explore different types of mechanisms and leverages and the conditions for them being effective.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12020297/s1, Table S1: Difference of governance style along information flow; Table S2: Digital agriculture policies of China and EU; Table S3: The role of stakeholders in promoting sustainable transformation in agriculture in China and the EU.

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Review

Digital Technology and Services for Sustainable Agriculture in Tanzania: A Literature Review

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Abstract: Digital technology has the potential to eradicate extreme poverty and food insecurity to the majority of smallholder farmers in the world. This paper aims to identify knowledge gaps on digital technology for sustainable agriculture and assess their availability to smallholder farmers worldwide. The particular case of Tanzania receives special attention. We conducted an extensive literature search from relevant databases for review. The advanced digital technology in agriculture, mostly used by large scale farmers, significantly contributes to sustainable agriculture. However, the existing digital services for smallholder farmers lack sustainability in the agriculture context and hardly meet the needs for a comprehensive set of services in a complete farming cycle. In most developing countries, Tanzania case included, digital technology and services respond to a challenge at a particular stage of the farming process or to a specific value chain. Based on this literature review, we identify inequalities among large and small farmers, as well as environmental challenges caused by ICT itself. To conclude we provide suggestions for improvements for smallholder farmers: developing a digital platform that addresses smallholder farmers' challenges in a complete farming cycle, bringing together the stakeholders at a country level, in order to achieve sustainable agriculture and support adoption of cutting-edge digital technology. These suggestions will be the starting point for future research.

Keywords: digital technology; sustainable agriculture; smallholder farmers; ICTs services; precision agriculture; smart farming; farmers services; Tanzania

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1. Introduction

The application of digital technologies in agriculture may eradicate extreme poverty and hunger in a yet constantly growing population—from 2019 to 2050 the population will increase by 2 billion people [1]. In recent years, digitization has changed the way the society performs its social-economic activities particularly due to increased interconnections through the internet and affordable digital devices creating a global digital ecosystem [2]. Digitization is increasingly becoming an essential tool of production, business and services to recover the society from unexpected novel corona virus pandemic that has brought devastating impact on the social, economic and environmental aspects [3]. The use of digital technology has proved useful in various sectors worldwide, such as Malaysian industries [4], healthcare [5] or manufacturing [3]. In the agriculture sector, digital technology has increased profitability, enhanced the quality of the products and somehow preserved the environment [6]. The current "Industry 4.0 digital transformations" apply advanced technology in the agricultural field for a more precise and real-time decision making in farming activities [7]. This new era of digital technology in agriculture uses knowledge from different disciplines, which include information science, computer and software engineering, environmental science, remote sensing, geographical positioning systems (GIS), crop and soil science and global positioning systems (GPS) [8]. The farm management system uses modern technologies such as artificial intelligence (AI), sensors, the Internet of Things (IoT), satellite images to collect data, big data and machine learning, contributing to higher productivity and profitability in this sector [6].

However, most small and medium-sized farmers cannot afford to adopt such modern technology for sustainable agriculture, which is contrary to the United Nations Sustainable Development Goals (SDG) principle of "leaving no one behind" [9]. Smallholder farmers generate enormous employment and income worldwide while producing over 70% of the world's food needs [10]. In Tanzania, the agriculture sector is the backbone of the economy with 26.7% of the GDP, employing more than 80% of the population, and women constitute 60% of the farm workforce [11,12].

Many scientists and organizations have used different approaches to enable digital technology by smallholder farmers to increase productivity and income. Efforts include developing mobile and online services that allow smallholder farmers to access various services such as weather information, farming information and knowledge, market information, and reliable buyers for their products [13,14]. According to Boyera and Grewal [15], and Gray et al. [16], digital technology and digital farmers profiling platforms for smallholder farmers could help farmers access essential services and improve productivity. However, despite all those efforts, the sustainability of these projects remains a significant challenge for achieving sustainable agriculture [10]. Furthermore, the application of digital technology requires the study of the value chain to meet the needs of services in the context of the farmer ecosystem.

This paper is part of a larger research project to harness digital technology for sustainable agriculture in Tanzania, which aims to identify knowledge gaps on digital technology and services available to smallholder farmers and sustainability in agriculture. Moreover, it suggests digital solutions for smallholder farmers towards sustainable agriculture in developing countries. The subject aligns with the United Nations SDGs, such as eradicating poverty and hunger, sustainable cities and communities, climate action and reducing inequality [9]. Developing new digital comprehensive artifacts could solve the existing problems of digital exclusion of smallholder farmers, such as access to credit, farming knowledge, farm inputs, government services and control, and the market for their products [17–20]. Responsible agriculture actors could adopt the artifact according to their country context. Therefore, this review addresses the following questions:

1. What digital technology and services are available to support the agriculture sector?
2. What is the relationship between digital technology and sustainable agriculture? How do smallholder farmers fit in?
3. What is the state-of-the-art use of digital technology and services by smallholder farmers in Tanzania?
4. What challenges need to be addressed in relation to the above questions?

The last question concerns the future research agenda and will be further developed in a subsequent publication. In this paper we focused on digital technologies and services in agriculture, with a specific emphasis on smallholder farmers and sustainability.

We organized this paper as follows. Section 2 describes the authors' methods to select papers for this review. Section 3 reviews related works that answer the above first three questions, which guides this review. Section 4 responds to the fourth question; it analyzes and synthesizes gaps regarding the availability of digital technologies and sustainable agriculture (as defined in this paper) to smallholder farmers. Section 5 concludes with a summary of the review and suggests future work.

2. Research Methods

We used PRISMA guideline in this study [21], which is a standard protocol and an evidence-based framework for doing systematic review studies. We conducted an extensive literature search based on a complex query in the Web of Science (WoS), IEEE Xplore and related databases (Food and Agriculture Organization, Google Scholar and

Research4Life). The aim was to find and review the latest literature in digital technology and sustainable agriculture in relation to smallholder farmers. The researchers combined the following keywords using the Boolean operators ("AND" and "OR") and parentheses during the search: digital technology, ICT services, smart farming, precision agriculture, digital farmer profiling, smallholder farmers and sustainable agriculture. The final search string was "('digital technology' OR 'ICT services' OR 'precision agriculture' OR 'smart farming' OR 'digital farmer profiling') AND 'sustainable agriculture' AND 'smallholder farmers'". However, the search string could not yield good results to FAO database due to type and differences in functionality. We conducted a search in October and November 2021, obtained and imported a total number of 1981 articles to Mendeley Desktop reference manager software (https://www.mendeley.com, accessed on 4 October 2021).

We applied exclusion criteria to the obtained results to identify relevant papers in digital technology, smallholder farmers and sustainable agriculture. We restricted the obtained results to the year of publication from 2015 to 2021 to get the latest articles in the subject area. We filtered out duplicated papers (using duplicate function in Mendeley software), articles without full text and not written in English. The inclusion criteria were as follows: (i) modern digital technologies in agriculture (e.g., smart farming, digital farmer services) including the sustainability components (economic, environmental and sustainability of the ICTs infrastructure and resources) and (ii) availability of the technology to smallholder farmers. Finally, we selected a total of 36 articles: 24 articles on global literature (21 for recent digital technologies and sustainable agriculture, three on general digital service platforms developed for smallholder farmers) and 12 for the Tanzanian case.

We separately searched the literature in the Tanzanian case in local repositories (Sokoine University of Agriculture Institutional Repository), WoS and Google Scholar. In this search, we did not limit the literature by the year of publication to obtain more detailed background information in the country's ICTs and smallholder farmers' services. We obtained 18 articles from local repositories for analysis as the result of the complex query "digital technology" OR "ICT services" AND "smallholder farmers" OR "agriculture" AND "Tanzania". We selected 12 articles for the review after filtering five articles which were similar to articles from Google Scholar and WoS, (see Table 1).

Table 1. Reviewed literature under PRISMA guideline.

Search Category	Identification		Screening		Included
General literature	Records identified from databases (N = 1981)	Duplicate removed (N = 85)	Records screened (N = 1687)	Records excluded (N = 1581)	Studies included in review (N = 24)
		Removed for other reasons (N = 209)	Reports sought for retrieval (N = 106)	Reports not retrieved (N = 11)	
			Reports assessed for eligibility (N = 95)	Reports excluded by the study criteria (N = 71)	
Tanzanian case	Records identified from databases (N = 18)	Duplicate removed (N = 5)	Records screened (N = 13)	Records excluded (N = 1)	Studies included in review (N = 12)
		Removed for other reasons (N = 0)	Reports sought for retrieval (N = 12)	Reports not retrieved (N = 0)	
			Reports assessed for eligibility (N = 12)	Reports excluded by the study criteria (N = 0)	

3. Results

We present the results of this paper in response to the research questions. First, the results of the digital technology and services available to support the agriculture sector worldwide. Second, the results of the relationships between digital technology and sustainable agriculture, focusing on smallholder farmers inclusion in digital transformation.

Furthermore, we re-defined sustainable agriculture in the context of this paper to address the identified gaps in existing literature. Finally, the results of the Tanzania case current status in the use of digital technologies in agriculture and challenges towards sustainable agriculture.

3.1. Digital Technology and Services in Agriculture

For a long time, the agriculture sector has embraced new technologies to increase production and profitability while improving the environment. The Organization for Economic Co-operation and Development (OECD) defines digital technologies as: "ICTs (information communication technologies), including the Internet, mobile technologies and devices, as well as data analytics used to improve the generation, collection, exchange, aggregation, combination, analysis, access, searchability and presentation of digital content, including for the development of services and apps" [22].

Farmers use digital technologies in different domains of agriculture (summarized in Table 2). These domains include digital technology for farm management, financial services, market services, and farming knowledge and information services. Additionally, some digital platforms provide all essential services to farmers in the farming ecosystem. Many ICTs projects for farmers at the country level offer solutions to a particular farming problem, mainly for a specific value chain.

Table 2. A summary of digital services for farmers.

Services		Digital Artifact Solutions	Sources
Farm management	IoT	Sensors: Fixed position, UAV, Satellites, UGV	[23–27]
	Data Management and Analysis	Farm Management Information Systems (FMIS)	[7,28,29]
	Decision-making and Variable Rate Technology	Variable rate nitrogen fertilizer (VRNF), CLAAS VRT, Automated yield monitoring system II (AYMS II), fuzzy logic DSS, AgroDSS	[30–33]
Financial services		Index-based agricultural insurance, AFPOH, M-Banking	[34–38]
Knowledge and information		Weather forecasts, pesticides, and fertilizer information; KALRO mobile applications, Farmers Advisory Systems	[39–41]
Market		eSoko, Tru Trade, E-Wallet Scheme, E-Krishok and Zero Hunger	[35,41–43]
e-Government		Online Fertilizer Recommendation System (OFRS) in Bangladesh, AFPOH in India, KALRO in Kenya	[35,40,44]
Profiling platform		Digital farmer profiling platform	[10,15,16]

Source: Author's compilation.

3.1.1. Farm Management

The current industry 4.0 digital transformation in agriculture integrates IoT, cyber-physical systems, AI, Big Data, Machine Learning and Cloud computing with agricultural machinery [45]. It is more common to precision agriculture whereby innovative ICT solutions and IoT components such as sensors monitor spatial and temporal variability in farm production [7,46]. Site-specific farm management provides an understanding of soil and crop characteristics unique to each field, thus enabling farmers to apply farm inputs (such as irrigation, fertilizers, pesticides and herbicides) in small portions where needed for the most economical production [47]. Controlled farm inputs increase farm productivity and profitability and conserve the environment, promoting sustainable agriculture development [48]. Precision agriculture and smart farming rely on data management to make valuable decisions. The embedded digital technology components can be categorized into three phases: (1) data collection (IoT), (2) data management and analysis, and (3) decision making and variable rate technology (actuation) [6].

Data Collection—IoT

IoT in agriculture uses sensors—devices used to collect data from the field for easy monitoring of the crops and other digital tools to collect essential data for profitable decision-making in farming [6]. The sensors are mounted in the mobile farm machinery or fixed in the field, such as a local weather station. For instance, Kilin [23], used a network of automated stations in the vineyards to detect areas affected by pathogens for site-specific application of pesticides. The stations collect real-time data such as airborne particles, temperature and relative humidity of the air and soil, solar irradiance, spores, and leaf humidity. AI is then used to analyze the spatio-temporal heterogeneity data based on optical particle counters (OPC) to identify areas affected by the pathogen (i.e., *Plasmopara viticola*) [23]. The results allow farmers to apply pesticides in specific field zones leading to cost-effective, healthy products and environmentally friendly farming practices. Saiz-Rubio [6], classified sensors into three: remote sensing, aircraft, and proximal sensing. Remote sensing, most often satellites, has been an essential tool for collecting field data in smart farming. The satellites used to provide agricultural data include WorldView 2 and WorldView 3 multispectral satellite sensors using Normalized Different Vegetation Index (NDVI) standard [24,49]. Furthermore, the European Sentinel 2 satellite system, which gives access to 10 m 4-band multispectral data for "NDVI imagery of soil and water, covers the Earth every 10 days; the American Landsat satellites provide spectral data from the Earth each 16 to 18 days" [6,49].

Aircraft sensing, usually "remotely-piloted aircraft (RPA) and unmanned aerial vehicles (UAV)" such as drones, capture field data at a closer distance of up to 100 m, contrary to the order of 700 km of satellites [2]. Although aircraft sensing is expensive and requires high skills to generate quality field data, they are flexible and reach field areas where other equipment cannot. Proximal sensing is the latest technology based on "autonomous ground systems", promising new agriculture transformation [2]. According to Saiz-Rubio [2], in comparison to remote and aircraft sensing, proximal sensing monitors the crop in the ground at less than 2 m between a crop scanned and sensor. The payload of sensors is placed in ground vehicles that move around the field to collect accurate and quality data from the crops. Proximal sensing allows a real-time application, such as applying fertilizer where needed and spraying herbicides and pesticides where weeds or pests have been detected [25].

Robotic technology in farming is another area of interest and part of proximal sensing where unmanned ground vehicles (UGV) collect data and manage various farm activities [26]. The farmers use UGVs for soil analysis, seeding, transplanting, harvesting and crop scouting. Thus, UGVs allow a continuous field data collection process to monitor crop status and growth conditions [50]. VineRobot and Vinescount, funded by the European Commission, are examples of robotic technologies in smart farming that monitors vineyards by collecting data from the vines' canopy and creating water and nutrition status maps [6]. Industries manufacturing agricultural tools are also producing scouting robots. For example, Rowbot Systems LLC of USA introduced a multitask robotic platform to map crop growth zones, apply fertilizer and other related tasks [27]. Another example is the robot Oz the autonomous weeding and seeding [51].

Data Management and Analysis

A digital system receives data from different IoT devices and helps generate meaningful information for production. Large scale and commercial farmers use farm management information systems (FMIS) to acquire data, store, analyze and manipulate data in precision and smart farming. FMIS enables farmers to manage various farming activities from the initial planning stage to harvest and record important information of the performed activities [28]. Farmers can extract information such as field maps to determine crop and field conditions necessary for actions related to minimal use of resources, compliance with standards, and quality of agriculture production. There are different FMIS on the market (most are proprietary) with various features to manage farm generated data. The systems manage farm operations based on data acquired and processed automatically for planning, monitoring, supporting decision-making and keeping valuable records [29]. Hrustek [7], mentioned that FMIS records critical information, including "harvests and yields, profits and losses, farm task scheduling, weather prediction, soil nutrients transport and field mapping". A few examples of FMIS are ADAPT, Agrivi, Agroptima, Farmleap, owned mainly by companies from developed countries. More advanced FMIS provides early warning, financial management and integrates other actors such as input suppliers and product distributors.

Decision-Making and Variable Rate Applications

Farmers need to decide on the vast volume of collected data, considering different field parameters. Managing such complex data manually is difficult, time-consuming and possible for ineffective decision-making. [7]. Hrustek [7], added that farmers could use artificial intelligence (AI) and machine learning to support decision-making in agriculture through available big data. Wolfert [30], argued that agriculture has many areas for applying different AI technologies. For instance, Giusti and Marsili-Libelli [31] developed a decision support system (DSS) based on fuzzy logic to manage irrigation considering the soil characteristic and type of crop. Additionally, Bazzani [52] developed a decision-support system (DSS) that analyzes short- and long-term availability of water based on soil type, machinery and irrigation systems. Furthermore, Rupnik et al. [32], developed AgroDSS cloud-based DSS that allow farmers to upload data or integrate with FMIS through an application programming interface (API) to get different output decisions such as farm pest management.

The variable rate technology (VRT) has made it possible for the decision to be made autonomously. According to Hrustek [3], actuation is the execution of activities in the field following decision making from collected data. VRT includes robots used to perform different farm activities (farm preparation, planting, pest and weed control, fertilization, harvesting) previously conducted by human labor or conventional farm machines [24,31]. The variable-rate device receives commands from a computerized DSS. It performs various farming tasks such as applying fertilizer, pesticides and herbicides in the specific field zones where needed (real-time applications) and harvesting [53]. A few examples of VRT machines include the automated yield monitoring system II (AYMS II) made of unique "eye" color cameras and real-time kinematics-GPS for wild blueberry harvesting [54]. A sensor-based variable rate nitrogen fertilizer (VRNF) measures nitrogen with a multispectral sensor and fertilizer spreader mounted on a tractor, for real-time application conforming to the measured nitrogen in the crop [33]. The CLAAS VRT is used to apply nitrogen fertilizer, compatible with the "ISARIA" sensor [7]. VRT increases production and preserves ecological balance through efficient farm inputs, i.e., less crop fertilizer and chemicals [55]. Figure 1 presents the three main categories of smart farming data life cycle.

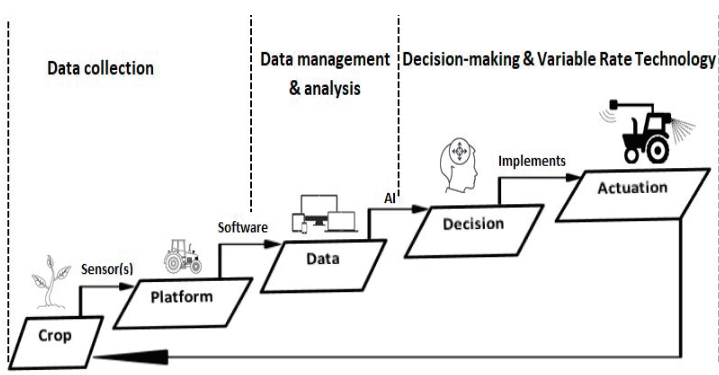

Figure 1. Smart farming data life cycle inspired by Saiz-Rubio and Rovira-Más [2].

3.1.2. Financial Services

Smallholder farmers face the challenge of access to financial services affecting agriculture production and income of many rural communities in developing countries [17]. Digital technology is an essential tool for improving access to finance and the commercialization of smallholder agriculture. A study on the awareness and use of m-banking (mobile banking) shows that most smallholder farmers in Kenya use the technology to access finance for agriculture-related activities [34]. Kirui [34], concluded that m-banking enables smallholder farmers to access investment capital for purchasing quality seeds, farm machinery, fertilizer and pesticides, leading to increased production and income. The Association for People of Haryana (AFPOH) is an ICT-based agriculture initiative in India that enables most smallholder farmers to access finance for improved agriculture [35]. Different countries embrace digital technology to allow the commercialization of smallholder agriculture as poverty alleviation and food security strategy.

Furthermore, agriculture insurance is an essential service for smallholder farmers. The farmers normally encounter various production and market risks which lower their income and ability to produce year after year. Hess and Hazell [36], mentioned natural disasters such as extreme droughts, floods, hurricanes and pest outbreaks are common risks for smallholders. The risks cause severe impacts in economic development which leads to extreme poverty. In the past, governments and organizations designed several insurances to help small farmers towards sustainable agriculture. However, agricultural stakeholder and organizations considers index-based agricultural insurance as more effective for smallholder farmers in developing countries [37,38]. Still, majority smallholder farmers particularly in Africa have no access to insurance. For instance, approximately 650,000 farmers have access to insurance in Africa out of around 40 million smallholder farmers in Sub-Saharan African alone. [36]. The current trend of climatic change requires financial investment for agriculture transformation, including increasing availability and access to credit and insurance by smallholder farmers [56].

3.1.3. Knowledge and Information Services

Dissemination of agriculture information and knowledge is a critical move towards improved farming. Most smallholder farmers lack farming information and knowledge, so they rely on friends, family, and experience, resulting in low production [57]. Access to data in a complete farming cycle, from farm preparations, inputs, finance, harvesting and market of the products, creates high value in the commercialization of smallholder agriculture. Ali et al. [39], examined the critical information needs of farmers in Pakistan and developed a digital solution to deliver weather forecasts, pesticides and fertilizer information. E-agriculture initiatives in India emphasize disseminating information to most rural smallholder farmers through ICT, including management information systems, knowledge management systems and expert systems [35]. Sanga et al. [58], developed an information dissemination system to enable smallholder farmers to access critical farming information and knowledge from experts, bridging the gap of extension services through ICT. Scientists and organizations have developed mobile applications to disseminate different crops and livestock information. For instance, Kenya Agricultural and Livestock Research Organization (KALRO) has produced more than fourteen mobile applications for crops and livestock to help farmers access information and adopt modern farming techniques for increased production [40].

3.1.4. Market Services

Most large scale farmers use advanced FMIS, which provide linkage to critical services, including the market [42]. For instance, we can mention the combination of different methodologies to design information integration in the Netherlands for information sharing that supports the food supply chain—a movement of food into various stages from farmers to consumers and movement of money paid for the food by the consumers back to the farmers via the same steps in the reverse direction [59]. Wolfert et al. [59] argue that big data in smart farming is appealing as farmers can either be part of the closed, proprietary systems or of an open, collaborative system. A proprietary system is a highly integrated system of stakeholders bounded by terms and conditions. In contrast, with "open, collaborative systems" farmers are free to choose any stakeholder as business partners in a food supply chain. In either of the two (closed or open) scenarios, the food supply system enables farmers to exchange information with other actors in a supply chain (two-way traffic), harnessing essential knowledge for production based on consumer needs and other factors in the supply chain.

Smallholder farmers face the challenge of market access for their products [42,60]. Intermediaries force farmers to sell their products at a low price, resulting in unprofitable production. Thanks to ICT, smallholder farmers can access market information and participate in better-paying agricultural production. Market access is one of the critical components in e-agriculture initiatives in India. Rural farmers are linked to the market and get fair prices, improving income and sustainable life [35]. ICT related cases in Africa include "eSoko" in Ghana, "Tru Trade" in Uganda and "mFarming" in Kenya, Ghana and Tanzania [43]. These programs address the challenge of access to market information and fair price for smallholder farmers' products.

Furthermore, Nigeria's "E-Wallet Scheme" enables smallholder farmers to access subsidized inputs through mobile phones. Meanwhile, "E-Krishok and Zero Hunger" in Bangladesh and "Farmes' Advisory Information System" in Tanzania provides extension services to farmers, mainly advising farmers on farm input products [41–43,58,61]. These and many other related efforts not included in this paper are promising ICT initiatives for smallholder farmers access to the market.

3.1.5. e-Government Services in Agriculture

Governments play a fundamental role in developing any economic sector, including agriculture. For a long time, most governments have provided various services in agriculture, most often through extension agents responsible for linking with farmers [62]. However, several limitations to using extension agents include the difficulty of reaching the many smallholder farmers scattered throughout the rural areas, the inability to deliver multiple agriculture services to farmers and the high involved costs [63]. Governments have a central role of monitoring, controlling and bringing together agricultural stakeholders for services deliverance at a single access point; thus, promoting digital technology for sustainable agriculture at a country level. OECD [22], mentioned that ICT promotes government transparency and accountability to the community. Therefore, e-government provides opportunities for the government to deliver multiple, coordinated and timely services under one roof through a network of agricultural actors. Ntaliani et al. [64] assessed the potential of e-government in the agricultural sector which suggests that government should use the e-government model to offer services to farmers and rural communities. The Indian government, through the ministry of agriculture, supports various ICT programs for smallholder farmers to access essential services such as farm inputs, financial services, subsidies and market for increased production and income [35].

3.1.6. Digital Farmer Profiling Platforms and Services

Apart from precision agriculture and smart farming, many ICT services provide isolated solutions packages to farmers' needs. Digital farmer profiling is a business model developed in the past few years to provide essential solutions to smallholder farmers' needs. The platform service manages farmers' data based on blockchain technology to allow farmers to share their data with other stakeholders (such as credit and insurance companies) [16]. Digital farmers profiling seems promising in service delivery to the smallholder farmers. Studies in Africa, Asia and Latin America show how digital farmers profiling enables smallholders to access essential services such as financial services and marketing of their products [10,15,65,66]. Service providers manage the data (for a fee) on behalf of other actors, including the farmers. Despite the long debate over who owns the data (between service providers and farmers), Grameen Foundation—as experienced experts in the farmer profiling platform business model, has stated that sustainability of the project is a significant challenge once the project fund ends [16]. In addition, Boyera and Grewal [15] concluded that each country and value in the crop or livestock chain would have its approach to implementing a farmer profiling platform.

3.2. Digital Technology and Sustainable Agriculture

According to Bhakta et al. [53], Giray and Catal [67], sustainable agriculture refers to agricultural practices that ensure long-term increased farm production and farmers' income while protecting the environment. Precision agriculture and smart farming present a high level of sustainability using the most cutting edge technology to control farm inputs such as fertilizers, irrigation, herbicides and pesticides [6]. Farmers apply farm inputs to only parts of the field that need, thus improving product quality, reducing input cost, increasing productivity, preserving the environment, and achieving economic and environmental sustainability [7,67]. Social sustainability in agriculture results from economic and ecological sustainability, whereby, refers to the availability of enough food for all people, animals, and plant species in the world [7]. Literature on sustainable agriculture mainly focuses on agricultural operations and business models for increased profit while minimizing the use of agrochemicals to promote a healthy environment and higher production quality. The new "fog computing model" is useful for a clean environment in smart agriculture. Unlike cloud computing, the fog computing model reduces carbon emissions through energy-efficient digital hardware and renewable energy resources since data are processed closer to where it is collected [68].

In addition to previous sustainability approaches, this paper focuses on the fundamental component of sustainable agriculture in the digital era: the sustainability of infrastructures and resources that support digital agriculture services for smallholder farmers. Thus, this paper categorizes sustainable agriculture into three main topics: (i) sustainability of the infrastructure and resources offering digital services, (ii) economic sustainability—long-term increased productivity and profitability, and (iii) environmental sustainability—conservation ecology and minimizing ICT pollution through green computing (Table 3).

Table 3. Sustainable agriculture.

Components	Definition/Meaning	Characteristics
ICTs Infrastructure and resources sustainability	The ability to maintain digital systems (hardware and software) and human resources (such as IT specialists, services providers and data collectors) for long-term services to farmers.	Regular maintenance Hardware replacement Software upgrades Budget for human resources and service providers Energy consumption Environmental impact of production and disposal of ICT hardware
Economic sustainability	Refers to a long-term increased farm production that eventually increases farmers' income.	Less input cost High production Good market price Increased farmers' income
Environmental sustainability	Refers to actions taken consistently for conservation ecology by minimizing harmful agriculture and ICTs' environmental impacts.	Less use of agrochemicals Use of fortified agrochemicals Use of renewable energy Energy-efficient hardware Use of recyclable hardware Less carbon emission from data centers

Source: Author's compilation.

The literature review provides current status digital technology for sustainable agriculture, services available for smallholder farmers and Tanzania's case. Most established digital services for smallholder farmers lack environmental sustainability and sustainability of the infrastructure and resources that support the services. Some of the services in developing countries propose charging farmers and other beneficiaries to achieve sustainability of the services. For instance, the farmer profiling platform business model suggests that service providers receive revenue through interest paid on credit by farmers, commission on farm inputs and fees charged from buyers of the farm produce [16]. Although the model may achieve sustainability of the digital services, the burden cost is primarily on farmers, limiting the economic sustainability of individual farmers and farmers' organizations. Table 4 presents the availability of general digital transformations and agriculture sustainability to smallholder farmers.

Table 4. Digital services, smallholder farmers and agriculture sustainability.

	Literature	Availability to Smallholder Farmers	Digital Technology and Agriculture Sustainability: ICTs Infrastructure and Resources Sustainability	Economic Sustainability	Environmental Sustainability: Conservation Ecology	Environmental Sustainability: Green Computing
Digital technology for farm management	Data collection—IoT [6,23,26,44,49,50]	×	×	√	√	×
Digital technology for farm management	Data management and analysis [7,29,45]	×	×	√	√	×
Digital technology for farm management	DSS and VRT [25–27,30–32,51,53,69]	×	×	√	√	×
Digital farmer profiling platform	[10,15,16]	√	√ *	√ *	×	×
Agriculture sustainability	Economic sustainability [6–8,33,53,67]	×	×	√	√	×
Agriculture sustainability	Environmental sustainability: Conservation ecology [6–8,33]	×	×	√	√	×
Agriculture sustainability	Environmental sustainability: Green computing [68]	×	×	√	√	√

Source: Author's Compilation. Note: √ (Addressed) √ * (Addressed with limitations) × (Not Addressed).

3.3. Digital Technology and Tanzanian Agriculture

The Tanzanian government has consistently supported smallholder farmers and the agriculture sector. Since the 1960s, the government introduced 16 National Agriculture Input Voucher Systems (NAIVS) for farmers to access and use modern farm inputs (seeds and fertilizers) through contracted agro-dealers for improved production and income [70]. However, due to lack of government control, cheating and fraud, contracted agro-dealers sell the subsidized inputs at full market price, leading to deficient programs' impact on farmers [71].

Indeed, since the adoption of ICTs in the national development plans in 2003, many ICTs related projects have been conducted to address various challenges in the agricultural sector. Generally, the target areas are agricultural information dissemination by agricultural research institutions (ARIs) and extension services to farmers and farmers organizations (FOs) [13,14]. The increased use of mobile technologies also triggered projects on mobile farm services such as Global System for Mobile Association (GSMA) "Mobile for Development" projects and mobile applications to support farmers in different value chains [14], mobile application for poultry farmers [72], and mobile decision support systems [73,74]. Furthermore, the design of farmers digital advisory service called "Ushauri" to provide access to context-specific information from extension agents increases capabilities in decision-making and adaptation to changing environments [75]. These digital services don't meet the needs of a farmer's entire ecosystem; nor are they sustainable, as some of the mentioned services don't exist due to lack of sustainability plans or because farmers do not use the service. Digital technology intervention could attenuate the challenges and improve smallholder farmers' access to services for increased production and income. Table 5 presents the summary of existing digital artifact solutions and services addressing some challenges of farmers in Tanzania.

Table 5. A summary of digital services to farmers in Tanzania.

Services	Problems	Digital Artifact Solutions	Sources
Financial	Lack of access to credit	None	[19,76]
Farm inputs	Counterfeit fertilizers, pesticides and herbicides	Agro-inputs Products Verification System (APVS) mobile application	[77]
Market	Access to market and market information	mFarming mobile service	[43,78]
Agriculture knowledge and information for decision making	Lack of information, farming knowledge and extension services	mAgri tracker GSMA Mobile for Development projects	[14]
		Android mobile application for poultry farmers	[72]
		A web and Mobile-Based Farmers' Advisory System for extension services	[41,58]
		A mobile Decision Support System for access to climatic information	[73]
		A mobile and web-based extension support system for horticulture farmers	[74]
		"Ushauri" digital advisory service	[75]

Source: Author's compilation.

Despite all the efforts, smallholder farmers in Tanzania still face many challenges in accessing services from other actors in a farmer ecosystem. Challenges include access to credit [19,76], substandard agricultural inputs from uncertified agro-dealers [77,79,80], unfair market prices due to the involvement of middlemen and lack of government oversight [14,60,81,82].

4. Discussion

This paper emphasized the digital technology and services in agriculture, focusing on the smallholder farmers' participation in sustainable agriculture. So far, similar to other sectors such as manufacturing industries, agriculture sector is undergoing major digital transformations through the application of cutting-edge digital technologies.

Inequalities: It is also important to note that digital transformations in agriculture are highly characterized by digital inequalities between large- and small-scale farmers, and between high-income and low-income countries. Governments, researchers, organizations and other stakeholders need to address factors leading to digital inequalities for smallholders to engage into sustainable agriculture. Sustainable agriculture by smallholder farmers require digital solutions for solving common challenges, which need strong commitment and collaboration among agricultural stakeholders at a country level, and then the adoption of advanced digital solutions such as precision technology.

Technology advancements create possibilities for solving many social-economic challenges that the world faces. Smart agriculture is the latest technology that uses the most advanced tools and software such as remote sensing, big data, IoT, information systems, AI, decision support system (DSS) and variable rate application (VRA) in farm management [6,7,53]. However, these digital advancements in agriculture are not equally available around the globe due to different social-economic factors. While developed countries are fast-moving in cutting-edge agricultural technologies (agriculture 4.0), developing countries are lagging, leading to low production and environmentally unfriendly practices [83,84]. Some of the developing countries are making steps towards precision agriculture. For instance, Bangladesh's online fertilizer recommendation system (OFRS) enables smallholder farmers to efficiently apply fertilizer for sustainable agriculture production [44]. A review study shows opportunities for adopting precision agriculture by smallholder farmers in Sub-Saharan Africa (SSA). Nevertheless, these technologies are mostly experimental and mainly used by large-scale commercial farms in few SSA countries [85].

ICT—an environmental concern: The uneven adoption of new technologies in agriculture affects more than one billion smallholder farmers worldwide, which the FAO considers the world's largest food producer by 70% [16]. Nonetheless, precision agriculture is challenged by the environmental sustainability issues caused by ICT. Therefore, green computing—"maximizing the efficiency of computing resources and minimizing environmental impact" [86], could be more useful to smallholder farmers due to its reduced costs and economic and environmental sustainability. The most established digital agriculture services have sustainability issues and exclude smallholder farmers.

Challenges: Despite the promising developments in technology, digital services in agriculture are yet to achieve complete sustainability. As the latest digital transformation, precision agriculture lacks the component of green computing, causing environmentally unfriendly practices. Precision agriculture is also poorly adopted by farmers, especially in developing countries, leaving most smallholder farmers behind in sustainable agriculture, in addition to the fact that, in general, small farms produce proportionally more greenhouse gas emissions than very large ones [87]. Furthermore, ICT infrastructure and resources sustainability are fundamental components for long-term agricultural production and profitability.

Profiling platform: A digital farmer profiling platform business model was recently designed to enable smallholder farmers' access to different services for increased production and income [10,15,16]. The model could achieve economic sustainability, but service providers charging smallholder farmers directly and indirectly for infrastructure and resources sustainability affect farmers' profit margins. Lack of government participation in the model could lead to unsolved smallholder farmers challenges to some countries where government, for example, should control market price and subsidies to targeted poor farming communities. Digital farmer profiling also lacks environmental sustainability components.

Summary: Many large-scale farmers such as commercial farmers, wholesalers, traders and exporters have long invested in the use of ICT with well-developed farm inputs and market functions. For instance, precision agriculture uses advanced technology such as farm management information systems (FMIS), social networks and other complex customer and farm management systems [42]. Therefore, large-scale farmers are not often confronted with the sustainability of ICT infrastructure and resources as they cooperate in the business plan for investment. Digital services for smallholder farmers usually are established by the stakeholders such as the government, donors, commercial service providers, scientists and public–private partnerships; thus, the modality requires a proper mechanism for sustaining the infrastructure and other resources supporting the services.

Furthermore, the literature places more emphasis on economic and less onenvironmental sustainability. Engineers should also prioritize green computing when developing digital services for ecological sustainability in agriculture. The current digital technology systems in smart farming use cloud computing model to manage voluminous data through data centers. However, the data centers are highly wasteful in terms of expenses, energy consumptions and carbon emissions [88]. Furthermore, ICT hardware has an immense effect on the environment throughout its life cycle. The manufacturing phase involves using rare earth metals extracted under unfavorable environmental practices, which causes water, soil and air pollution, with high energy consumption in the use phase and e-waste produced in the final phase [89]. The cloud computing model commonly used in precision agriculture has also an immense negative impact on the environment due to carbon emission from data centers that host massive data [68]. To achieve the component of environmental sustainability, engineers propose using energy-efficient hardware, using renewable energy such as solar and wind, recycling e-waste and designing new tools such as cooling systems and datacenters with minimal impact to the environment [86,89–91]. We acknowledge the environmental impact of solar panels in their production and disposal phases; however, our focus is on the usage phase.

5. Conclusions

5.1. Literature Summary

This article provides an overview of the current status of digital technology and services available in agriculture sector, their contribution to sustainable agriculture and relationship to smallholder farmers. The digital technology varies from simple mobile and web-based applications, mostly for smallholders to complex autonomous, information and cyber-physical systems used by large scale farmers. Digital transformation seems promising and changing all aspects of life in different disciplines, leading to new business models, services and products. The use of digital technology in agriculture may solve the challenge of food insecurity in yet a constant population increase in the world. The literature analysis has shown that sustainable agriculture is a reality through digital technology and services. However, the cutting-edge digital technology in agriculture (smart farming) is not accessible to smallholder farmers who, despite their small size, produce over 70% of the world's food. The existing digital models for smallholder farmers, including the Tanzanian case, lack vital components of sustainable agriculture. They mainly address the needs of smallholder farmers at a particular stage of a farming cycle, such as farm preparations. Furthermore, the services are primarily for a specific country and crop value chain; examples are Tanzania (Table 5) and Kenya's KALRO mobile applications for different crops and livestock.

We found that the literature relates sustainable agriculture more with the precision technology. However, is it always needed, especially real-time precision agriculture, or sustainability can be achieved with other means? For instance, smallholder farmers are often reluctant in adopting precision technology even in developed countries [92], where management differs greatly between large and small farms. Perhaps establishing advisory services specifically for smallholder farms can be more efficient than using precision technology that communicates directly with the producer. Indeed, we believe that if smallholder farmers can access financial services (credit and insurance), quality farm inputs, subsidies, advisory services and market, they can increase production and profitability, adhere to environmentally friendly farming practices hence sustainable agriculture. Therefore, organizing agriculture stakeholders (including the government) at a country level and developing digital solutions that address common challenges of smallholder farmers could lead to sustainable agriculture and adoption of precision farming in developing countries. The limitation of this study is emphasized in identifying smallholder challenges towards sustainable agriculture in Tanzania case and proposing digital solutions. The needs of smallholder farmers may differ among countries and could need a thorough study to adopt the proposed digital solutions in a particular country's context. Additionally, the study focused more in crop farming, thus, did not cover digital technologies used for instance in livestock management.

5.2. Towards a Comprehensive Digital Platform for Sustainable Agriculture in Smallholders Farms

In the future, we plan to design and implement a digital platform for smallholder farmers to access all essential services (subsidies, credit, insurance, government services, market and farming information) under one roof. The platform will address the needs of smallholder farmers in a complete farming cycle—from farm preparations, farm inputs, harvesting and post-harvesting activities by consolidating agriculture stakeholders at a country level. The platform will also adhere to all critical components of sustainable agriculture, namely the sustainability of digital infrastructure and resources offering the services, economic and environmental sustainability.

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Article

The Agricultural Cooperative as an Instrument for Economic Development: An Approach from Spanish Investors' Preferences through a Choice Experiment

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Abstract: The cooperative is one of the most important forms of business in the agricultural sector, due to its special characteristics for small farmers and livestock producers in order to gain access to greater comparative advantages. In addition, cooperatives are a driving force in the social economy, which means that investment in agricultural cooperatives can be seen as a sustainable investment. The aim of this paper is to analyse the preferences of investors in agricultural company cooperatives, looking in depth at the role of the cooperative as a business form. In order to achieve this objective, the choice experiment methodology was applied by carrying out a questionnaire to a total of 282 investors. Latent class models were also used to identify possible groups of investors. Two classes of investors have been identified based on their preferences: owners (return seeking) and workers (risk averse).

Keywords: cooperatives; choice experiment; ownership; agronomy

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1. Introduction

The cooperative in the agricultural sector has several relevant factors to justify its existence and development. In particular, the literature on economic organization shows the ability of cooperatives to reduce transaction costs and their capacity to develop countervailing power [1]. Thus, the recognition of the efficiency of agricultural organization is fundamentally determined by two factors, the efficiency of the division of labour and the efficiency of control activity, of which the second reason is more relevant. In this sense, cooperatives have a key role to contribute to the efficiency of the control activity, resulting in a form of continuity of the family farms that characterize the agricultural organization.

The cooperative company can be defined as the association of members (workers, producers, clients, etc.) to achieve an economic and social objective, taking decisions in a democratic manner, in comparison to the definition of other types of companies that are usually set up with independent shareholders and management. In the cooperative company, ownership and control of the company is usually shared, which leads to a coordination of objectives and elimination of opposing interest groups, as is the case in other types of companies. In turn, cooperative investment is affected by financial constraints in a relevant way [2], which highlights the importance of knowing how it is possible to invest in this type of financial product.

The cooperative as a legal form in Spain is developed in Law 27/1999 on Cooperatives (BOE, 1999), which specifies that there are basically two types of members: those members who carry out the corporate activity and collaborating members who do not necessarily have to carry out this activity. However, the collaborating partners have limitations in terms of both the percentage of capital and voting rights. In this sense, decision-making, management and control end up residing with the members who participate in the cooperative.

The legal form of a cooperative has a few economic and social advantages for society. Specifically, this type of enterprise contributes to the financing, maintenance, and stability of job creation [3]. It also allows the incorporation of women into the labor market, creating opportunities and meeting different needs in rural areas, contributing to more sustainable development [4]. Furthermore, investment in agricultural cooperatives is of vital importance for the sustainability of the agricultural system [5].

Currently, there are some 3699 agricultural cooperative companies in Spain, with a turnover of 30,556 million euros in 2019, representing 68% of final agricultural production. The total number of members amounts to more than 1 million, with a contribution to employment of around 112,000 employees. This shows the economic importance of the agricultural cooperative in Spain [6]. Cooperatives can be classified as first grade cooperatives if their members are individuals and second grade cooperatives if their members are, in turn, other cooperatives. The majority of cooperatives are located in first and second grade cooperatives, accounting for a total of 91%, with most of them concentrated in Andalusia, Castilla la Mancha and Castilla y León.

On the other hand, the social economy has shown great growth, especially in the area of the entrepreneurial business sector [7]. In this field, the agricultural cooperative is one of the key instruments in the development of this type of economy. Furthermore, cooperatives promote and foster the achievement of several Sustainable Development Goals, including poverty reduction, food security and good nutrition, sustainable energy, promotion of stable and peaceful societies, etc., ("Cooperativas hacia 2030", 2018; Internacional, 2015).

In this sense, investment in this type of company provides solutions to the current capitalist market, as they contribute not only economically but also by incorporating social and environmental aspects that are not usually addressed by other types of companies [8]. Therefore, localizing investment in cooperatives involves allocating resources towards a more socially responsible investment policy than the traditional one that only pursues economic profit. For all these reasons, the cooperative form in the agricultural sector can be considered as an instrument for the sustainability of the system.

The literature provides a significant number of papers on cooperatives. From works that analyse the control rights in cooperatives determined by the types of members that configure it [9,10], the investment behaviour of members [5,6,11–13], cooperative social inclusion [14], cooperative social responsibility and the cooperative [15], to efficiency and productivity [16,17].

However, the literature has not paid much attention to the willingness of non-member investors to invest in agricultural cooperatives. Only the work carried out by Alho, 2017, which analyses the investment preferences in agricultural cooperatives for a set of investors in Finland, stands out. Its main findings show that there is a willingness to invest in agricultural cooperative investment instruments and that a significant part of the sample is particularly interested in the attribute related to voting rights. Knowing what the investment preferences are in this type of instrument is useful to develop possible measures to increase the attractiveness of the investment for investors.

In this regard, the aim of this paper is to analyse the preferences of investors to invest in agricultural cooperatives and to analyse how various attributes influence their decision. The importance of raising funds for the agricultural cooperative is key to the sustainable development of the agricultural economy, in addition to the potential rural development that this type of enterprise brings. The importance of knowing the preferences of investors is relevant for planning investment projects and generating legal structures to attract investment to cooperatives. In addition, it also explores whether preferences are heterogeneous, trying to identify different groups of investors according to their preferences and characteristics. To achieve the proposed objective, a total of 282 investors were interviewed. A choice experiment was used to analyse the preferences and obtain the most important attributes. Additionally, latent classes were applied to identify homogeneous groups.

2. Material and Methods

2.1. Database

The database to carry out the objective of this work has been obtained from a questionnaire conducted on a sample of Spanish investors by means of random sampling. The final sample is made out of 282 individuals who have invested in some financial product and, therefore, can be considered investors (both investors and working members). The questionnaire is composed of information on the socio-economic environment as well as variables on risk perception and sustainability. The main descriptive statistics of the sample are shown in Table 1.

Table 1. Main descriptive statistics of the sample.

Variable	Mean (or %)
Age	41.48
Sex (female)	47.72%
(male)	52.28%
Income less than 900 €/month	11.19%
More than 900 and less than 500 €/month	24.19%
More than 1501 and less than 2500 €/month	37.55%
More than 2501 €/month	27.08%

The sample obtained was collected by means of simple random sampling without being able to count on an objective representativeness given that the characteristics of Spanish investors are unknown. We do not know the target population since no data are available on the investor population in Spain. The status of an investor has been determined by asking whether he/she has ever invested in financial products.

The questionnaire was prepared using Google Forms, as this type of online tool is increasingly used in research due to its advantages in terms of flexibility, speed of data collection and lower cost than traditional surveys [18–20].

2.2. Choice Experiment

The paper is based on the choice experiment conducted by [16] but adapting the attributes and levels to the Spanish regulations. Choice experiments have been widely used in the field of economics to analyse preferences [21–24]. These experiments are based on the idea that a product can be decomposed as the sum of several attributes that characterise it. Specifically, the following attributes have been incorporated: the voting rights of the shareholder, the profit entitlement, the share price and the expected return and risk. The selection of attributes and levels has been based on the literature review and the current legal configuration of the cooperative in Spain. All the attributes, as well as the different levels, are listed in Table 2.

Voting rights refer to the configuration of voting rights held by the shareholder or owner/investor of the cooperative. Profit entitlement is the form in which the shareholder/owner/investor's investment is remunerated. Capital price to the way in which the price is configured, whether in a secondary market or not. Finally, the level of risk and profitability of the investment is included.

Considering the four attributes mentioned above, with the different levels in each case, a total of 6,480 ($3 \times 3 \times 3 \times 3 = 81$) possible combinations of plausible scenarios can be established. Given the large number of resulting comparisons, for economic and time reasons it was decided to apply a factorial design. This procedure resulted in a total number of 16 alternatives, which meant that each respondent was faced with a set of eight choices. This type of design practice is frequently used in choice experimentation [25]. Figure 1 shows an example of a choice set.

Table 2. Attributes and levels of the Choice Set.

Attribute	Levels	Coding
Voting right	No voting rights	SIN
	Voting rights of producers	PROD
	Voting rights owners	PROP
Profit entitlement	Dividend	DIDV
	Fixed remuneration	FIJA
	Mixed	MIXTA
Capital price	Value on a secondary market	SECUND
	Capital is returned at par value	NOMINAL
	Capital is returned at nominal value plus an appreciation	APRECIA
Expected return and risk	6% high risk	HIGH
	4% medium risk	MEDIUM
	2% low risk	LOW

Attribute	**Opt 1**	**Opt 2**	**Opt 3**
Voting right	Voting rights owners	Voting rights of producers	Not investment (Neither)
Profit entitlement	Dividend	Fixed remuneration	
Capital price	Capital is returned at par value	Capital is returned at nominal value plus an	
Expected return and risk	4% medium risk	6% high risk	
Selection			

Figure 1. Example Choice Set.

2.3. Econometric Model

The model used to analyse investors' preferences for participation in agricultural co-operatives was the conditional logit model, and a latent class model was also implemented in order to study unobservable heterogeneity and different types of investors based on the response of the responses to the valuation.

These models, which are a derivative of random utility models [26], assume that the utility function of each individual is the sum of two terms, a deterministic part that can be described as a function of the factors that influence individuals' utility and a random, unobserved part that is considered stochastic. So, following [27] we can assume a sample of N individuals with a choice between J alternatives on T occasions, where the utility of an individual n derived from the choice of alternative j on occasion t is as follows:

$$U_{njt} = \beta'_n x_{njt} + \varepsilon_{njt} \tag{1}$$

where β'_n is the vector of individual-specific coefficients, x_{njt} is the vector of observable attributes of individual n and alternative j at choice occasion t, and ε_{njt} is the random term that we assume to be an independently and identically distributed extreme value. Therefore, the probability of respondent n choosing alternative I at choice t is given by the following expression:

$$L_{nit}(\beta_n) = \frac{exp(\beta'_n x_{nit})}{\sum_{j=1}^{J} exp(\beta'_n x_{njt})} \tag{2}$$

Expression [2] is the conditional logit formula [26] In this paper we will use the simulation approach [28,29] where the log likelihood is given by equation [3]:

$$SLL(\theta) = \sum_{n=1}^{N} ln\left\{\frac{1}{R}\sum_{r=1}^{R} S_n(\beta')\right\} \tag{3}$$

where R is the number of repetitions and H_{nq} is the rth draw from $f\ (\theta)$.

On the other hand, in order to identify unobservable heterogeneity and groups, latent classes are applied, which are estimated from:

$$SLL(\theta) = \sum_{n=1}^{N} ln\left\{\sum_{q=1}^{Q} H_{nq} \prod_{t=1R}^{T} \prod_{t=1R}^{J} \left[\frac{exp\left(x'_{njt}\beta^r_n\right)}{\sum_{j=1}^{J} exp\left(x'_{njt}\beta^r_n\right)}\right]^{y_{njt}}\right\} \tag{4}$$

where H_{nq} is the probability of membership in a given class and is obtained from:

$$H_{nq} = \frac{exp\left(z^t_n\gamma_q\right)}{\sum_{q=1}^{Q} exp\left(z^t_n\gamma_q\right)} \tag{5}$$

Therefore, the functional form of the U_{njt} derived from individual n for alternative j in choice set t can be defined as follows:

$$\begin{aligned} U_{njt} \;&= \beta_0 ASC + \beta_1 SIN_{njt} + \beta_2 PROD_{njt} + \beta_3 DIDV_{njt} + \beta_4 FIJA_{njt} + \beta_5 SECUND_{njt} + \beta_6 NOMINAL_{njt} \\ &+\beta_7 HIGH_{njt} + \beta_8 MEDIUM_{njt} + \varepsilon_{njt} \end{aligned} \tag{6}$$

The ASC (alternative specific constant) is defined as the alternative that represents the third option in each comparison, i.e., the alternative of not choosing any investment. The following values have been taken as base values (reference values): for voting rights, owner's voting rights (PROP); for profit entitlement, mixed remuneration; for capital price APRECIA, and finally for profitability and risk LOW.

3. Results

The results obtained after applying the methodology proposed above to the sample obtained are shown below. Specifically, Table 3 shows the results of the logit model for the full sample. A positive (negative) sign for a coefficient indicates that it increases (decreases) the probability of choosing the investment in agriculture cooperative alternative.

Table 3. Results of the choice experiment.

	Coefficient	Stand Error	Z	p-Value
ASC	−1.0474	0.1199	−8.73	0.000
SIN	−0.4685	0.0611	−4.21	0.000
PROD	−0.0843	0.1300	−1.38	0.168
DIDV	0.0172	0.0618	0.13	0.894
FIJA	−0.0264	0.6183	−0.43	0.669
SECUND	0.2652	0.0862	−3.08	0.002
NOMINAL	−0.4779	0.0783	−6.10	0.000
HIGH	−0.3756	0.0860	−4.36	0.000
MEDIUM	−0.3615	0.0659	−5.49	0.000
Loglikehood	−2399.1635		Observ	6.840

The results show that the option of not investing in any of the proposed options has a negative utility given the negative and statistically significant coefficient of ASC. On the other hand, the fact that the investment in agriculture cooperative has a dividend is the only parameter that has a positive utility, although it is not statistically significant. The rest of the parameters have a coefficient of negative utility. However, it should be noted that the coefficients for voting for producers and a fixed remuneration are not statistically significant.

This shows that investors have a strong preference for the coefficients used as a baseline in the logit regression for the investment in agriculture cooperative, an investment set up in which voting rights are given to the owners, with a mixed payout consisting of a fixed part and a dividend, additional appreciation to the nominal value of the capital in its return, and relatively low levels of return and risk.

In terms of the level of importance of each attribute, which is determined by the value of Z, it can be seen that the ASC comes first, the quotation parameters second, the corresponding profitability in percentage terms third, followed by the cooperative's control and voting rights, and finally, the form of owner remuneration.

Next, to deal with heterogeneity, we proceed to estimate latent classes as shown in the methodology section. The models have been estimated with different number of latent classes and subsequently the model fit parameter has been obtained. Table 4 shows the traditional statistical tools to select the optimal number of classes according to the model fit.

Table 4. Statistical parameters for fit the class number.

Class Number	AIC	CAIC	BIC
2	8797.02	8885.417	8866.417
3	8920.64	9055.565	9026.565
4	8905.651	9087.098	9048.098
5	8949.319	9177.291	9128.291

Table 4 shows the AIC, CAIC and BIC statistics, which show a better fit the lower the number obtained. In this sense, it can be seen that for both statistics the optimal model to estimate would be the one composed of two latent classes.

Table 5 shows the results of the choice experiment with latent classes.

Table 5. Results of the choice experiment with latent classes.

	Class 1				Class 2			
	Coefficient	Stand Error	Z	*p*-Value	Coefficient	Stand Error	Z	*p*-Value
ASC	−0.4132	0.1199	−1.91	0.000	−0.5135	0.1541	−3.33	0.001
SIN	−0.8571	0.0611	−6.44	0.000	−0.0857	0.1473	1.81	0561
PROD	−2.2225	0.1300	4.38	0.168	0.1599	0.0884	1.81	0.071
DIDV	3.4309	0.0618	4.32	0.894	0.1939	0.1535	1.26	0.206
FIJA	1.6894	0.0862	−4.09	0.669	0.0145	0.0781	0.19	0.853
SECUND	−1.4408	0.0783	−7.98	0.002	0.3793	0.1184	3.20	0.001
NOMINAL	−4.4254	0.0860	6.32	0.000	0.0141	0.0971	0.15	0.884
HIGH	2.8411	0.0659	5.39	0.000	−0.7189	0.1047	−6.86	0.000
MEDIUM	2.1762	0.4034	−0.79	0.000	−0.7021	0.0896	−7.83	0.000
Class share	27.5%				72.5%			
Const (Class 1)					−0.9732	0.1672	−5.82	0.000
Loglikehood	−2399.1635		Observ	6.840				

The ASC coefficient is negative and statistically significant in both classes. The first class consists of 27.5% while the second class comprises 72.5% of the respondents. The first class has statistically significant and positive coefficients for medium and high return and risk, while the coefficients are negative and statistically significant for no voting rights, secondary market listing and a return of nominal value, i.e., they prefer to have a vote as owners and a return of capital taking into account the nominal value plus a premium with high levels of return and risk. This type of class can be referred to as return seeking or ownership.

In the case of the second class, it can be observed that the coefficient of owners' voting rights is positive and statistically significant together with the secondary market price. However, both fixed and dividend remuneration, no voting rights and nominal return have a statistically insignificant coefficient. On the other hand, high and medium returns and risk report statistically significant but negative coefficients. In this sense, this majority group could be referred to as risk averse or working.

4. Discussion

The aim of this paper is to analyse the preferences of Spanish investors regarding investment in agriculture cooperative instruments in agricultural cooperatives and to determine which factors are most relevant. The cooperative in the agricultural market in Spain plays a fundamental role for the development of the sector in general and in particular for certain areas that otherwise would not find a way to develop and obtain economic growth, especially those located in non-urban centres.

The overall results show a trend towards an investment in an agriculture cooperative model that is characterised by a demand for instruments that have rights for owners to vote for control of the cooperative, with relatively low levels of return and risk, more in line with traditional investments in agriculture cooperative and that do not have high volatilities [29,30]. This result is in line with that obtained for a similar analysis in the Finnish case [13], although it differs in the profitability attribute, where the latter has a higher tendency towards profitability and high levels of risk.

Control of the cooperative is one of the most relevant attributes, apart from the return of capital, which shows that the organisation and governance of the cooperative is an attribute that is very important in this type of enterprise, as shown by various studies [31–33]. One possible explanation for this result lies in the fact that this type of instrument places greater emphasis on the investor's involvement in the management and growth of the company than on the pure holding of the stake.

The fact that the ASC has a negative result shows a certain rejection of this type of instrument, unlike the results obtained for the Finnish case [13]. However, this result can be explained by the cultural aspect of both countries, with Spain being a country that is more reserved when it comes to non-traditional investments, and investment in cooperatives may fall outside what is traditionally considered a traditional investment.

Moreover, an investment in cooperatives can be seen as an illiquid product (as most of them are not listed), as evidenced by the high importance given by investors to listing as an attribute. This fact could lead to higher levels of trading of the shares, although it is also true that this would probably lead to greater volatility marked by the prices at which they are listed.

The estimation by latent classes has made it possible to obtain two types of investors. On the one hand, those referred to as owners or seeking return and those that we can call risk adverse or working. The identification of two groups is slightly lower than that obtained by [13], which manages to separate those investors who are owners from those seeking returns, but the types of investors can be considered similar, although it is true that the probability of belonging or class size is very different. Again, the explanation for this lies in the cultural factor as has been shown internationally with other investment products.

Preferences for investing in cooperative instruments clearly show a higher probability and size group, which are workers or risk-averse, which shows that this type of investment in agriculture cooperative is more focused on workers who own the enterprise and want at least effective control or representation in the enterprise, rather than high profitability. This group could become the actual owners of the cooperatives and channels a way to avoid the financial constraints that agricultural cooperatives face in terms of possible financing [2].

The results of class 2 are in the opposite direction to those obtained by studies that analyse investment in agricultural cooperatives from the point of view of the owner in countries such as Greece or China [5,33,34], although this approach is different, it can serve as an approximation and comparison to the results obtained in this paper. However, regional differences in these countries must be taken into consideration. In these studies, profitability is one of the determining factors, but also the future strategies of the cooperative, as well as the governance of the cooperative, the latter of which seems to be in line with the results obtained in this study.

5. Conclusions

The aim of this paper has been to analyse investors' preferences for investment products located in agricultural cooperatives. Agricultural cooperatives play a fundamental role in the development and growth of the agricultural sector. Therefore, it is essential to know which are the most demanded preferences and characteristics in order to be able to organise this instrument in an adequate way. A segmentation of investors by latent classes has also been carried out in order to identify investors with their own independent characteristics.

The main results have shown that profitability is one of the determining factors in investment in cooperatives, although control of the cooperative and, therefore, voting rights is a factor that is very present when investing in this type of instrument. The most relevant factor, apart from the ASC, is the price, due to the possible lack of liquidity of the instrument. In this sense, an organised market for investment in cooperatives could lead to a greater increase in this type of product, as its investment would be more liquid and it would be easier to invest.

The latent classes have made it possible to identify two types of investors: those who can be described as owners who expect a high return on their investment and who have turned out to be the minority group and, on the other hand, a group of investors who are more risk-averse and prefer greater control by the producers, who have been described as risk averse or working, this group being the most numerous or probable in the estimation of the latent classes.

The identification of these two groups clearly shows that this type of instrument is aimed at investors who wish to become involved in the business in which the agricultural cooperative operates and, therefore, influence its management. This seems to indicate that two types of shareholdings could be articulated for the ownership of cooperatives, as is currently regulated in Spain. The results obtained are in line with those obtained in the case of Finnish investors.

The research carried out has several implications for the stakeholders. First of all, for the managers of the cooperative to know what the preferences of the investors are in the cooperative and to act accordingly. For governments, they can take these preferences into account in carrying out future reforms. Finally, for investors, knowledge of their preferences can show those projects that may be more attractive for attracting capital and, therefore, for business success. In this way, such projects can have more resources and the investor can locate its resources there.

This paper presents future lines of research to be developed, which at the same time can be assumed as limitations of the study. Firstly, it would be interesting to know the difference between those who are already owners of agricultural cooperatives and those who are not and could become so. Secondly, an interesting aspect to develop would be to find out the main motivations that investors have for allocating their funds in these instruments, beyond the characteristics or attributes mentioned above, as observed in various studies.

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Sustainable Communication in the B2C Market—The Impact of Packaging

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Abstract: The purpose of this study was to widen the knowledge about the recycling behaviour of consumers in order to understand their motivations related to the separate collection of household waste. This work encompasses a segmentation analysis revealing discrepancies between the respondents, who were profiled into three clusters: *Engaged in green*, characterised by high values of pro-environmental attitudes; *Indolent adopters*, described by respondents revealing moderate attitudes towards sorting waste; and *Ecological objectors*, who do not appreciate the benefits of recycling. The results showed that regardless of the cluster type, the level of actual knowledge about segregation rules was similar and insufficient, which hinders the correct sorting of household waste. It was also found that special attention should be paid to the quality of the information provided by FMCG packaging. Our study highlighted the need for a mandatory, precise, and coherent system of packaging labelling in order to promote pro-environmental attitudes and enhance the effectiveness of recycling.

Keywords: sustainable communication; recycling behaviour; consumer; packaging; labelling; segmentation; quality

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1. Introduction

Global pollution has become one of the most important environmental issues. This problem affects not only emerging economies, where it is the most visible due to the lack of effective waste collection systems, but it is also an urgent issue in developed countries. According to World Bank data, food and green waste, as well as paper and plastics, represent major waste streams. Since the latter ones are valuable secondary resources, recycling should be a preferred treatment operation applied for waste management [1]. In the European Union (EU-28) during the period of 2004–2018, the quantity of waste recycled increased from 45.9% (870 million tonnes) in 2004 to 54.6% (1184 million tonnes) in 2018, while the quantity of waste subjected to disposal decreased from 54.1% (1027 million tonnes) to 45.4% (984 million tonnes), respectively. In 2018, 37.9% of the total treated waste was recycled, 10.7% was backfilled, and 6.0% was treated using energy recovery. Among the remaining 45.4% of the total quantity, 38.4% was landfilled, 0.7% incinerated without energy recovery and 6.3% disposed of otherwise [2]. According to Eurostat data [2], there are significant differences among the EU Member States regarding various treatment methods. In 2019, the highest values of recycling rates of municipal waste were denoted for Germany (66.7%), Slovenia (59.2%), Austria (58.2%), the Netherlands (56.9%), Belgium (54.7%), Denmark (51.5%), and Italy (51.3%), while in the remaining countries the values were below 50% [3]. However, taking into account the increasing amount of municipal waste generated in the European Union (EU), recycling rates are still not sufficient. Therefore, waste management is one of the key elements of the European Union's environmental policy, the EU's legal framework, and a crucial part of an action plan regarding the transition to a circular economy. As a result, the amended Waste Framework Directive introduces ambitious targets for re-use and recycling rates defining the amounts which shall be increased to a minimum of 55%, 60%, and 65% by weight by 2025, 2030, and 2035, respectively [4]. A recommended way for the Member States to reach these undoubtedly challenging sustainability goals is the development of implantation plans (roadmaps) on a national level. In Poland, an appropriate document prepared by the Interdepartmental Circular Economy Group was approved by the Council of Ministers in September 2019 [5]. The Polish Roadmap focuses on several key areas such as sustainable industrial production and sustainable consumption, secondary raw materials and waste management, as well as innovation and investments. It also reflects recent changes in Polish rules of law since the implementation of the Waste Framework Directive induced several legislative amendments and had a considerable impact on the waste management system in Poland. Current regulations in this area are based on the European waste management hierarchy, strictly coherent with the circular economy model. Within the established five-step "waste hierarchy", prevention is the most preferred method, followed by preparing for re-use, recycling, and recovery, while disposal should be the last option [4]. The Polish waste collection and management system has been established stepwise since 2016 [6]. In order to comply with European Union regulations, it is based on five fractions with assigned colours: blue (paper), yellow (plastic and metal), green (glass), brown (biowaste), black (mixed waste). Since September 2019, selective waste collection in Poland is mandatory. However, despite the obligation to handle waste in a particular way, the recycling rates are still insufficient in comparison with other European countries [7,8]. In 2020, in the EU, 505 kg of municipal waste were generated per capita and 48% was recycled (including composting), while in Poland the corresponding values were 346 kg and 39%, respectively [9,10]. Furthermore, with the adoption of the actual recycling targets for the EU, this issue is even more crucial. According to the decree of the Minister for the Climate and Environment of 19 December 2021 on the annual recycling rates of packaging waste [11], the values of 30% for plastic, 51% for aluminium, 55% for ferrous metals, 66% for paper and cardboard, 62% for glass, and 19% for wood are expected to be achieved in 2022. Other increased recycling targets set for 2029, are: 54%, 59%, 78%, 83%, 74%, and 29%, respectively, to the above-mentioned fractions. Selective collection is still a challenging task for Polish consumers, although the situation is slowly changing. In 2019, only 55% of Poles declared that they segregate waste into five fractions, while in 2020 this amount increased to 77% [12,13]. Nevertheless, their actual knowledge about selective waste collection rules is on an unsatisfactory level. According to the data gathered by ARC Rynek i Opinie, only 15% of the respondents answered correctly on three questions related to the disposal of paper tissue, the wrapping for a cube of butter, and a carton package for juice [14]. One of the reasons is the lack of environmental awareness and knowledge about waste management rules combined with inaccurate information placed on the packaging, which does not refer directly to a particular fraction. Recent studies related to these issues, however few, also indicate the importance of other socio-economic aspects determining the engagement of Poles in a separate collection of waste [12–16]. Among them, the recycling behaviour of Polish consumers and their attitudes to eco-labelling in relation to waste management are of importance, pointing out a crucial role of packaging as a sustainable communication tool [17].

Packaging, from the legal regulation's perspective [18–22] and the functions performed [23–25], is a carrier of a lot of information, signs, and symbols. Displayed altogether, they might be counterproductive. The provided information is not only related to the need to ensure product and consumer safety but also necessary from the marketing point of view. It also has a direct impact on the multi-sensory customer experience at different stages of interaction with the packaging [26–32]. Communication through packaging helps build brand awareness and distinguishes the company from its competitors [28].

Packaging can be considered in its physical dimension, focusing mainly on material and constructional issues, but also in its functional dimension, which consists of elements determining its purchase-consumption nature. Purchase packaging affects the consumer at the time of buying, while consumption packaging has a greater impact at the time of use [33,34]. Packaging as an information carrier is the starting point for the further analysis of the presented research.

Various research points out that consumers, unfortunately, do not receive appropriate and understandable information, which results in confusion or indifference [35–37]. The informative function of packaging refers to the provision and uninterrupted transmission of relevant data to all participants, both in logistics chains and to individual consumers. In addition to the traditional descriptive form, information can be conveyed by pictograms, signs, and graphic symbols, which theoretically accelerate the identification of content and facilitate the understanding of the message. Data presented in graphic form (drawing, photograph, sign, pictogram) are often universal and accessible regardless of the language level of the recipient. It should be noted that the information value of packaging, determined by the obligatory code and the optional code, is an important component of its communication value. The correct choice of signs and codes forming the visual layer of packaging affects the correct perception of the product and, consequently, purchasing decisions. An excess of information or its inappropriate placement on packaging may cause information noise and the wrong perception of product features [38–40].

The information value of packaging plays also a crucial role in shaping the recycling behaviour of consumers, therefore proactive efforts are globally being made by researchers to improve the knowledge in this area [41–45]. The results of several works highlight the potential of packaging as an initiator of waste-sorting activity and indicate its impact on recycling effectiveness. However, it should be noted that the national perspective differs due to the various policies, segregation rules, and waste management systems existing in analysed countries. Nevertheless, good practices and success stories may be shared between other regions and provide the basis for a broad discussion in order to support the environmental attitudes and activities of consumers.

The aim of this study is to widen the knowledge about the recycling behaviour of consumers in order to understand the motivation of Poles related to the separate collection of waste. This paper encompasses segmentation studies based on attitudes towards recycling. It gives an insight into the environmental awareness and actual knowledge of Polish consumers related to selective waste management according to the legal requirements in Poland. Finally, it is also an attempt to provide information about factors important for consumers, which can stimulate the effective separation of waste with a particular emphasis on the information-related function of FMCG packaging.

2. Materials and Methods

2.1. Sample and Data Collection

The study was conducted using a computer-assisted web interview (CAWI) in January and February 2021 on a representative sample of adult Poles (N = 1029) in terms of gender, age, and education, according to Social Diagnosis reflecting the population of Polish consumers being active internet users. The study was carried out using the Market and Opinion Research Agency “SW Research” panel of respondents. The socio-demographic characteristics of the participants involved in the survey are presented in Table 1.

2.2. Questionnaire

The study was based on a specially designed questionnaire which consisted of six parts. The first part included 8 statements concerning consumers’ attitudes towards recycling scored on a 5-point Likert scale enabling respondents to specify their level of agreement: (1) strongly disagree, (2) disagree, (3) neither agree nor disagree, (4) agree, (5) strongly agree. The second part contained 4 statements describing the respondents’ experiences and attitudes regarding the selective collection. The third part included a set of 7 statements regarding the practical information about the selective collection of household waste which was scored on a 5-point Likert scale in order to verify the importance of examined factors from consumers’ perspective. The fourth part explored the level of awareness of the respondents regarding the selective collection of household waste. In this part, the actual knowledge was verified using a set of statements describing the separative waste management rules in relation to the six popular types of waste. The respondents could choose the answer between true or false. The fifth part investigated the potential of packaging innovations regarding extended information about the product and packaging's characteristics. The last part included questions regarding the socio-demographic data of the respondents, such as gender, age, education level, and place of residence.

Table 1. Socio-demographic characteristics of the participants.

Variable	Characteristics	Surveyed Group (%)	N
Gender	Women	51.8	533
	Men	48.2	496
Age	Up to 20	9.2	95
	21–30	25.6	263
	31–40	25.9	266
	41–50	16.7	172
	51–60	14.9	153
	over 61	7.8	80
Education level	Primary	6.4	66
	Vocational	18.7	192
	Secondary	40.4	416
	Higher	34.5	355
Place of residence	Villages	20.1	207
	Suburban	7.7	79
	Cities up to 50,000	24.5	252
	Cities over 50,000	47.7	491

2.3. Cluster Analysis—Understanding Consumer Recycling Behaviour

A cluster analysis was applied to segment Polish consumers according to their attitudes towards selective waste sorting. Segmentation study allows us to classify respondents in groups and to show the similarities and differences between them in relation to attitudinal variables. The cluster analysis was used to give an insight into the motivations of respondents regarding their environmental awareness, values, and social norms as well as their level of knowledge. It may be noted that several studies were published concerning the environmental awareness and recycling behaviour of Poles [12–16,46,47]; however, only limited data were available regarding the profiling of Polish consumers [15]. The results showed important discrepancies between respondents indicating the need for tailored communication and marketing activities that should be undertaken in order to promote pro-environmental attitudes. The reported data also revealed a large information gap concerning selective waste management and its negative impact on the effectiveness of recycling. Therefore, the present study is aimed at the identification of the segments of Polish consumers in terms of their recycling behaviour in order to widen the knowledge about factors that may stimulate and promote selective waste collection. The role of packaging as a communication tool providing extended information was also explored.

In the scientific literature, two main approaches are applied in a cluster analysis [41]. One is based on socio-demographic criteria and another on psychographic and behavioural criteria. The theory of reasoned action (TRA) [48] and the theory of planned behaviour (TBP) [49], revealing the relationship between attitudes and behaviours, were successfully implemented for investigations regarding recycling, consumers' choices concerning sustainable packaging, and green consumer behaviour [50]. The TBP is a conceptual extension of the theory of reasoned action (TRA) [51], which regards a consumer's behaviour as influenced by behavioural intention. TBP assumes a rational basis for consumers' behaviour, which is influenced by three variables: attitude towards the behaviour [51], subjective norms (the perception of the pressure of others' opinions), and perceived behavioural control (the person's perception of their own ability to perform a behaviour) [50,52]. An interesting approach regarding the understanding of consumer recycling behaviour was proposed by Park and Ha [53]. They showed that recycling intention is determined both by attitudes toward recycling and by perceived behavioural control from TPB, as well as by personal norms from the norm action model (NAM, Shwartz 1997 [54]). They suggested that subjective norms indirectly influence recycling intention, having an impact through attitude, personal norms, and perceived behavioural control [53]. According to NAM, personal norms refer to the individual's self-expectations for a specific behaviour [53], which originate from a moral obligation to perform a behaviour [55]. Previous scientific studies have shown that personal norms directly affect environmental behaviour [55–57].

In this work, the above-mentioned relations were taken under consideration in order to study the recycling behaviour of Polish consumers. Assuming the importance of the range of information provided on FMCG packaging for effective recycling, selected guidelines covering this issue were also used as the segmentation base.

2.4. Statistical Analysis

Statistical data analysis was conducted using 3 kinds of tests:

- A clustering of respondents based on normalised answers from questions included in the first and the third part of the questionnaire (K-means method were chosen and performed—3 clusters were chosen);
- Chi-square tests comparing cluster alignments and other answers (socio-demographic data and questions about knowledge and attitudes towards innovative packaging solutions);
- An ANOVA with posthoc tests was conducted to determine the significance of the differences between clusters in the area of actual and declared knowledge about segregation.

A cluster analysis was conducted in order to segment respondents into groups based on similarities (in the case of the same cluster) and on differences (in the case of belonging to different clusters). Two questions from the questionnaire (15 variables), included in the first and third part of the questionnaire, were taken into consideration. Other questions were used for comparison purposes. All questions were standardised (the Z-score was used) in order to avoid errors. Cronbach's alpha test for the internal consistency of diagnostic tools (questionnaire) was also performed.

3. Results

Cluster Analysis Results

The high value of Cronbach's alpha determined for analysed questions indicated an internal consistency of the questionnaire (0.844). Three clusters were identified due to the consistency of groups and the abundance of members of each group. The final centres of the clusters were shown in Table 2. The mean refers to the standardised value (positive values indicate being above average, negative values indicates being below the average of the question). Table 3 shows a description of the clusters with respect to the demographic attributes.

Cluster 1: *Engaged in green* is characterised by high values of pro-environmental attitudes as well as components related to the respondents' ability to sort waste separately. It comprises of people who express an inner conviction that sorting waste is beneficial for the environment and for society. They are strongly influenced by social values and personal norms.

Cluster 2: *Ecological objectors* is represented by respondents who do not appreciate the benefits of sorting waste to protect the environment and society. They are extremely indifferent to social and personal norms and find sorting waste difficult.

Cluster 3: *Indolent adopters* is described by respondents revealing moderate attitudes towards sorting waste. It is also characterised by an average impact of social and personal norms. Cluster 3 covers respondents who perceived difficulty regarding selective sorting of waste on a medium level.

Table 2. Results of cluster analysis.

Variables	Cluster 1 *Engaged in Green* (N = 411)	Cluster 2 *Ecological Objectors* (N = 123)	Cluster 3 *Indolent Adopters* (N = 495)
Express your opinion on the following statements.			
I believe that sorting waste is my responsibility and beneficial for the environment	0.46015	−1.61321	0.01880
I believe that sorting waste brings benefits to society	0.54088	−1.73426	−0.01816
I sort waste because it is consistent with my beliefs	0.64573	−1.70284	−0.11302
I sort waste to avoid a penalty	0.31475	−0.52154	−0.13174
I sort my waste because mass media encourage me to do this	0.47402	−0.93232	−0.16191
I think that sorting waste is easy	0.62982	−1.37859	−0.18039
I am used to sorting waste	0.66655	−1.38761	−0.20864
I have enough space in my household to sort waste and find it convenient	0.56001	−0.95271	−0.22824
What kind of information would be helpful when sorting waste?			
Waste fraction type (colour)	0.53825	−1.21995	−0.14377
Empty prior to discharging	0.66585	−1.05523	−0.29065
Wash prior to discharging	0.63472	−0.88103	−0.30809
Compress empty packaging prior to discharging	0.59999	−1.01113	−0.24692
Unscrew/separate closure prior to discharging	0.57860	−1.01399	−0.22845
How to separate various elements of packaging	0.64656	−1.01730	−0.28406
Remove the label from the package	0.58891	−0.73804	−0.30558

An analysis of the composition of the clusters with respect to socio-demographical attitudes has shown some differences between them (Table 3). Cluster 1 (Engaged in green), the second-largest group in the study (N = 411), constituted 39.94% of the surveyed population. This cluster is dominated by women (60.8%, Chi-square 27.56, *p*-value 0.000), which indicates their strong involvement in environmental issues. Cluster 1 is mainly represented by people between 21 and 40 years of age, with secondary or higher education, who live in cities. Interestingly, this cluster is also characterised by a significant group of people above 51 years of age (Chi-square 19.35, p-value 0.036), which implies that respondents of this age are engaged in the selective collection of waste. Cluster 2 (Ecological objectors) constitutes 11.95% of the studied population. Although this is the smallest group, it is worth observing and analysing in order to recognise the causes for a negative attitude towards waste segregation. This group is dominated by men aged up to 40, with secondary or higher education, living in large cities. Cluster 3 (*Indolent adopters*) is the most numerous group (48.11%, N = 495) among all distinguished. Without a clear gender representation, Cluster 3 is characterised mostly by young people aged 21 to 40, and city dwellers with secondary or higher education. Since it constitutes such a large group of respondents, the lack of conviction may result in the strengthening of attitudes visible in Cluster 2 (Ecological objectors), which, as a consequence, would be decisive for the further efficiency of selective waste sorting. Therefore, intensive information activities and educational campaigns to motivate consumers to adopt pro-ecological habits are of importance. It was also observed that neither the place of residence nor the level of education were significant from the cluster analysis point of view.

Table 3. Description of the clusters with respect to the demographic attributes.

Variable	Characteristics		Cluster 1 *Engaged in Green*	Cluster 2 *Ecological Objectors*	Cluster 3 *Indolent Adopters*	Total
Gender	**Women**	N	250	45	238	533
		% of Cluster	60.8%	36.6%	48.1%	51.8%
	Men	N	161	78	257	496
		% of Cluster	39.2%	63.4%	51.9%	48.2%
Age	Up to 20	N	27	15	53	95
		% of Cluster	6.6%	12.2%	10.7%	9.2%
	21–30	N	94	31	138	263
		% of Cluster	22.9%	25.2%	27.9%	25.6%
	31–40	N	119	31	116	266
		% of Cluster	29.0%	25.2%	23.4%	25.9%
	41–50	N	62	27	83	172
		% of Cluster	15.1%	22.0%	16.8%	16.7%
	51–60	N	70	12	71	153
		% of Cluster	17.0%	9.8%	14.3%	14.9%
	over 61	N	39	7	34	80
		% of Cluster	9.5%	5.7%	6.9%	7.8%
Education level	Primary	N	18	11	37	66
		% of Cluster	4.4%	8.9%	7.5%	6.4%
	Vocational	N	77	26	89	192
		% of Cluster	18.7%	21.1%	18.0%	18.7%
	Secondary	N	164	51	201	416
		% of Cluster	39.9%	41.5%	40.6%	40.4%
	Higher	N	152	35	168	355
		% of Cluster	37.0%	28.5%	33.9%	34.5%
Place of residence	Villages	N	91	16	100	207
		% of Cluster	22.1%	13.0%	20.2%	20.1%
	Suburban	N	30	11	38	79
		% of Cluster	7.3%	8.9%	7.7%	7.7%
	Cities up to 50,000	N	106	23	123	252
		% of Cluster	25.8%	18.7%	24.8%	24.5%
	Cities over 50,000	N	184	73	234	491
		% of Cluster	44.8%	59.3%	47.3%	47.7%

The purpose of this study was also to examine the level of actual knowledge of respondents regarding selective waste sorting rules since separate collection is mandatory in Poland, and certain efforts to promote recycling, as well to provide particular guidelines, have already been undertaken at regional and national levels. In order to determine the level of knowledge, respondents were asked to indicate whether the six statements, concerning the separate collection rules of six popular types of household waste, were correct (true) or incorrect (false). Interestingly, the results showed that regardless of the cluster type, the level of actual knowledge of respondents was similar, since the differences between them were statistically insignificant (Tables 4 and 5). As can be seen from Table 4, slightly more than three correct answers (from six questions) were chosen, while the best results were denoted for cluster 1 (Engaged in green) and the worst for cluster 2 (Ecological objectors), however statistically insignificant.

Table 4. Description of clusters in terms of the level of knowledge regarding selective waste sorting.

	Cluster 1 *Engaged in Green*	Cluster 2 *Ecological Objectors*	Cluster 3 *Indolent Adopters*	Total
N	411	123	495	1029
Mean	3.36	3.11	3.26	3.29

Table 5. Results of one-way ANOVA—the level of knowledge regarding selective waste sorting.

	Sum of Squares	df	MS	F	*p*-Value
Between groups	678.720	2	339.360	1.893	0.151 [a]
Within group	183,921.280	1026	179.261		
Total	184,600.000	1028			

[a] No significant differences between clusters with ANOVA (p-value > 0.05).

In the case of the rest of the questions, the results were statistically significant, and posthoc tests (the Tukey test) revealed that all clusters differed. Considering the answers in detail, it can be observed from Table 6 that within Cluster 1 (Engaged in green), the worst results were denoted in the case of question 2 (about receipts), since only 28% of the answers were correct. The analysed clusters do not differ significantly in the case of questions 2 (about receipts), 4 (about bottles for edible/engine oil), 5 (about glass containers for drugs), and 6 (about light bulbs). In the case of questions 1 and 3, Cluster 1 (Engaged in green) answered in the best way, while Cluster 2 (Ecological objectors) answered the worst.

Table 6. Description of clusters with respect to practical knowledge about recycling rules.

Question	Answer (T—True/ F—False)	Cluster 1 *Engaged in Green*	Cluster 2 *Ecological Objectors*	Cluster 3 *Indolent Adopters*	Chi-Square	*p*-Value
1. Carton for liquids— yellow bin (plastic waste)	T	57.9%	43.1%	53.3%	8.506	0.014 [a]
2. Receipt—blue bin (paper waste)	F	28.0%	33.3%	31.5%	1.928	0.381 [b]
3. Cans—yellow bin	T	77.1%	63.4%	67.9%	13.287	0.001 [a]
4. Bottle for edible/engine oil —(yellow bin) plastic waste	F	38.7%	44.7%	42.0%	1.824	0.402 [b]
5. Glass container for drugs —(black bin) mixed waste	F	64.0%	63.4%	62.4%	0.240	0.887 [b]
6. Light bulbs/fluorescent tubes—glass waste	F	70.8%	62.6%	69.3%	2.999	0.223 [b]

Significant differences between the clusters, Chi-square test ([a] p-value < 0.05). No significant differences between the clusters, Chi-square test ([b] p-value > 0.05)

For further consideration, the questions analysed in the ANOVA analysis were also taken into a cross-table analysis in order to show the distribution of results. Chi-square tests were additionally calculated (Table 7).

Table 7. Description of clusters in terms of experience with selective waste collection.

Statement		Cluster 1 *Engaged in Green*	Cluster 2 *Ecological Objectors*	Cluster 3 *Indolent Adopters*	Total
I can sort and it is easy for me	N	311	28	249	588
	% of Cluster	76.6%	21.9%	50.3%	57.1%
I can sort, it is easy but cumbersome	N	87	67	203	357
	% of Cluster	21.4%	52.3%	41.0%	34.7%
I find sorting waste difficult	N	7	20	41	68
	% of Cluster	1.7%	15.6%	8.3%	6.6%
I do not segregate waste	N	1	13	2	16
	% of Cluster	0.2%	10.2%	0.4%	1.6%
Total	N	406	128	495	1029
	% of Cluster	100.0%	100.0%	100.0%	100.0%

Significant differences between the clusters, Chi-square = 199.1, p-value < 0.001.

The results presented in Table 7 show that there are statistically significant differences (Chi-square = 199.1, p-value < 0.001) between experiences with sorting waste among the analysed clusters. Respondents concentrated in Cluster 1 (Engaged in green) declared the most frequently that selective waste sorting is easy for them. On the contrary, Cluster 2 (Ecological objectors) is characterised by the highest number of respondents who do not segregate waste. They also declared more often that sorting waste is difficult. Interestingly, it was observed that 1.6% of the total number of respondents declared that they do not segregate waste, although the selective collection of waste is mandatory in Poland.

Moreover, the results revealed statistically significant differences between clusters (Chi-square = 271.9, p-value < 0.001) regarding the potential of interactive packaging. Cluster 1 (Engaged in green) covers respondents who declared more frequently that interactive packages can serve as a sustainable communication tool providing information useful for efficient waste sorting (Table 8). Cluster 3 (Indolent adopters) represents a group of respondents with a moderate attitude towards the segregation of waste and the opinion that extended information on packages, regarding sorting waste, can be useful and helpful. In most cases, the obtained values are a little bit below the average, which means that they assessed the potential of additional information as less important. Cluster 2 (Ecological objectors) comprises a group of consumers with negative attitudes towards sorting waste. They also assessed the usefulness of additional information provided on packaging regarding the sorting of waste lower than respondents representing other clusters.

It was also observed that there are statistically significant differences between clusters (Chi-square = 246.3, p-value < 0.001) regarding opinions about innovative packaging solutions, such as interactive packages with "extended labels", which are delivering information about the way the product can be prepared for consumption, about allergens, food origins, etc. (Table 9). The results showed that Cluster 3 declared more frequently that interactive packaging could be useful as an attractive and valuable communication tool.

Table 8. Description of clusters regarding the potential of interactive packaging as a tool useful for efficient waste sorting.

Statement		**Cluster 1** *Engaged in Green*	**Cluster 2** *Ecological Objectors*	**Cluster 3** *Indolent Adopters*	**Total**
1—definitely not useful	N	2	11	3	16
	% of Cluster	0.5%	8.9%	0.6%	1.6%
2—useless	N	11	21	37	69
	% of Cluster	2.7%	17.1%	7.5%	6.7%
3—hard to say	N	39	49	115	203
	% of Cluster	9.5%	39.8%	23.2%	19.7%
4—useful	N	138	33	252	423
	% of Cluster	33.6%	26.8%	50.9%	41.1%
5—very useful	N	221	9	88	318
	% of Cluster	53.8%	7.3%	17.8%	30.9%
Total	N	411	123	495	1029
	% of Cluster	100.0%	100.0%	100.0%	100.0%

Significant differences between the clusters, Chi-square = 271.9, p-value < 0.001.

Table 9. Description of clusters regarding the potential of interactive packaging as a tool for extended information about the product characteristics.

Statement		**Cluster 1** *Engaged in Green*	**Cluster 2** *Ecological Objectors*	**Cluster 3** *Indolent Adopters*	**Total**
1—definitely not useful	N	2	6	1	9
	% of Cluster	0.5%	4.9%	0.2%	0.9%
2—useless	N	11	19	22	52
	% of Cluster	2.7%	15.4%	4.4%	5.1%
3—hard to say	N	33	47	122	202
	% of Cluster	8.0%	38.2%	24.6%	19.6%
4—useful	N	143	39	260	442
	% of Cluster	34.8%	31.7%	52.5%	43.0%
5—very useful	N	222	12	90	324
	% of Cluster	54.0%	9.8%	18.2%	31.5%
Total	N	411	123	495	1029
	% of Cluster	100.0%	100.0%	100.0%	100.0%

Significant differences between the clusters, Chi-square = 246.3, p-value < 0.001.

4. Discussion

A cluster analysis of the obtained results revealed three segments representing different attitudes towards selective waste collection: Engaged in green, Indolent adopters, and Ecological objectors. Engaged in green (48.11% of the total number of respondents) is characterised by consumers highly involved in effective waste sorting. Respondents in this cluster are strongly convinced that sorting waste is beneficial to the environment and society and find it easy. They are influenced by the pressure of social and personal norms. Engaged in green are also the most interested in precise information on how to handle packaging prior to discharging to make recycling more effective. Cluster 2: Ecological objectors (11.95%) encompasses respondents who do not consider sorting waste as an activity beneficial for the environment or society, nor as a habit. They are poorly influenced by social and personal norms and find selective waste collection difficult. Indolent adopters (39.94%) comprises respondents who perceive the sorting of household waste as moderately beneficial for the environment and society and find it cumbersome. They are rather indifferent to social and personal norms. In light of the above, it can be stated that there is still a need for more intensive information activities and educational campaigns in order to motivate consumers to adopt pro-ecological habits. Moreover, the precise and direct information provided by packaging may promote and facilitate selective waste sorting and enhance the effectiveness of recycling. The discussed results showed some similarities with other studies undertaken by the Market and Opinion Research Agency SW Research in March, June, and October 2020 [15], although different criteria and bases for segmentation were applied. According to the data presented in the above-mentioned report, five profiles of respondents were distinguished: Eco-attentive (35% of the analysed population), Eco-enthusiast (29%), Eco-confused (11%), Sceptical about green marketing (13%), and Eco for show (12%). The most numerous groups are composed of respondents with good environmental awareness (Eco-attentive and Eco-enthusiast), who undertake several pro-ecological activities such as saving electricity or water and sorting waste; however, their actual knowledge of segregation rules was not assessed. Eco-confused do not demonstrate negative attitudes towards pro-ecological activities, but they are passive. Together, respondents described as Sceptical about green marketing and Eco for show constitute a group of people who should be encouraged to get involved and who need the motivation to take part in pro-ecological activities.

The cluster analysis results showed that within Engaged in green, women were the most involved in effective waste sorting. This is coherent with the data provided by the ProKarton Foundation (Poland), which were collected in September 2021, revealing that women segregated waste more often than men [13].

The results of our study also showed that regardless of the cluster type, the level of actual knowledge of respondents about waste sorting rules was similar and insufficient. It implies that notwithstanding the environmental awareness and degree of involvement of respondents in recycling, there is an information gap that hinders the correct sorting of household waste. Our results reflect the current legal situation in Poland, where there is no obligatory labelling of packaging in terms of the type of material or handling hints regarding selective waste sorting. Although there are guidelines for municipalities and residents referring to the selective collection of various types of household waste, laid down by the Ministry of Climate and Environment [58], their application in practice by consumers remains difficult. There are also some discrepancies in separate collection rules among particular regions in Poland, which may contribute to information noise. Our results showed that, similarly, facultative eco-labelling still remains problematic [59]. The most popular examples of eco-labelling used in product packaging are presented below (Figure 1).

It was observed that consumers are often not familiar with their meaning. Moreover, none of them serve as a direct guideline referring to a particular type of waste fraction. Eco-labels are often combined with a set of other symbols concerning the product's characteristics or handling rules, applied within the entire logistic chain (Figure 2). However, it must be underlined that excessive labelling or improper application is not communicative but, rather, confusing. Misleading consumers and greenwashing are legally prohibited.

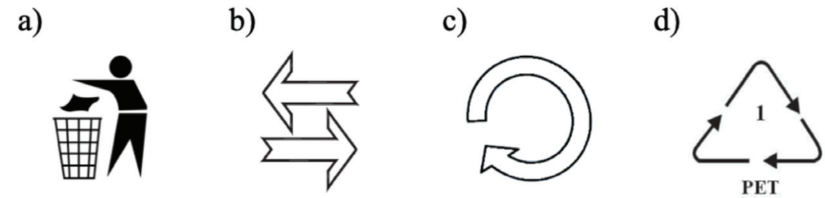

Figure 1. Chosen types of eco-labelling: (**a**) dispose of according to the local regulations, (**b**) reusable packaging, (**c**) packaging suitable for recycling, (**d**) packaging material type: 1—poly(ethylene terephthalate). Source: (**a**) ČSN 77 0053 Packaging—Packaging waste—Instructions and information on manipulation with used packaging, Obaly—Odpady z obalů—Pokyny a informace pro nakládání s použitým obalem [60]; (**b**–**d**) Ordinance of Minister of Environment on the templates of packaging labelling of 3 September 2014 [61].

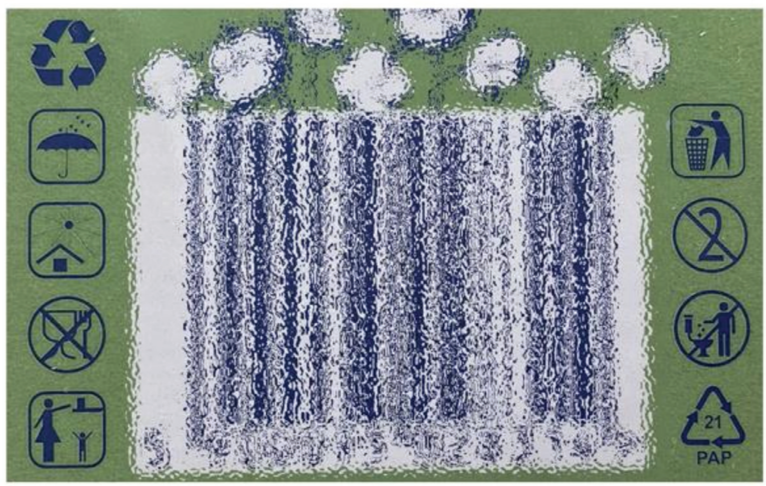

Figure 2. An example of a purchase packaging that conveys information concerning the product's characteristics and handling rules.

It is worth noting that these issues are considered highly important at the community level, while the packaging industry and consumer product manufacturers endorse the need for relevant and consistent information on how to segregate household waste correctly in order to support circular economy initiatives [62]. Simultaneously, in the Polish market, there are initiatives undertaken by several retailers regarding the labelling of packaging with a particular fraction of waste [63]. However, the proposed systems are not coherent due to the different symbols used to indicate selective waste sorting rules or to provide detailed information about particular packaging elements when the packaging is composed of varied materials.

In light of the above, the information should be precise, detailed and reliable. In some cases, two-dimensional labelling may be enhanced with interactive packaging solutions in order to provide additional assistance. Digital packaging offering virtual content, provided by QR codes, augmented reality, or invisible watermark coding, enables customised features, content, and style and opens a new way of communication with consumers. It may also provide professional information which is not available on a traditional label. Therefore, the interest in such a tool was taken into consideration. The results showed that 87.4% of respondents representing *Engaged in green* and 68.7% from *Indolent adopters* declared that extended information provided by interactive packaging would be useful (33.6% and 50.9%, respectively) and very useful (53.8% and 17.8%, respectively) in household waste sorting. The survey results are a part of the project "Interactive packaging as a new communication tool on B2C market" conducted from 1 September 2020 to 28 February 2022, devoted to the exploration of consumers' experience with interactive solutions using qualitative and quantitative research methods.

5. Conclusions

The results showed that consumers' recycling behaviour is influenced by personal norms and behavioural intentions as well as their actual knowledge. A segmentation analysis revealed important discrepancies between respondents, who were profiled into three clusters: *Engaged in green*, characterised by high values of pro-environmental attitudes; *Indolent adopters*, described by respondents revealing moderate attitudes towards sorting waste; and *Ecological objectors*, who do not appreciate benefits of sorting waste. Therefore, tailored communication and marketing activities regarding different types of consumers should be proposed to promote pro-environmental attitudes. Regardless of the cluster type, the level of the actual knowledge of the respondents about waste sorting rules was similar and insufficient. It implies that notwithstanding the environmental awareness and degree of involvement of respondents in recycling, there is an information gap that hinders the correct sorting of household waste. Assessing the role of packaging as a tool affecting separate waste collection, special attention should be paid to the information it provides since a majority of respondents (*Engaged in green* and *Indolent adopters*) declared that more precise guidelines are needed in order to facilitate the sorting of waste, which in fact determines the effectiveness of recycling. Our study highlighted the need for a mandatory, precise, and coherent system of packaging labelling in order to provide consumers with explicit and comprehensible recycling guidelines. Confused consumers, even those involved in pro-ecological activities, turn their doubts into recycling mistakes.

6. Research Limitations

The limitations of this study include the fact that the survey was conducted using the CAWI method, including internet users only, which do not fully cover the country's population. However, the survey encompassed a representative sample in terms of gender, age, and education according to data from the Polish Central Statistical Office and the SW Research Market and Opinion Research Agency's panel of respondents. Secondly, the cluster analysis reflects the attitudes of respondents among the Polish population, considering actual legal requirements in Poland. Therefore, although selective waste management is one of the key elements of the EU environmental policy, national perspectives may differ within the other Member States, while recommendations regarding post-consumer waste collection and segregation systems are not homogeneous. Nevertheless, the authors assume that the obtained results may be useful not only from a national perspective but also contribute to a wider discussion regarding the informative value of packaging on the European market and its potential in supporting the environmental attitudes and activities of consumers.

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Review

Issues and Challenges in Short Food Supply Chains: A Systematic Literature Review

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Abstract: Consumers increasingly prefer more direct and more transparent food distribution channels, such as short food supply chains (SFSCs). Nonetheless, SFSCs face a variety of issues and challenges in their creation and functioning, resulting in limited performance and sustainability, as well as in difficulties of upscaling. This study aims at improving our understanding of SFSCs' issues/challenges through a systematic review of the most recent literature. We perform a full-text content analysis of 44 studies, looking for answers to the research questions: At which parts of the SFSCs do the issues/challenges occur? How can we characterize the issues/challenges in SFSCs? While doing so, we offer a holistic perspective on SFSCs. We make use of the SCOR model to define SFSC processes as well as to describe the nature of these issues/challenges. The findings of this study shed light on the nature and strategic-tactical-operational level of the issues/challenges in SFSCs and point out the limitations in the existing literature such as the SFSC processes that are neglected. The holistic approach we suggest and the insight on SFSCs' issues/challenges we provide can help researchers offer effective solutions and strategies to support the overall development of SFSCs.

Keywords: short food supply chain; alternative food network; local food system; sustainability; logistics processes; supply chain modeling; SCOR model

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1. Introduction

1.1. Motivations of the Study

In recent years consumers' habits concerning food purchases have been changing due to a desire for healthy eating and sustainable consumption. Consumers who look for food products of high quality and well-known origins turn increasingly to more direct and more transparent supply chains (SCs). This trend further accelerated during the first year of the COVID-19 pandemic, leading to discussions about whether these alternative distribution channels can meet demand and improve food system resilience and sustainability. In this context, short food supply chains (SFSCs) respond to the demand of consumers for more proximity and quality, while providing small-scale producers an opportunity for autonomy and enhanced income.

The French Ministry of Agriculture, Food, and Forestry defines SFSCs as the "commercialization of agricultural products through direct selling or indirect selling when only one intermediary is involved" [1] (p. 198). According to this definition, even though the locality of the food and the minimized number of intermediaries make part of ideal-type SFSCs, these distribution channels are not limited to direct sales [2] or local food [3]. Similarly, SFSCs can be limited to organic products, but this is not always necessarily the case. Figure 1 below presents the scope of SFSCs as accepted in this study, with regard to directness, locality, and organic production.

SFSCs typically involve producers with limited production and logistics capacities. By participating in SFSCs, they find themselves suitable marketing channels that enable them to become entrepreneurs. Nevertheless, several studies argue that producers often cannot upscale their activity through short distribution channels [4–6] due to their limited access to markets and financial resources. In certain cases, the inability of SFSC stakeholders to upscale their production and distribution leads to a mismatch between demand and supply in the face of the escalating consumer demand for SFSC products. During lockdowns caused by the COVID-19 pandemic, for example, there was a peak in demand for SFSC products, and the producers needed to show great agility to handle the dramatic increase [7].

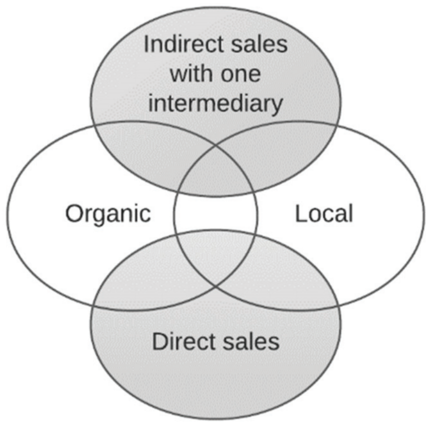

Figure 1. Scope of SFSCs as accepted in this study, represented by the regions highlighted in gray.

To satisfy the increasing demand and contribute to the creation of more sustainable and resilient food systems, SFSCs need to increase their overall impact [8]. To participate in SFSCs and expand their supply capacities, many active and potential stakeholders need the local, national, and supranational authorities to facilitate the access to infrastructure [9,10] and financial resources [11,12] as well as to training [13] and networking opportunities [11]. Policymakers also play an important role in facilitating the functioning of SFSCs through policy reforms [12,14,15]. On the other hand, contributions of the scientific community are equally critical for identifying and overcoming the issues and challenges that complicate the establishment, performance improvement, and upscaling of SFSCs (i.e., increased production and/or logistics capacities, increased number of producers) [16,17]. Moreover, in our opinion, the novelty of SFSC initiatives adds to the importance of methodically studying these issues and challenges, since these recent initiatives often include insufficiently experienced practitioners and the lack of an established culture of scientific management and optimization, resulting in poor performance and impeding their upscaling.

1.2. Originality of the Study

Literature reviews about SFSCs focus on characterization [18], sustainability properties [19,20], and logistics [17] of SFSC, as well as on the coexistence of long and short FSCs [21]. To the best of our knowledge, however, a systematic review of the issues and challenges in SFSCs is not available yet in the scientific literature. This study, therefore, offers a systematic review of issues and challenges that SFSC stakeholders encounter during the creation and functioning of these initiatives.

Even though there is no such systematic review in the literature, many studies mention the existence and acknowledge the importance of SFSC issues and challenges such as costly distribution [22], distribution channel diversification [23], and use of digital technologies [3]. Nonetheless, these studies typically focus on one specific SC process or activity, particularly on production and distribution processes [24], without discussing the other parts of the SC. Moreover, most studies tend to adopt a one-dimensional perspective in their evaluation of SFSCs; some approach the subject of SFSCs from a purely social point of view, while some limit it to an optimization problem. In other words, the scientific research on SFSCs does not embrace a holistic approach, resulting in a lack of effective models and solutions to support the overall functioning and improvement of SFSCs. To overcome this limitation, we need to study SFSCs holistically by considering all the processes of SFSCs [17] and by embracing a multidimensional perspective (e.g., consideration of economic, social, environmental, and health-related aspects).

As a first step toward a holistic SFSC vision, we identify the main processes that compose an SFSC by benefiting from the SC processes defined in the supply chain operations reference (SCOR) model by the Association for Supply Chain Management. The use of the SCOR model and the definition of SFSC processes can help forge a link between the supply chain management field and SFSCs research, thus ensuring that we do not ignore any processes while aiming for performance improvement and upscaling. For the same purpose, we also define 12 issue/challenge (i/c) natures such as economic, optimization, social, and so on (see Section 2.2.1 for the complete list). Finally, we make use of strategic-tactical-operational levels to help characterize the issues and challenges encountered in SFSCs.

1.3. Objective of the Study

According to Pato [25], solving issues and minimizing difficulties in SFSCs require the participation not only of supply chain stakeholders but also of civil society organizations, public institutions, and scientific researchers. The contribution of this study, hence, is to provide these groups with a holistic approach to SFSC issues and challenges, contributing to the proposal of realistic and comprehensive solutions and strategies to support the performance improvement and upscaling of SFSCs. To improve our understanding of the issues and challenges that the SFSC stakeholders encounter, this study aims to answer the research questions (RQs) below in light of the existing scientific literature:

- RQ 1: At which parts of the SFSCs do the issues and challenges occur?
- RQ 2: How can we characterize the issues and challenges in SFSCs according to the SFSC processes that they relate to, i/c natures, and the level of the solutions that they require?

To answer these questions, the remainder of the study is structured as follows: The Section 2 describes the steps of the study, including a general literature review and the systematic literature review on SFSC issues and challenges. The dimensions we defined to reach our results (SFSC processes, i/c natures, and i/c levels) are also described in this section. Section 3 provides background information, particularly on the emergence and characteristics of SFSCs and includes a SWOT analysis as well as a thematic classification. Section 4 interprets the findings by making observations related to each research question. Finally, Section 5 summarizes our findings, states the limitations of the study, and provides perspectives for future research.

2. Materials and Methods

2.1. Review of the SFSCs Literature

We started our study with a broad review of the SFSCs literature. To complement our review with quantitative information, we also made a thematic classification of SFSC studies according to their focus: in other words, their main subject. In September 2020, out of the 474 studies we reached in the Scopus database that had been published since 2000 we identified 172 that directly handled SFSCs. (The search was cut off in 2000 since the first study to use the term SFSC was published that year [26]). We classified these studies according to their main interest, mainly based on their titles, author keywords, and abstracts. In this classification, we defined 26 themes such as emergence of SFSCs, characteristics of SFSCs, SC strategies, economic sustainability, and so on (see Section 3.3 for all the themes). Most studies were classified under more than one theme. The qualitative and quantitative results of this literature review are presented in Section 3.

2.2. Systematic Literature Review on SFSC Issues and Challenges

Following our broad literature review, we identified the need for a more detailed review of the literature with a particular focus on the issues and challenges (i/c) in SFSCs. To do so, we opted for a more systematic approach where we focused on the most recent publications, performed a full-text reading, and looked for particular information, namely SFSC issues and challenges (i/c). For this detailed literature review, we limited the timespan to 2020–2021 since we wanted to focus only on the most recent literature due to all the changes that have occurred in the sector, particularly the impact of the COVID-19 pandemic that increased the popularity of SFSCs among consumers and researchers. Among the 44 studies included in our review were three papers that were literature reviews ([17,20,21] in the reference list of the study). As a result, the impact of past research is still inherent in our study.

At the beginning of our systematic literature review of i/c in SFSCs, we made a keyword search in Web of Science database in September 2021, using the keyword string presented in Table 1. Later, we methodically selected the studies to include in our review as demonstrated in Figure 2. Among the 106 studies that were published in 2020 and 2021, five were eliminated after reading the abstracts since these studies were about sectors other than food (e.g., forest products), but they still appeared in the results due to keyword resemblance. Out of the 101 remaining studies, 57 were eliminated after full text browsing since they did not focus on SFSCs but rather mentioned them very briefly or only as an example.

Table 1. Keyword string used in Web of Science database.

Title		Abstract		Author Keywords
"short * food * supply chain *" OR "short * agri-food * supply chain *" OR "short supply chain *"	OR	"short * food * supply chain *" OR "short * agri-food * supply chain *" OR ("short* supply chain *" AND ("agri *" OR "food *" OR "farm *"))	OR	"short * food * supply chain *" OR "short * agri-food * supply chain *" OR "short supply chain *"

In Web of Science database, the asterisk (*) represents any group of characters or no characters.

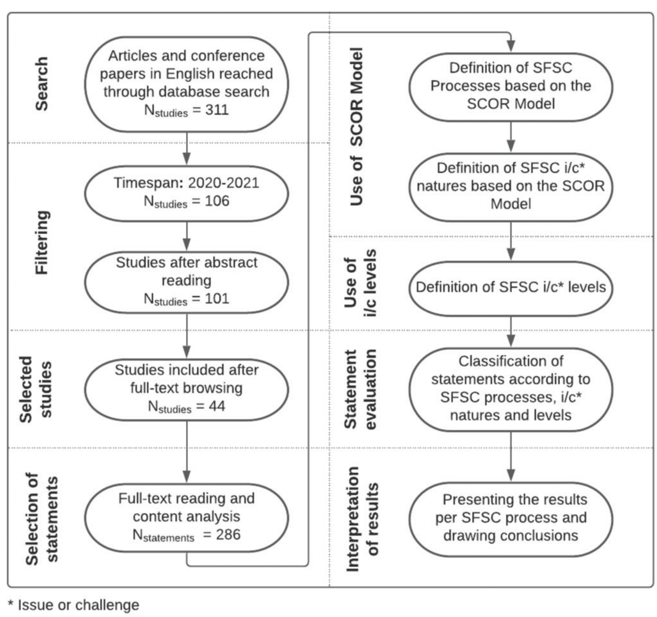

Figure 2. Steps of the systematic literature review.

During the full-text reading of the selected 44 studies, we looked for statements that pointed out the i/c that SFSC practitioners face. We opted for full-text reading since this information is not explicitly defined as "issue", "problem", "barrier", "success factor", or "challenge" most of the time, and it is often embedded in the text, requiring in-depth content analysis (see, for example [21] from the SFSC literature for another study that uses a similar content analysis method). As a result of the full-text content analysis, we reached 286 i/c statements that implied an i/c in SFSCs from the 44 selected studies. Concerning the identification of i/c, it is important to note that we considered only the statements that specifically concerned SFSCs and not any other similar concepts such as alternative food networks or local food systems.

2.2.1. Definition of 3 Dimensions for SFSC i/c: SFSC Processes, i/c Natures, and i/c Levels

Following the identification of relevant information in each selected study, we defined 3 dimensions to help us evaluate and interpret the selected i/c statements in a way to include every stage and every aspect of the SFSCs in our study.

To develop the definitions of the first two dimensions, SFSC processes and i/c natures, we used the SCOR model, proposed by the Supply Chain Council (APICS). The SCOR model is a comprehensive and well-known tool in the SCM domain that helps describe, analyze, and improve SCs by providing a methodology as well as benchmarking and diagnostic tools [27]. As displayed in Figure 3, the SCOR model proposes six main SC processes: "plan", "source", "make", "deliver", "return", and "enable".

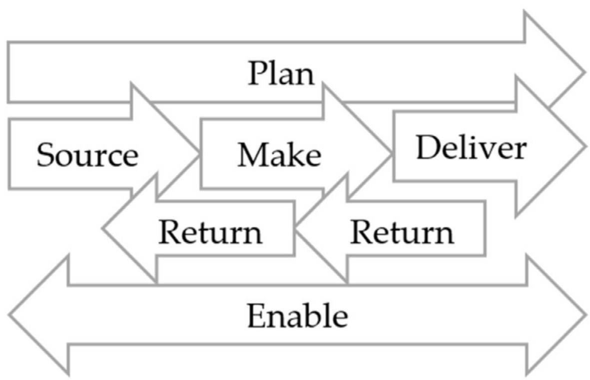

Figure 3. Six main processes in the SCOR model.

The processes, "source", "make", "deliver", and "return", refer to SC processes where material movement or transformation takes place, whereas the process, "plan", concerns determining the courses of action regarding these processes. On the other hand, the SCOR model includes a sixth far-reaching process, "enable", that is associated with the whole supply chain. "Enable" integrates processes such as human resources processes, financial processes, and ICT (information and communication technologies) processes with the supply chain processes [27]. Accordingly, we used the planning and execution processes defined in the SCOR model to propose SFSC processes (see Table 2), while we used "enable" for the definition of another dimension: i/c natures (see Table 3). As per the identification of i/c natures, we shared some keywords that describe the themes we frequently encountered in the selected studies in Table 4.

Table 2. Definition of SFSC processes based on SCOR model processes.

SCOR Model Processes	SFSC Processes
Plan	Planning of agricultural production Planning of food processing Planning of logistics activities
Source	Sourcing agricultural input Sourcing packaging material
Make	Agricultural production Food processing
Deliver	Product distribution: Order management Packaging Transportation Sales Consumption Waste management Storage
Return	Reverse logistics

Table 3. Describing the nature of SFSC i/c based on the SCOR model process Enable.

SCOR Model Process: Enable	i/c Natures
Supply chain business rules Supply chain risk Supply chain performance Supply chain procurement	Optimization and resilience Upscaling and marketing Economic Environmental
Supply chain human resources	Labor and competences Social Health-related Culture- and habit-related
Supply chain assets	Physical infrastructure
Supply chain contracts Supply chain network	Cooperation, collaboration, and coordination
Regulatory compliance	Political, bureaucratic, compliance
Data and information Supply chain technology	Data, information, and technology

Concerning the definition of SFSC processes, below are some clarifications:

- We include “product distribution” as an umbrella process even though we already defined several processes within it. This is because many i/c statements we encountered were related to product distribution in a general sense and often the relevant process within product distribution (e.g., order management, storage) was not specified.
- We use “distribution”, “logistics”, and “transportation” in such a way to refer to different concepts and not interchangeably. Accordingly, logistics includes any activities relating to sourcing, product distribution, and reverse logistics, while transportation refers only to moving products using a vehicle.
- “Order management” concerns tracking, preparing, and shipping customer orders.
- “Sales” process represents when customers purchase the food products, for example by selecting products and paying for them in a farmers’ market, or by placing an order online and paying by bank card.
- “Consumption” involves what comes after the sales process. In other words, it implies food preparation and consumption for consumers.
- “Waste management” consists of food and packaging material waste that occur during production distribution.

Table 4. Some keywords for each class of i/c natures.

Optimization and Resilience	Data, Information, and Technology	Upscaling and Marketing	Labor and Competences	Physical Infrastructure	Cooperation, Collaboration, Coordination
Logistics efficiency Small product volumes High distribution costs Delivery schedules Harvest schedules SC disruptions Responding rapidly to changing conditions Joint planning	Information about products Market information Data analytics Digitalization Online SFSCs Smart technologies Use of IT Information asymmetry Customer demands and trends	Product diversification Distribution channel diversification Demand Target clientele High-quality products Public interest Image, reputation Certification, labeling, branding Promotion, advertisement Competition Integrating new participants Niche market	Knowledge Skills Experience Creativity Training, education, mentoring Cross-learning Expert advice Small workforce Qualified labor Long working hours Volunteer work	Using LFSC infrastructure Access to land Access to transport Processing facilities Points of sale Internet infrastructure Food hubs, collection centers Electric vehicles Refrigerated vehicles Storage areas	Relationships with other actors Synergies Shared interests Sharing resources Networks Cooperatives Building communities Volunteers Communication among stakeholders Joint decisions Commitment Risk sharing Collective knowledge
Economic	**Environmental**	**Social**	**Health-Related**	**Culture- and Habit-Related**	**Political, Bureaucratic, and Compliance**
Investment Economies of scale Cost accounting Product pricing Capital shortage Price competition Survival Willingness to pay Distribution costs Wages Subscription fees for consumers	Organic farming Seasonality of agriculture Use of natural resources Eco-labels Packaging Waste	Access of low-income consumers Dedicated customer groups Face-to-face interaction Trust-based relationships Proximity relations Conflict resolution Fair prices Communication skills	Organic products Food quality Quality assurance systems Food safety Hygiene standards Nutritional recommendations COVID-19	Resistance to change Changing operation methods Purchasing and consumption routines Unwillingness for upscaling Ideological motivations Cultural barriers to cooperation Eating preferences	Incentives Proposals and grants Political support Policy reforms Tax policiesPublic procurement policies European projects Reduction the bureaucracy Lack of quality control Disabling regulatory frameworks Hygiene rules

2.2.2. Evaluation of i/c Statements According to 3 Dimensions

We identified 286 i/c statements in selected studies, each of which pointed out an issue or a challenge in SFSCs. We evaluated each i/c statement according to its relation to different SFSC processes, its nature, and the level (e.g., strategic, tactical, operational) of the potential solutions that can address it. The potential solutions were not necessarily mentioned in the reviewed studies.

Through such a methodology that combines several perspectives for evaluating the issues and challenges of SFSCs, we aimed to draw comprehensive and multidimensional conclusions about the limitations and difficulties of SFSCs.

Below, an example statement taken from the study of Borcic [14], as well as the Tables 5 and 6 are used to explain our approach when evaluating the i/c statements:

> "Another problem related to boxes is that demand is usually much lower in the most productive times of the year. For example, in summer, when the yield is very high and producers can offer the richest boxes, many consumers are on vacation. One of the methods to save their produce from going to waste is to process it, for example by pickling, juicing, drying, making jams, etc." [14] (22p.).

Table 5. Evaluation of the example statement according to first two dimensions.

Relevant Part of the Statement	Inference Made		Details
	SFSC Process	Issue/Challenge Nature	
" ... demand is usually much lower in the most productive times of the year."	Sales	Upscaling and Marketing	Variability of the demand throughout the year relates to Marketing nature. Lower demand relates to the Sales process.
" ... in summer, when the yield is very high ... "	Agricultural production	Environmental	Higher productivity in summer takes place among natural properties of agricultural production.
" ... save their produce from going to waste is to process it ... "	Waste management, Planning of food processing, Food processing	Economic Social	Food waste is considered an economic and a social issue.

Table 6. Evaluation of the example statement according to the third dimension.

Inference Made	Details
Issue/Challenge Level	
Strategic	We classify this statement as "strategic" since the i/c can be addressed by investing in processing and/or storage infrastructure, making food processing a part of the business strategy.
Tactical	We classify this statement as "tactical" as well, since the i/c can be addressed by using local infrastructure for processing and/or storage. The excess products can also be processed with the existing resources, without investing in infrastructure. In this case, food processing is performed only when necessary and potentially for a smaller quantity of products.

While interpreting the results we obtained, we formed and made use of a matrix that summarized the review results according to the SFSC processes that we defined (see Section 4). This matrix enabled us make observations related to our research questions.

3. SFSC Characteristics and Issues

To better understand the limitations of SFSCs and the need for overcoming them, we should first have a clear idea about the emergence and characteristics of SFSCs, as well as the obstacles to achieving their expected benefits. For this purpose, this section provides such background information, followed by a SWOT analysis and a thematic classification that complements the provided information.

3.1. Emergence of SFSCs

Even though industrialization in food systems via long food supply chains has obtained great success in reducing production and distribution costs and in making food available for more people, it has also attracted criticism due to its negative impact on the environment and society [19,28] as well as because of the food safety problems it causes [19]. Consequently, in recent years academics have extensively analyzed the drawbacks of industrialized food systems [18]. The main drawbacks concern environmental damage caused by intensive production and distribution [18,29,30], unfair distribution of margins among supply chain stakeholders [31,32], food safety issues that raise health concerns [18,29,33], and adverse social impacts on society [34]. Over recent decades these drawbacks have led to the emergence of alternative food distribution channels and SFSCs [29,35–38].

3.2. Characteristics of SFSCs

Marsden et al. [26] (pp. 424–425) describe SFSCs through their role in "shifting the production of food commodities out of their 'industrial mode' and potentially 'short-circuiting' the long, complex and rationally organized industrial chains within which a decreasing proportion of total added value in food production is captured by primary producers". They emphasize the recently increasing interest in "more local" and "more natural" food products as a trigger for the development of such supply chains, which typically brings back the social interaction between food producers and consumers ("resocializing food"), as well as providing food products with an identity through their spatial aspects ("respatializing food"). The authors claim that "locality" of food is a major characteristic of SFSCs but point out that these supply chains can also be "spatially extended" [26]. Kneafsey et al. [2] argue that many researchers who have studied SFSCs accept the description of SFSCs by Marsden et al. [26] and note that some other newer definitions condition the minimum number of (ideally zero) intermediaries. Among the newer definitions in the literature, the below is a comprehensive one that incorporates the main characteristics of SFSCs, offered by Michel-Villarreal et al. [39] based on the SC definition made by Christopher [40]:

> "Short Food Supply Chains (SFSCs) are networks of connected and interdependent actors mutually and cooperatively working together to control, manage and improve the flows of information-embedded products, services, resources, and/or information, from farm to fork, seeking a reduction of intermediaries and physical distance between producers and consumers." [39] (3p.).

On the other hand, the European Network for Rural Development [41] emphasizes the enormous variety of SFSCs in EU member countries and concludes that we can interpret them in a flexible manner according to the context and the area in which they function. Accordingly, we use the term SFSCs in this study to include both direct and indirect distribution channels (with one intermediary as suggested by the French Ministry of Agriculture) as well as both spatially proximate and spatially extended settings. It is crucial to emphasize that the core characteristics of SFSCs need to remain valid even in indirect and/or extended scenarios. Accordingly, an initiative should provide their consumers with clear information about products and production processes, establish personal links among all SC stakeholders through fewer intermediaries, offer high quality (e.g., organic, ecologically produced, fresh . . .) food products with spatial identity, and strive to contribute to sustainable production, distribution, and consumption practices to qualify as an SFSC.

3.3. Thematic Classification of SFSC Studies

A further analysis that can help describe the characteristics and issues of SFSCs is a thematic classification of the studies in the SFSCs literature. Table 7 below presents in detail the results of the thematic classification we conducted for developing a deeper insight into the literature with regard to the studied topics, while Figure 4 provides a more compact presentation of the same results.

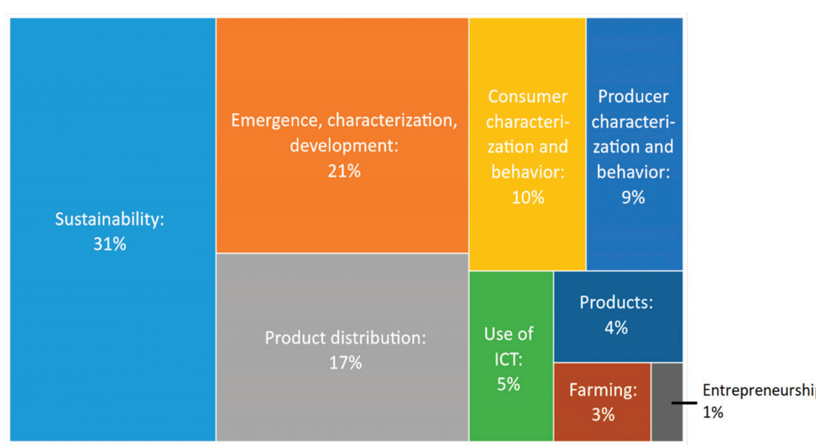

Figure 4. Thematic classification results with the themes grouped.

Table 7. Thematic classification results in detail.

Group of Themes	Theme	Number of Times the Theme Was the Focus of a Study
	Farming	9
Emergence, characterization, development	Emergence of SFSCs	19
	Market access in SFSCs	11
	Development of SFSCs	29
	Characteristics of SFSCs	8
	SC stakeholders	3
Product distribution	Distribution practices	2
	Distribution infrastructure	5
	Issues in distribution	5
	SC disruptions & resilience	11
	SC strategies	28
	Innovations in distribution	5
	Entrepreneurship, business model, organizational innovation	3
	Use of ICT	17
Sustainability	Economic sustainability	38
	Environmental sustainability	33
	Social sustainability	30
	Food self-sufficiency	2
Consumer characterization and behavior	Purchasing decisions of consumers	26
	Characteristics of consumers	3
	Perceptions of consumers	6
Producer characterization and behavior	Participation of producers in SFSCs	19
	Perceptions of producers	4
	Competences of producers	3
	Challenges of producers	3
	Products	14
	Total	336

According to these results obtained through 172 studies published between 2000 and 2020, we can conclude that the evaluated studies frequently concerned the characterization of SFSCs, the producers, or the consumers who participate in them. Based on the findings of the classification, we can also conclude that the sustainability properties of SFSCs are frequently handled in the scientific literature. We can also argue based on the figures that strategic, operational, and organizational aspects of SFSCs such as product distribution, use of information and communication technologies (ICT), and their business models have not had much attention in comparison.

3.4. Obstacles to Achieving the Expected Benefits of SFSCs

To facilitate and optimize the movement of food items from production to consumption, conventional food systems function through long food supply chains that involve numerous intermediaries, each of which often specializes in performing one specific activity in the most efficient way possible. SFSCs, on the other hand, are established on the principle of eliminating these intermediaries by putting the producers in the center of commercialization, enhancing their autonomy, and increasing their responsibility along the supply chain.

SFSC stakeholders and researchers often agree on the social benefits brought by SFSCs but not always on the environmental and economic ones [20], which points out the need for further studying and improving the environmental and economic performance of SFSCs. However, ADEME (French public agency for ecological transition) [42] argues that the high variety of SFSC initiatives makes it difficult to study the environmental performance of SFSCs and to confirm that they systematically have a lower negative impact on the environment. Similarly, studying their economic viability (costs, profitability, and capacity to expand if necessary) also requires a consideration of specific cases.

Producers who opt for distributing their products through SFSCs are typically small- and medium-scale farmers with limited production and logistics capacities due to insufficient availability of resources such as workforce, infrastructure, skills, and capital. Coupled with their increased responsibility, their smaller scale brings about various issues and challenges that complicate establishing a new SFSC initiative or improving the performance of an existing one. Clearly, the type and significance of these issues and challenges depend on the features of the producer, the farm, the relationship with consumers, as well as the specific initiative of SFSC [43] since these can greatly change from one example to another. For this reason, Borcic [14] argues that farmers engaged in SFSCs must tackle problems that are quite different from those of conventional farmers and that they need to be creative and innovative concerning problem-solving.

Despite the huge variety of SFSCs that requires adapted solutions and strategies, stakeholders of SFSCs often face similar issues and challenges. For example, Rucabado-Palomar and Cuellar-Padilla [6] generalize the issues and challenges of SFSCs under the four groups below:

- Need for logistical infrastructure;
- Importance of social links;
- Need for diversifying the distribution channels;
- Product-related constraints.

All in all, distinctive characteristics of SFSCs that attract more and more consumers and producers do not suffice to ensure overall performance and scalability of such SCs. The market conditions in which they operate, and the lack of experience and resources of the participants lead to limitations to achieving their sustainability benefits, which are not limited to economic and environmental dimensions but also include a social aspect (e.g., enabling the access of more people to SFSCs by scaling up). To synthesize all the information about both the strong and weak sides of SFSCs analyzed in the literature, we propose a SWOT analysis as shown in Table 8. Our discussions with 10 SFSC practitioners who are representatives from community supported agriculture initiatives and from logistics service providers for SFSCs as well as individual producers involved in diverse initiatives confirmed the relevance and importance of the elements that are included in the analysis.

Table 8. SWOT analysis for SFSCs.

Strengths	Weaknesses
Local, fresh, and healthy food [31,44–46]	Inefficient and costly distribution [3,55–60]
Organic production [14,16,47–49]	Limited product availability (e.g., quantity, variety) [17,61,62]
Decreased food miles [41]	Lack of processing and/or distribution infrastructure [18,30,63]
High traceability of products during distribution [50]	Limited marketing skills of producers [41]
Increased profits [47]	Reaching only a small range of consumers [30]
Urban proximity [16,51,52]	Unfamiliarity of consumers with SFSCs [3]
Greater autonomy for producers [14,53,54]	
Direct communication between producers and consumers [41]	
Opportunities	**Threats**
Collaboration with other producers and/or consumers [1,41]	Global and efficient food supply chains with easy-to-reach sales channels (e.g., supermarkets) [60]
Financial support by governments and/or EU [3,32]	High prices for buying land [41]
Public catering (e.g., school/hospital canteens) [64,65]	Highly time-oriented buying habits of consumers (e.g., demand for immediate access to products) [72]
Development parallel to other sectors (e.g., agritourism) [66]	Excessive standards and/or legal requirements [50]
Use of existing infrastructure (e.g., sales points) [41]	Finding the balance between scaling up and preserving SFSC characteristics [30]
Food hubs/platforms [65]	
Increased consumer knowledge and trust in producers [67–70]	
Development and attractivity of e-grocery [3,71]	

The “weaknesses” and “threats” presented in the SWOT analysis acknowledge the existence of various issues and challenges that hinder better performance and scalability, supporting our motivations to conduct this study.

4. Results and Discussion

Despite the growing demand for SFSC products and the potential of SFSCs for improving the sustainability and resilience of food systems, performance improvement and upscaling of such SCs remain difficult to achieve due to numerous issues and challenges. The systematic literature review that we conducted was aimed at providing the reader with a better understanding of the i/c in SFSCs through a holistic evaluation of the scientific literature.

In this section, we share the results of the systematic review and interpret the results to look for answers to each research question of the study. Table 9 below summarizes the results of the review in terms of i/c statements identified per SFSC process. On each line, the ratio of statements that relate to each i/c level and each i/c nature are represented as percentages. The cells are highlighted in different shades, differentiating between 0% to 25%, 26% to 50%, 51% to 75%, and 76% to 100%. For example, concerning the SFSC process of “product distribution (in general sense)”, we identified 178 statements in 41 studies. Of these statements 99% are classified as “strategic” and 74% of them as “upscaling and marketing”.

Table 9. Findings of the systematic literature review, per SFSC process.

			% of Times That the Statements Are Classified														
			Level			Nature											
SFSC Process	Number of Statements	Number of Cited Studies *	Strategic	Tactical	Operational	Optimization and Resilience	Data, Information, and Technology	Upscaling and Marketing	Labor and Competences	Physical Infrastructure	Cooperation, Collaboration, Coordination	Economic	Environmental	Social	Health-Related	Culture- And Habit-Related	Political, Bureaucratic, and Compliance
Planning of agricultural production	10	5	100	70	40	70	50	70	80	30	40	50	40	50	30	20	20
Planning of food processing	6	4	100	67	17	50	50	84	67	17	34	50	34	67	34	0	34
Planning of logistics activi-ties	24	16	100	92	79	96	50	67	50	30	46	55	50	50	9	25	17
Sourcing agricultural input	1	1	100	100	0	0	0	0	0	0	0	100	0	0	0	0	0
Sourcing packaging mate-rial	1	1	100	100	0	0	0	0	0	0	0	100	0	0	0	0	0
Agricultural production	70	31	99	64	36	28	36	78	40	25	28	46	35	26	20	26	23
Food processing	58	22	98	50	24	38	38	83	49	35	23	56	16	26	23	18	26
Order management	2	2	100	100	50	50	100	100	100	50	50	50	50	50	50	50	0
Packaging	5	4	100	40	40	80	20	80	40	40	40	60	20	40	20	0	20
Transportation	28	19	100	82	82	86	29	68	40	43	33	58	58	33	15	22	25
Sales	167	39	100	50	33	32	44	90	38	23	31	51	16	45	18	25	22
Consumption	4	3	100	75	25	25	50	75	50	0	50	50	25	50	25	75	25
Waste management	5	4	100	80	40	40	20	80	20	20	20	60	60	60	20	20	20
Storage	6	5	100	100	50	67	50	100	67	67	34	67	67	50	34	34	0
Product distribution (in general sense)	178	41	99	46	28	34	38	74	45	24	45	43	17	48	15	22	24
Reverse logistics	1	1	100	100	0	0	0	0	0	0	0	0	100	0	0	0	0

* Refer to Table A1 in Appendix A for the list of cited studies per SFSC process.

4.1. RQ 1: At Which Parts of the SFSCs Do the Issues and Challenges Occur?

4.1.1. Observation 1: Most Studies Focus on i/c Encountered in Product Distribution and Production Processes in SFSCs

The findings confirm the motivation behind this study that the existing literature tends to focus on some parts of the SFSCs while neglecting to take into consideration some others. Referring to Section 1, the results of our review support the argument that most studies focus on product distribution and production i/c in SFSCs [24]. As seen in Table 9 above, most of the selected studies mention at some point an i/c about the product distribution (in general sense) (93% of cited papers) or the sales process within product distribution (89% of cited papers). Following the product distribution and sales, 70% and 50% of the cited studies, respectively, specify agricultural production and food processing issues and challenges. About the tendency to focus on the product distribution process, we also observe that the transportation and planning of logistics activities processes also take place among the frequently mentioned SFSC i/c, 43% and 36%, respectively.

4.1.2. Observation 2: Authors Tend to Overly Generalize Their Statements about Product Distribution i/c in SFSC: Product Distribution (in General Sense)

The large number of statements and cited studies that mention the product distribution process in SFSCs in a general sense confirm the importance of this process. Nonetheless, they also show that the literature tends to overly generalize the occurrence of SFSC i/c and that it does not mention the specific process within the product distribution (namely order management, packaging, consumption, waste management, and storage).

4.1.3. Observation 3: Planning, Sourcing, and Reverse Logistics Are Under-Studied SFSC Processes

In addition to the overlooked processes within product distribution, the results also point out three different groups of SFSC processes that are under-studied. First, consideration of the SC process planning is limited to the logistics activities in the SFSCs research. Planning of food processing and planning of agricultural production are neglected subjects, even though they are critical in terms of aligning supply and demand. Second, the SC process of sourcing is completely an under-studied subject in the SFSCs literature. Finally, the existing studies do not pay attention to the reverse logistics process.

4.2. RQ 2: How Can We Characterize the Issues and Challenges in SFSCs?

4.2.1. Observation 1: Strategic and Tactical i/c with Upscaling-Marketing and Economic Nature Are Dominant along the SFSC

Identified i/c statements in SFSCs point out a large dominance of strategic and tactical levels. This is due to the small scale and limited resources of such initiatives, leading to the conclusion that most problems they encounter can be addressed by long-term plans such as investing in infrastructure, gaining knowledge and experience, and restructuring the SCs. As per the i/c natures, the results show that upscaling-marketing and economic i/c are crucial along the SFSC. The dominance of strategic and tactical levels as well as of upscaling-marketing and economic natures supports the claimed difficulty in upscaling the SFSCs (refer to the Introduction) and leads to the conclusion that this difficulty mainly relates to a lack of financial and human resources, a lack of infrastructure, as well as to a need for better marketing organization (e.g., facilitated flow of materials) and for optimization (e.g., cost minimization) along the SC.

4.2.2. Observation 2: Planning of Logistics Activities and Transportation Can Be Improved over a Shorter Term Than Other Processes

According to the overall results, 99% of all i/c statements relate to the strategic level and 54% to the tactical level, while only 32% relate to the operational level. However, as seen in Figure 5, the distribution among the three levels differs according to the SFSC processes. Based on the number of statements identified, only the SFSC processes that have a higher number of statements are considered here.

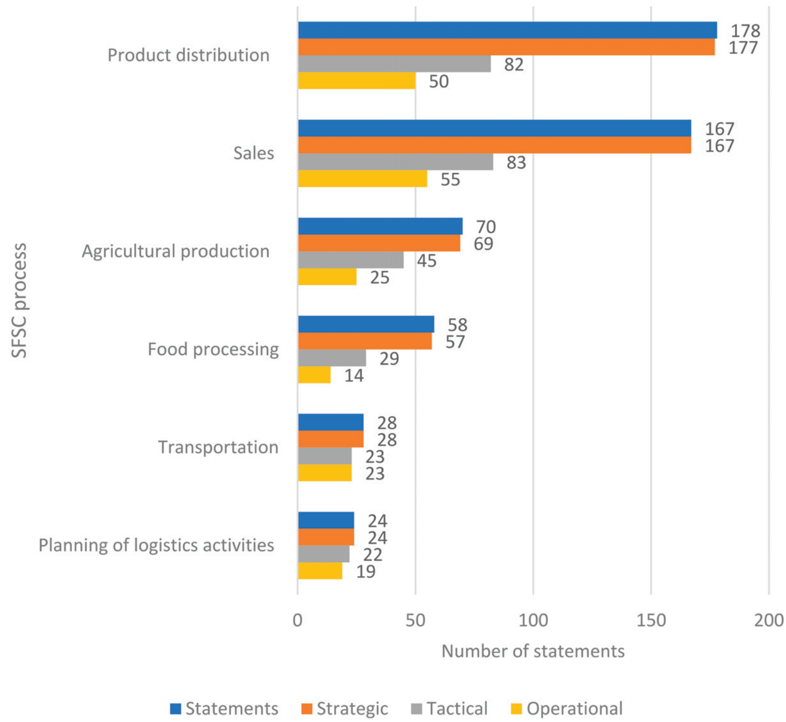

Figure 5. Number of i/c statements and their levels per SFSC process.

As in Figure 5 above, we observed that agricultural production, food processing, sales, and product distribution (in general sense) all have a heterogeneous distribution among the strategic, tactical, and operational levels. For these processes, nearly all the i/c mentioned require the implementation of strategic-level plans or solutions. Considering the statements that led to these findings, this is due to the need for improved infrastructure in such processes.

On the other hand, the processes planning of logistics activities and transportation have rather homogeneous distributions among the three levels. In other words, issues and challenges encountered in these processes can also be addressed by adopting solutions implemented in the short-term without needing to make heavy investments. In a way to support this claim, we also observed that the dominant i/c nature for these processes is optimization-resilience, which relates to operational-level improvement approaches such as vehicle routing.

4.2.3. Observation 3: Health-Related, Culture- and Habit-Related, and Political-Bureaucratic Aspects of SFSC i/c Are Under-Mentioned

In the scope of this study, we defined health-related, culture- and habit-related, and political-bureaucratic natures based on our knowledge of SFSCs, by assuming that they take place among important aspects of such SCs. However, interestingly, the results show that they do not take place among the frequently mentioned i/c natures. This can be because they are frequently handled in the context of SFSC characterization but not in terms of the issues and challenges encountered in SFSCs.

5. Conclusions

5.1. Main Findings and Contributions of the Study

SFSCs have been gaining popularity among producers and consumers in recent decades. However, their stakeholders have faced various issues and challenges that result in poor performance and difficulties in upscaling. To meet increasing customer demand and realize their claims of more sustainable and resilient food systems, SFSCs need to overcome their issues and challenges and become better performing and more scalable.

The goal of this study was to use SCM knowledge to offer a holistic, end-to-end, vision for SFSCs by examining their issues and challenges. To do so, we conducted a systematic review of the recent literature through full-text content analysis. We used SFSC processes and issue/challenge natures that we defined based on the SCOR model and our knowledge about SFSCs, as well as strategic-tactical-operational issue/challenge levels while conducting the content analysis. We used the results we obtained to find answers to the research questions of this study.

The findings helped improve our understanding of the issues and challenges in SFSCs holistically, by questioning every SFSC process, issue/challenge nature, and issue/challenge level and pointing out several gaps in the existing literature. First, most studies only focus on i/c in production and distribution processes in SFSCs. While mentioning product distribution issues and challenges, they often generalize them and do not particularly discuss order management, packaging, or storage processes. In line with the general tendency to handle product distribution and production issues and challenges, SFSC processes such as planning, sourcing, and reverse logistics are under-studied. Furthermore, strategic and tactical levels, as well as upscaling-marketing and economic natures are dominant along the SFSC. The only SFSC processes that appear to have operational issues and challenges are the planning of logistics activities and transportation. Among the SFSC issue/challenge natures we defined, health-related, culture- and habit-related, and political-bureaucratic issues and challenges are under-mentioned.

This study contributes to the literature by offering a holistic overview of issues and challenges encountered in SFSCs. The identification of SFSC processes that we have conducted in this study to ensure an end-to-end consideration of SFSCs is, to the best our knowledge, a first in the literature. Moreover, the definition of natures and the use of levels for characterizing the issues and challenges of SFSCs is also a novelty offered in this study. Developing a deeper insight into the issues and challenges of SFSCs and embracing a holistic perspective while doing so are particularly critical in this area of research since SFSC initiatives are newly emerging, and there is a crucial need for improving their performance. Such a contribution is particularly important because the SFSC literature is mostly built around describing the characteristics of these initiatives rather than focusing on their problems and searching for solutions to these problems. Therefore, a review of their issues and challenges points out the need for studying SFSCs not only with a descriptive, but also with a diagnostic and prescriptive approach.

5.2. Limitations

This study also has limitations concerning its methodology as well as limitations that derive from its materials.

First, the systematic review was based on full-text reading and content analysis, where we identified statements that implied issues or challenges, made their connections to SFSC processes, classified them into different issue/challenge natures, and decided the levels of potential solutions according to our understanding. To reduce the impact of subjectivity, we followed keyword patterns in our decisions.

Another limitation concerns the materials we used and comes from the general and/or ambiguous expressions used in the cited studies while mentioning SFSCs' issues and challenges. For example, agricultural production and food processing processes are often generalized as "production", requiring attributing the statement to both processes during evaluation. This limitation decreased our ability to detect agricultural production and food processing issues and challenges separately and blurred the line between these two processes.

A further limitation that derived from the materials was the use of the term SFSC in the literature. Even though there is an abundance of definitions for SFSCs, there is a consensus that they are not necessarily local, organic, or direct supply chains (see Figure 1 in Section 1). Nonetheless, researchers frequently reduce the scope of SFSCs to local food supply chains in their studies. More accurate use of the terminology can facilitate the researchers' access to the studies with the right focus and enable them to make historically more extended literature reviews.

5.3. Perspectives for Future Research

To conclude the study, we offer some perspectives for future research about SFSCs based on the findings of the systematic literature review. In our opinion, it is important to include the under-studied SFSC processes such as planning, sourcing, reverse logistics, order management, packaging, consumption, waste management, and storage in future theoretical efforts and case studies. The impact of these processes on the performance of SFSCs needs to be studied to propose appropriate solutions and strategies for an overall improvement of SFSCs' performance. Similarly, under-mentioned i/c natures such as health-related and culture- and habit-related aspects can be considered more in future endeavors. Another further research direction concerns identifying the relations among the SFSC processes, for example by making use of the issue/challenge natures. This way, the literature can evolve toward a holistic and integrated SFSC vision and offer more realistic and effective modeling approaches and improvement strategies.

Finally, reviewing the literature in terms of the issues and challenges of SFSCs in the years to come can enable researchers to observe and verify the changes that occur in the distribution of the issues and challenges handled in the literature. For example, the attention paid to sourcing issues and challenges can increase due to concerns about supply chain disruptions as experienced during the COVID-19 pandemic.

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Appendix A

Table A1. Studies where we found i/c statements, per SFSC process.

SFSC Process	Studies That Mention Relevant Issues or Challenges
Planning of agricultural production	[14,16,62,73,74]
Planning of food processing	[14,16,62,74]
Planning of logistics activities	[3,9,10,14–17,20,23,25,62,74–78]
Sourcing agricultural input	[24]
Sourcing packaging material	[24]
Agricultural production	[3,6,8,10,11,13–17,20,21,23–25,61,62,64,73,74,77–87]
Food processing	[3,6,8,10,11,13,14,16,17,20,21,23–25,39,62,64,74,77,78,80,82]
Order management	[14,39]
Packaging	[6,17,24,74]
Transportation	[3,6,9–11,14,16,17,20,23–25,39,64,76,78,81–83]
Sales	[3,5,6,8,10–12,14–17,20,21,23–25,39,47,61,62,64,74,75,77–92]
Consumption	[14,47,83]
Waste management	[14,17,39,61]
Storage	[6,14,17,39,87]
Product distribution	[3–6,8,10–17,20,21,23–25,39,47,61,62,64,73–88,90,92]
Reverse logistics	[14]

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Consumers' Visual Attention and Choice of 'Sustainable Irrigation'-Labeled Wine: Logo vs. Text

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Abstract: Growing consumer awareness about the environmental impact of their food purchase decisions means having to create labels that better communicate sustainability aspects. The aim of this study is to explore consumers' responses to "sustainable irrigation" (SI)-labeled wine. To this end, the effect of two label factors, SI claims (no SI info, logo, and text), and their position (front- vs. back-labels) on consumer choice, reasons for choice, perceived sustainability, and willingness-to-pay is determined. Moreover, we determine, for the first time, for SI claims, the relationship between consumer choice and paid attention. Our results reveal that almost 90% of the 408 consumers participating in this study show an interest in the SI-labeled wines. The main reason for choosing the SI-labeled wines rather than the control (no SI info-label) was the following: 'I think it's more environmentally friendly', with an increase of two points on a nine-point sustainability perception scale. Consumers prefer the logo-label to the text-label, mainly because they find it more attractive, and a close relationship between paid attention and product choice probability is determined. The vast majority of consumers are willing to pay an extra cost of 15% or more for SI-labeled wine vs. the control. These results have relevant implications for the industry because they show that the SI logo is a useful way to draw consumers' attention to the sustainability of irrigation practices and positively affect their choice. Our findings indicate that this way of differentiating the product in the market can contribute to compensating the economic cost of implanting SI practices.

Keywords: sustainability; attention; label; irrigation; willingness to pay; logo

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1. Introduction

Water scarcity is one of the major challenges of our time that is expected to intensify as a result of climate change, and agriculture is both a major cause and casualty of it. On average, agriculture accounts for 70% of global freshwater withdrawals [1]. Thus, to guarantee the sustainability of agrifood production systems, growing pressure is placed on agriculture to more sustainably use water.

The wine industry is among the most important industries for which sustainable production has become a goal [2]. According to recent data, more than 7.3 million hectares are used for viticulture [3], and water use is one of the main concerns of the wine industry about its environmental impact [4].

Luckily, consumer awareness of the environmental impact of their food purchase decisions has significantly grown in the last few years [5], and they are becoming decisive actors in implementing measurements that lead to more sustainable production. At the end of the production chain, and regardless of this chain's length, consumers make a decision at points of sale whether to buy a product or not. This decision may be strongly influenced by the product credence attributes, i.e., all those characteristics related to health, production methods, environmental and social orientation, certification systems, etc. [6] provided by the seller.

Labeling plays a key role in drawing consumers' attention and providing information that may influence their purchase decisions [7–9]. To the best of our knowledge, only two studies have investigated consumer preferences for wines produced with reduced water use [10,11]. The latter study focused on young Italian consumers, and reported that, on average, they are willing to pay higher prices for 'low water footprint-' labeled wines. The water footprint concept was developed by Hoekstra's research group as an indicator to represent the freshwater resources needed to produce a product unit and corresponds to the volumetric measure of freshwater use and the impact of pollution [12]. It is a very useful concept from a research point of view, but for the time being, it still seems like an unclear concept as far as consumers are concerned [13]. As stated by Tait et al. [14], more research efforts are required to assist the wine industry in developing communication strategies related to sustainability aspects by means of labeling.

One of the main strategies to save water and increase the production system's sustainability of vineyards is to apply controlled deficit irrigation. Many studies have evaluated the response of vines to this practice from the agronomic and physico-chemical points of view [15,16]. However, there is no literature about consumer perceptions of wine produced by sustainable irrigation (SI) practices.

In today's context, a profounder understanding of consumer attitudes and their buying motives as regards different sustainability attributes is necessary [2], and sustainable irrigation is one of them. As stated by Sanchez-Bravo et al. [17], further research is necessary to fully understand the commercial actions taken by consumers in relation to water-saving products.

As previously commented, labeling has a very strong impact on consumer purchase decisions. Label formats are decisive in the effectiveness of transmitting information to consumers, and label designs may significantly influence consumers' interests and preferences [18–20]. Oliveira et al. [21] performed a study with probiotic milks and reported that consumers' health-related associations were generated by graphic designs, and not by textual product descriptions (i.e., probiotic milk). Claims position may also influence consumers' responses. There are reports that consumers attach more importance to front-labels than to back-labels when deciding on which wine to buy [22]. Moreover, several studies support the notion that not all the information that customers are provided with on labels is read, and too much information can mean that consumers do not assimilate it all [23–25].

By bearing all this in mind, the main objective of this study was to evaluate consumers' responses to SI-labeled wines by paying special attention to the label design effect. Thus, our approach was to compare consumers' responses to two SI-claims (logo vs. text), mainly about preferences and choice reasons, and then to capture and assimilate the provided information. This study was designed to answer the following questions: (1) Are consumers interested in SI-labeled wines and why? (2) Do consumers' responses depend on the type of SI claim (logo-label vs. text-label)? (3) Is there a link between the attention paid to labels/claims and choice?; (4) Are consumers willing to pay an extra cost for SI-labeled wines? (5) Is the SI-claim position (front- vs. back-label) a determinant for consumers' response?

2. Materials and Methods

2.1. Research Design

Figure 1 is an overview of the research design. The study was based on an online questionnaire that included different tasks intended to respond to all the above questions. The first questionnaire task involved choosing among wine bottles that differed as regards the following information about irrigation practices included on labels: no SI info, SI-logo, and SI-text. The first step of this study was to design the SI-logo, which was designed specifically for this end, and the wine labels.

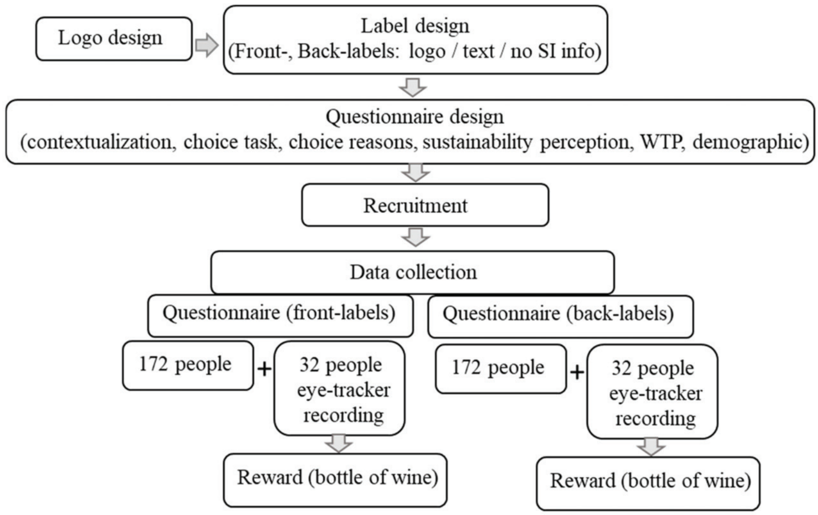

Figure 1. Overview of the experiment design.

The questionnaire also included multiple-choice questions, a sustainability evaluation, and WTP questions.

Wine-drinking people were recruited. All the participants were split into two groups. One group evaluated front-labels and the other back-labels. An eye-tracker device was used to record the choice tasks of one-sixth of the participants in each group, who were rewarded a bottle of wine after completing the entire questionnaire.

Eye-tracker devices allow the extent to which each label component captures consumers' attention to be investigated and quantified [26]. Its usefulness in evaluating the relationship between consumer behavior in choice experiments and their visual attention has been previously demonstrated [27]. Our initial hypothesis about this was that consumer choice is directly linked with the attention paid to different SI claims (Figure 2).

Figure 2. Initial hypothesis about the relation between visual attention and choice.

2.2. Participants

Four hundred and eight participants, all of legal age, participated in this study, 69% of whom were women. Convenience sampling was carried out with members of the Unió de Consumidors de la Comunitat Valenciana (Valencian Community Consumers Association). Word-of-mouth recruitment was also adopted using interpersonal relations and connections among consumers to reach a large number of participants. In order to not introduce bias due to word-of-mouth recruitment, the first 204 people were personally recruited, who covered both genders and a wide age range (18–63 years). This group of participants completed the questionnaire based on front-labels. All these participants were asked to invite one friend/family member to participate. This second group of participants (18–61 years old) answered the questionnaire based on back-labels.

Only the people who reported drinking wine at least once a month were invited to participate. They all signed an informed consent form before participation.

2.3. Labels Design

The effects of two label factors on consumer choice and willingness to pay (WTP) were evaluated as follows (Table 1): (1) SI claims (No SI info, SI-logo, and SI-text) and (2) SI claims position (front- vs. back-labels). To this end, six wine labels were designed and used as stimuli. Three were front labels, which were evaluated by half the participants, i.e., 204 people. The other three were back-labels, which were evaluated by the other 204 participants. In both cases (front- and back-labels), one of the labels was designed for a conventional wine bottle without adding SI information and acted as a control (Ctl-label). The other two labels included information about production by sustainable irrigation (SI) practices. Two different SI-labels were designed, one in which information was given as text (text-label) and another by means of a logo (logo-label). The text included on the front text-label was "Sustainable Irrigation" and it was as follows on the back-label: "This wine was made by applying sustainable irrigation". The logo placed on the front- and back-logo labels was the same and was specifically designed to this end. It showed a bunch of grapes with three drops of water at the bottom, and also included a shorter text "Sustainable Irrigation" at the top.

Table 1. Factors evaluated and the nomenclature used in this study. SI: sustainable irrigation. *Translation of "Riego Sostenible" included on the logo is "Sustainable irrigation".*

Label	Front-Label	Back-Label
Ctl-Label	No SI info	No SI info
Text-label	Text claim: *'Sustainable Irrigation'*	Text claim: *'This wine was made by applying sustainable irrigation'*
Logo-label	Logo claim:	

For the design of labels to be as realistic as possible, they included the most habitual information. The front-labels (Figure S1) included the brand, grape variety, and protected designation of origin (PDO). The brand displayed on the label was fictitious ('Pagos de Carrascosa'). However, variety and PDO were 'Bobal' and 'PDO Utiel-Requena', respectively. Bobal is a very common grape variety in the Valencia area, while 'PDO Utiel-Requena' is a well-known designation of origin in the same area. These two aspects were taken from real wine products so that the resulting labels would contain information that was familiar to the participants to a certain extent. Apart from the aforementioned information on the back-labels, further mandatory information was included (claim "contain sulfites", data on the manufacturer's origin, alcohol content, volume, bar code). In addition, some voluntary information, such as consumption recommendations (gastronomic combination, temperature drank at, storage conditions), and two logos (one about recycling and the other advising pregnant women not to drink wine), were added.

Sets of three bottles were created with the three front-label images. In the same way, sets were created by combining the three back-label images (Figure S1). To contextualize, each label was shown as part of a wine bottle in all cases.

For each set of three labels, the position was randomized to avoid any order effect. As previously explained, 204 participants were presented with the front-labels set and the other 204 with the back-labels set.

2.4. Data Collection

The study was based on a questionnaire that included several sections.

1. First, to provide the participants with a real buying situation, they were asked how much they usually spent on buying wine in supermarkets. The provided options were the following: 'less than €4′, 'between €4 and €10′, 'between €10 and €15′, 'between €15 and €20′, and 'more than €20′. This price range covers most wines offered in a standard supermarket for this PDO and variety;
2. Second, the participants performed a choice task. They were shown a set of three labels (front- or back-labels). They were asked to imagine that they were in the supermarket/winery and to choose the wine that they would prefer to purchase of the three they were offered by making a mouse click on it. They were asked to assume that the three wines cost the same price (the price they previously indicated as the price of the wines that they usually buy).

For 64 consumers, eye-tracking recordings were captured during the choice task performance to evaluate their visual behavior. Thirty-two corresponded to the consumers who had to choose from among the front-labels, and the other 32 to the participants who performed the same task among the back-labels. To thank them for their participation, these participants were given a bottle of wine after finishing the requested tasks.

3. After completing the choice task, consumers were asked to answer a series of questions designed to assess different aspects, such as their choice reasons, sustainability perception, or WTP.

A multiple-choice question with nine options was used to evaluate choice reasons. Multiple-choice questions have been demonstrated to be a useful tool to understand consumer behavior regarding the products they consume [28]. The question was formulated as follows: "What are the reasons for your choice? Check all the options you consider". The list of possible answers included the following: I think it'll be of a higher sensory quality; I think that the grower will have more benefits; I think it's more environmentally friendly; I think less water has been used to produce it; The label is more attractive; I think it's more handmade/crafted; I think it's healthier; I think I'll like it more; I don't like novelties. A preliminary list was initially drawn up based on previous studies [29,30], and was then adapted to the present work objective by checking it with 10 consumers.

The participants could check all the options they considered that applied to their choice. They also had the chance to write down any other reasons by using the 'others' option.

4. In the following section, the participants who had chosen any of the SI-labeled bottles (text- or logo-labels) were asked to indicate their WTP for the wine they had chosen and the Control wine. To this end, consumers were asked to assume that the control wine had a similar price to the wine that they normally bought (which they had indicated at the beginning of the survey). Then they were given the following four options to indicate the price that they were willing to pay for the SI wine that they had chosen: 0%, 15%, 30%, and 'more than 30%' of an extra cost in relation to the control wine. For example, the consumers who stated they normally spent between €4 and €10 on a bottle of wine were asked to assume that the control wine price was €7 (the mean value within this range). Then they had to select among €7, €8.05, €9.10, and 'more than €9.10′ to indicate the price that they were willing to pay for the SI wine.

The extra cost percentages were set after performing a pretest with 10 consumers. Previous literature in this regard reported that consumers were willing to pay an extra cost of between 12.5% and 20% for organic [29] and sustainable wines [31]. These two values (12.5% and 20%) were initially used in the pretest. However, the pretest participants suggested using higher percentages, and we adapted the scale according to their suggestions.

After completing this task, they were shown the two wine images again. They were asked to indicate how sustainable they thought each wine was on a 9-point scale, where 1 corresponded to 'Not sustainable at all' and 9 to 'Very sustainable'; this scale is an adaptation of the 4-point sustainability scale reported by Aerni [32]. Half of the participants first scored the wine bottle that they had chosen and then the control bottle, while the other half viewed the images in the inverse order.

Finally in the demographic data section, they answered questions, such as their wine frequency consumption, gender, and age.

2.5. Eye-Tracking Procedure

Eye-tracker data collection took place in a room equipped with a screen-based eye tracker (Tobii Pro-Nano, Tobii Technology, Stockholm, Sweden) with daylight-type illumination, controlled temperature, and airflow conditions. The participants were asked to sit at a distance of 65 cm from the monitor and were instructed to move as little as possible while performing the task. Before starting data collection, they completed the 5-point calibration procedure from the Tobii Pro Lab-Full Edition software (Version 1.152, Tobii Technology, Stockholm, Sweden). During the task, participants' eye movements were recorded at 60 Hz using the screen-based-eye tracker integrated into the monitor on which wine labels were presented. They were orally instructed to look at the image containing the three bottles of wine arranged side by side and were asked to make a mouse click on the wine that they would purchase. As there was no time limitation, each participant could observe the labels for as long as they wished once the image had appeared.

2.6. Data Analysis

The following areas of interest (AOIs) were defined on both the front- and back-labels: brand, variety, DOP, text, and logo. The last two areas were defined only for the SI-labeled wines. The AOI-label was also defined, which involved the whole label on each bottle. All these AOIs are exemplified in Figure S2.

For each AOI, the following metrics were analyzed using the eye-tracker's software: percentage of consumers who fixed their gaze on the AOI, total fixation duration (TFD: duration of all the fixations in an AOI), fixation count (FC: number of times that a participant fixed their gaze on an AOI), and the time to the first fixation (TTFF: time from the start of the label display until the participant fixed his/her gaze on the AOI for the first time) [26,27].

For brand, DOP, and variety, which were the AOIs present on the three labels evaluated by each participant, the TTFF selected for the statistical analysis was the minimum time spent on fixing one's gaze on a specific AOI, irrespectively of the label on which this value was detected. In parallel with FC and total TFD, after evaluating these parameters for the AOIs on the three labels, the maximum value for each AOI was selected for the statistical analysis.

As previously explained, each participant could spend as long as they needed to make a decision because there was no time constraint to complete the eye-tracking task. In view of the wide variability in the time that each participant spent on completing the task, the data corresponding to TFD and FC were normalized. To this end, the TFD values from the three AOI-labels (Ctl-label, logo-label, and text-label) were added, and the same was performed with the FC values. In this way, a value associated with the total time spent by each consumer on looking at the three labels was obtained. Then the TFD and FC data for the specific AOIs were divided by their corresponding total value (Table S1).

An analysis of variance (ANOVA) was carried out to evaluate eye-tracking metrics and sustainability perception data (LSD test, p-value<0.05). A z-test (multiple proportions) was performed to assess differences in the proportion of participants who chose each one of the three wines.

3. Results

The main objective of this study was to compare consumers' responses to logo-label vs. text-label, mainly as regards consumer attention, and then to capture and assimilate the provided information. Therefore, the data about the preference of SI wines vs. the control wine should be cautiously considered because there could be some bias.

3.1. Consumer Choice

The results from the choice task revealed a similar choice pattern irrespectively of the task being performed with the front- or back-labels (Table 2). The control wine was selected only by ≈ 12% of the consumers, the text-label by ≈ 36%, and the logo-label by the majority (≈ 52%).

Table 2. Percentage of choice among the three evaluated labels. Two hundred and four consumers evaluated the front-labels and the other 204 the back-labels.

		Front	Back	Total
% Choice	Ctrl	11.8 a	10.8 a	11.3 a
	SI-text	35.3b	37.7 b	36.5 b
	Logo	52.9 c	51.5 c	52.2 c

Different letters in the same column indicate significant differences in the proportion of choice according to the z-test.

3.2. Eye-Tracker Metrics and Its Relation to Consumer Choice

A similar pattern was observed after comparing the choice data of those consumers for whom the eye-tracker recordings were captured (64 participants) and those of the total dataset (408 participants). This implied that a few consumers with eye-tracker recordings chose the control wine (three participants with front-labels and one participant with back-labels). Therefore, in line with our study objective, the analysis of the eye-tracker data focused mainly on understanding the choice made between the two SI-labels (logo vs. text).

The eye-tracking metrics results obtained when whole labels were considered to be AOIs (Ctl-label, text-label, and logo-label) are shown in Table 3. The 'percentage of participants' metrics indicated that all the consumers fixed their gaze at least once on each shown label they had to choose from. This result indicates correct participants' performance because the three offered products were observed before the decision-making time. TTFF was not affected by label type, which can be explained by the balanced position of labels insofar as they were all shown the same number of times in each set position (left, central, right). Differences were, however, detected in FC and TFD because consumers spent longer looking at those labels with the SI information than the Ctl-label.

Table 3. Eye-tracker metrics for the AOI-label. %Pc- percentage of participants, TTFF-time for first fixation, FC-fixation counts, TFD-total fixation duration. TTFF is expressed as seconds. FC and TFD are relative values (sec) after normalizing data.

AOI	Front				Back			
	% Pc	TTFF	FC	TFD	% Pc	TTFF	FC	TFD
Ctl-label	100	1.3a	0.23a	0.22a	100	2.0a	0.28a	0.26a
Text-label	100	1.4a	0.34b	0.35b	100	1.9a	0.37b	0.38c
Logo-label	100	1.6a	0.30b	0.31b	100	2.3a	0.30a	0.32b

For each data column, different letters denote significant differences among the label types according to the LSD test (p-value<0.05). Same letters among label types mean no significant differences.

To well understand the relationship between paid attention and choice, besides attention paid to the whole label, we also investigated attention paid to SI-claims, i.e., if consumer choice was linked with the extent to which AOI-logo and AOI-text drew their visual attention (Figure 3).

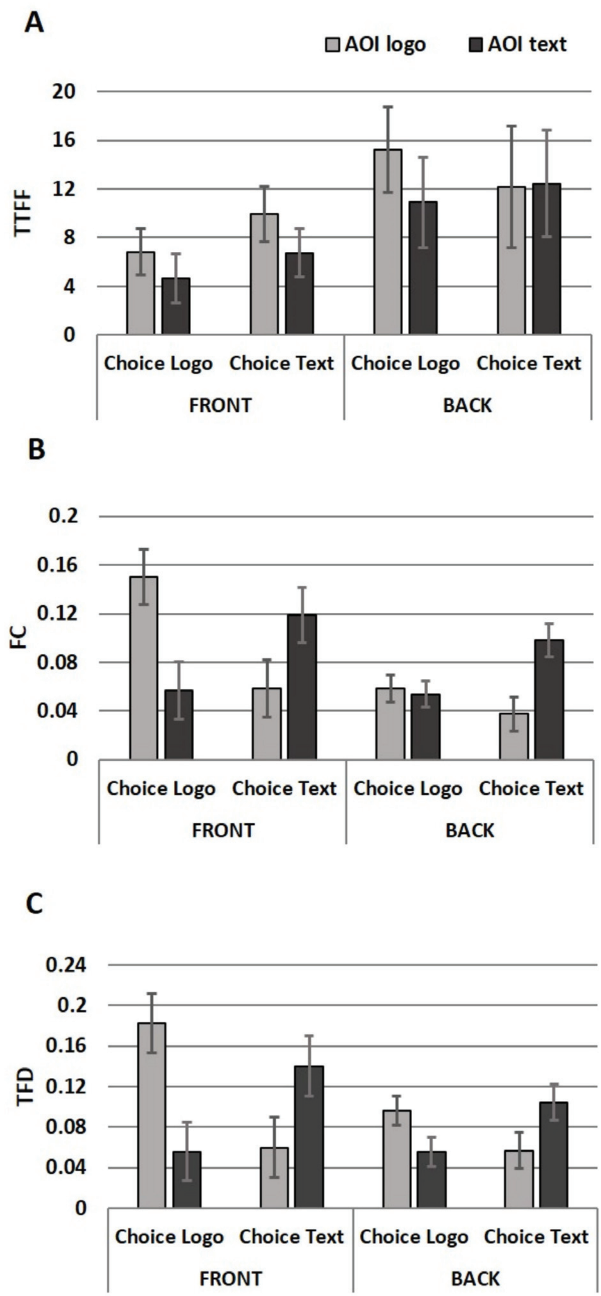

Figure 3. Eye-tracker metrics associated with both AOI-logo and AOI-text depending on consumer choice (logo-label or text-label). (**A**) Time to first fixation (TTFF), (**B**) Fixation Counts (FC) and (**C**) Total fixation duration (TFD). An ANOVA was performed independently of the front- and back-labels. Vertical bars represent the LSD interval (p-value < 0.05). TTFF is expressed as seconds. FC and TFD are relative values (sec) after normalizing data.

The TTFF in the AOIs logo and text was not a determining factor for the participants to choose among the front- or back-labels (Figure 3A). However, our results revealed a clear effect of captured attention, determined as FC and TFD, on participants' choices (Figure 3B,C). This effect was more evident in the choosing task of front-labels. Thus, the relative FC and TFD values of the participants who chose the logo-label were much higher for AOI-logo than for AOI-text. In parallel, the participants who chose text-label fixed their gaze on AOI-text more, and for a longer time, than those who chose logo-label. To offer an intuitive visualization of these results, Figure 4 shows heatmaps, which are the typical illustration of TFD in AOIs. As we can see in Figure 4A, those consumers who chose logo-label spent longer looking at the AOI-logo than at the AOI-text. Conversely, AOI-text captured more attention of the consumers who chose text-label (Figure 4B). In both cases, SI-claims were the AOIs on which consumers fixed their gaze longer, which suggests that they invested more time acquiring information from SI-claims than from any other AOI.

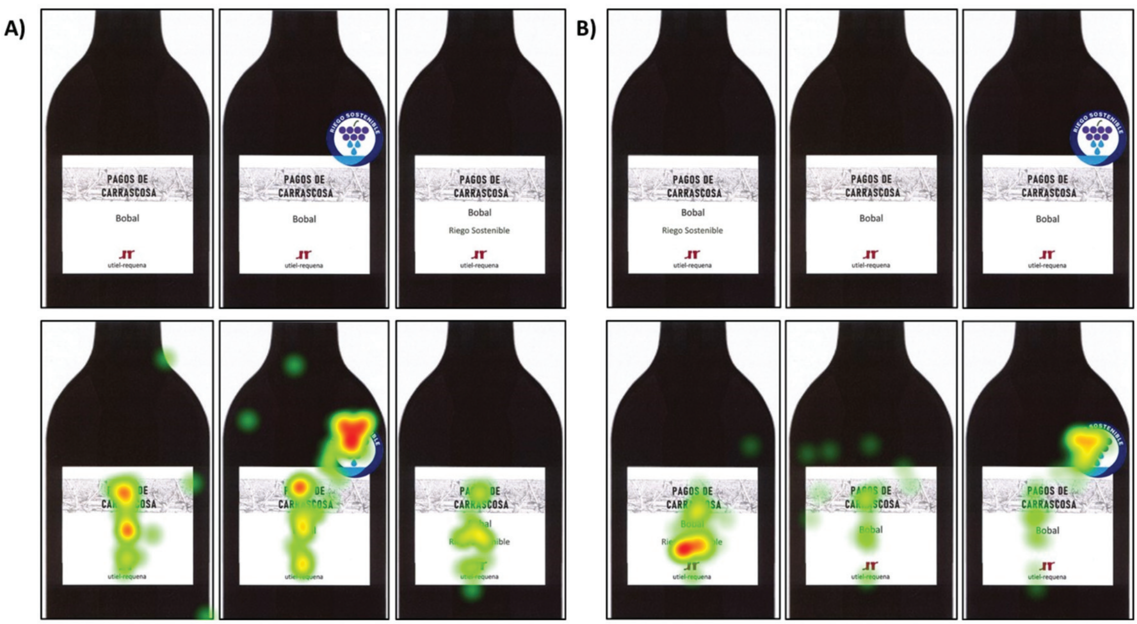

Figure 4. Heatmaps of visual attention (total fixation duration) of a consumer who chose logo-label (**A**) and for another who chose text-label (**B**). Dark red corresponds to long fixation durations and light green to short fixation durations. Both upper images are examples of how wine bottles were displayed on screens.

A similar visual attention and choice pattern were detected when the choosing task was performed with back-labels. In this case, the differences between the attention paid to the two AOIs were not so large (Figure 3), but the link between choice probability and visual attention was corroborated.

We were also interested in evaluating consumers' responses to SI-claims as regards the other information present on labels. Table 4 shows the metrics for the text- and logo-AOIs compared to brand-, PDO-, and variety-AOIs.

On both label types (front and back), the order in which the different AOIs captured attention was the same. Thus, the participants first looked at brand information, followed by variety, PDO, text, and logo.

Table 4. Eye-tracker metrics for the different AOIs. TTFF-time for first fixation, FC-fixation counts, TFD-total fixation duration.

	AOI	TTFF	FC	TFD
Front-label	Brand	0.40 a	0.12 cd *	0.14 c *
	Variety	2.35 b	0.05 a *	0.05 a *
	PDO	3.92b c *	0.14 d *	0.05 a *
	Text	5.45 c *	0.09 b	0.10 b
	Logo	7.74 d *	0.11 bc *	0.12 bc *
Back-label	Brand	1.78 a	0.04 a	0.04 a
	Variety	2.12 a	0.04 a	0.04 a
	PDO	10.60 b	0.09 b	0.03 a
	Text	11.53 b	0.07 b	0.08 b
	Logo	14.22 b	0.05 a	0.08 b

Different letters in the same column denote significant differences according to the LSD test (p-value < 0.05) among the AOIs on the same label. * indicates significant differences for a specific AOI between front- and back-labels.

On front-labels, which did not provide any more information than the five AOIs, the time to the first fixation on brand was 0.40 sec. The time that elapsed until the other AOIs were viewed was around 2 s. On back-labels, which included much more information (gastronomic combination, allergens, bar code, etc.), the TTFF on brand was 1.8 s, followed closely by variety (2.12 s). TTFF was markedly longer for the following other AOIs: PDO, text, and logo.

When focusing specifically on the AOIs that provided information about sustainable irrigation (i.e., text- and logo-AOI), TTFF increased by approximately 6.5 s when information was provided on back-labels compared to front-labels.

With regards to FC and TFD metrics, during the front-labels choice task, brand, logo, and text were the AOIs that mostly captured the participants' attention, as the higher relative FC and TTFD values reflect. For back-labels, the AOIs that informed about the sustainability of irrigation practices were those that drew the participants' attention for a longer time, with slightly more fixations for text- than for logo-AOI.

It is worth mentioning that the relative FC and TTFD values were generally higher on front-labels than on back-labels for all the evaluated AOIs.

3.3. Reasons for Choice, Sustainability Perception, and Willingness to Pay

Figure S3 shows the main reasons for choice reported by consumers depending on the wine bottle that they selected. The given reasons depended on choice, and not on the fact that selection was made between front- and back-labels. Therefore, to more easily view the results, Figure 5 shows the results obtained after combining the front- and back-label data.

Of the nine choice reasons that consumers received, the following three are highlighted as being the most mentioned ones by the consumers who selected either of the two labels with SI information (logo- and text-label): 'I think it's more environmentally friendly', 'I think less water has been used to produce it', 'The label is more attractive'. Of these three reasons, the main one given by those consumers who chose any of the SI claims was 'I think it's more environmentally friendly'. However, some differences were detected for the other two main reasons, depending on the SI-claim form. 'I think less water has been used to produce it', which is closely related to the environmental issue, was the second most mentioned reason reported by the participants who chose the text-label. However, for the logo-label selection, the second most reported reason was 'The label is more attractive'. The impact of label appearance was much less important for text-label selection. All the other reasons were mentioned much less often, with percentages below 10% in all cases.

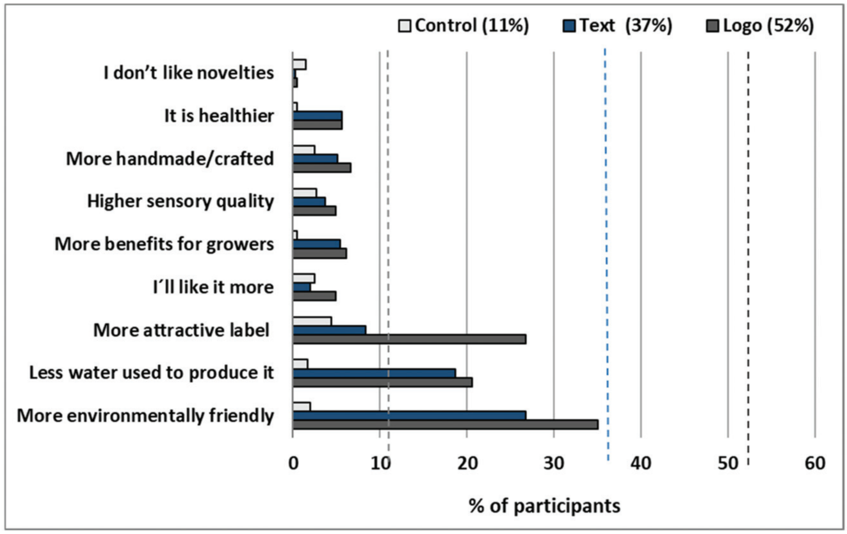

Figure 5. Percentage of all the consumers (408) who selected the different reasons for choice according to their label choice. The percentages in brackets in the legend indicate the percentage of consumers who chose each specific label (control, text, logo). The colored and dotted bars in the graph also represent these percentages.

As previously mentioned, the Ctl-label was selected by a few consumers, and as shown in Figure 5, there was no specific reason for their choice to highlight it from the others.

As for reasons for choice, the patterns observed for sustainability perception and WTP showed no differences between those consumers who evaluated front- and back-labels. For the consumers who chose either of the SI-labels (text- or logo-label), sustainability perception was significantly higher for the SI-labeled wines than for the control (Table 5). They rated the SI-labeled wines with 6.7–6.8 sustainability scores on a 9-point scale, while the Ctrl-labels were rated with scores of 4.4–4.7.

Table 5. Sustainability perception of the SI-labeled wines depending on label and consumer choice. The sustainability scale went from one-not sustainable at all, to nine-very sustainable. *SI-sustainable irrigation*.

		Front-Label		Back-Label	
		Ctrl	**SI-claim**	**Ctrl**	**SI-claim**
Choice	Text	4.67 a	6.80 b	4.42 a	6.71 b
	Logo	4.63 a	6.77 b	4.39 a	6.71 b

The same letters among the values in the table denote nonsignificant differences according to the LSD test (p-value < 0.05).

Both reasons for choice and sustainability perception data indicated that most consumers assimilated the sustainability information provided by the logo and text claims. However, it is worth mentioning that the frequency of mention of 'I think less water has been used to produce it' was lower than that of 'I think it's more environmentally friendly'. Therefore, it would seem that a certain number of consumers perceived SI wines as being more sustainable but did not assimilate the specific sustainability aspect, i.e., water-saving.

For WTP, no differences were detected between both SI-claims or between front- and back-labels. The global results for the SI wine were the following: 27% of the consumers indicated that they would not pay an extra cost for the SI-wine; 38% were willing to pay a 15% extra cost, and 30% were willing to pay a 30% extra cost. Only 4.5% of the participants indicated their WTP was more than 30% extra cost. To summarize these data, our results revealed that more than 70% of the consumers stated that they would pay a 15% or a higher extra cost for wine produced by SI practices.

4. Discussion

The choice task results showed that almost 90% of the participants were interested in the SI-labeled wines. This result should be interpreted cautiously given the possible gap between declared intention and real behavior. However, it clearly indicates consumers' interest in SI wines and corroborates previous results in this regard. After Tait et al. [14], studied the influences of different sustainability attributes on consumers' choice of Sauvignon Blanc, they reported that water resources management had a positive effect on choice and was among the attributes that consumers valued the most.

The eye-tracker technology allowed us to identify a link between paid attention and consumer choice. This result corroborated our initial hypothesis based on the previous literature [18,33]. When the eye-tracker data were analyzed after considering the whole label as the AOI, our results revealed that consumers paid more attention to the most preferred labels, i.e., consumers who chose any of the SI-labels had spent longer looking at them compared to the control. In our particular case, doubts may arise if this result is due to SI-labels including more information compared to the control. Therefore, to clarify this point, a data analysis was also performed that focused on the two SI-labels to evaluate choice in relation to the attention paid to AOI-logo and AOI-text. This analysis doubtlessly revealed that consumer choice was directly linked with the attention they paid to SI-claims as recorded by the FC and TFD parameters. Our data also revealed that the participants spent more time acquiring information from SI-claims than from any other AOI, which is likely related to top-down attention because SI-claims helped them make their choice decision. Top-down attention depends on consumers' interests and goals, and it is drawn to signs that can help them categorize a product [34,35]. It involves consumers' voluntarily searching for and paying attention to specific information [20]. On the contrary, bottom-up attention occurs automatically and is related to stimuli such as color, size, or shape.

This is the first time a link between claim attention and choice is described for SI-claims. It confirms that the 'attention-choice' association found in previous studies about different claims and products actually exists. Ballco et al. [18] reported a relationship between paying visual attention to nutritional claims on yogurt packaging and yogurt choice. This association has also been found in broader contexts. After Gidlöf et al. [33] performed an experiment related to supermarket shelves to evaluate the influence of internal and external factors on consumer choice, they reported that visual attention was by far the most important predictor of choice. These authors described this relationship as "looking is buying".

Despite this relation having been corroborated in different studies, in certain cases it simply does not apply. Thus, for example, Fenko et al. [8] found no direct evidence for the influence of visual attention paid to health labels on healthy food choices. They suggested that paying attention to health labels might indicate an interest in an unfamiliar food label, but does not necessarily indicate a healthier food choice. Contrarily to this hypothesis, a marked relationship between attention and choice probability was observed in the present study, despite consumers not being familiar with SI-labels.

Of the three eye-tracker parameters herein evaluated (TTFF, FC, and TFD), TTFF was the only one that was not linked with choice. In line with previous studies [21,36], our results showed that, irrespectively of label type, brand was the label component that first captured consumers' attention.

The eye-tracker device also allowed differences in captured attention between front- and back-labels to be investigated. TTFF increased by approximately 6.5 s when information was provided on back- vs. front-labels, and the relative FC and TFD values were generally higher on front- than on back-labels for all the evaluated AOIs. This result was not an unexpected one because back-labels contained much more information (gastronomic combination, allergens, bar code, symbols, etc.) than front-labels, and previous studies have described that consumer attention to specific label areas decreases as label information density increases [27]. This effect has been related to time pressure feelings linked with modern lifestyles, where people feel that they do not have enough time to do all that they wish to do in one day [37]. So, when too much information is provided, consumers adjust their attention process as follows: they accelerate information acquisition by reducing the duration of fixations on a stimulus [8].

The quantification of attention herein presented is key for better understanding how consumers process label information, which may help the wine industry design market strategies to incorporate sustainability aspects. However, it is important to mention a limitation aspect of this study regarding the choice task because it was not a time constraint. As this was the first time that such 'sustainable irrigation' claims have been evaluated and consumers are not used to them, we considered it appropriate to offer consumers the chance to take all the time they needed to perform the task. However, as previously mentioned, consumer behavior is usually conditioned by time-pressure feelings [19]. In order to overcome this limitation and to more accurately predict consumers' responses, future studies should be performed in more ecological contexts, such as those associated with real-choice experiments [38] or experimental auctions [39].

Determining reasons for choice revealed that most consumers assimilated the provided information irrespectively of the SI-claim type (logo vs. text). Nevertheless, it would seem that a certain number of consumers did not assimilate the specific water-saving aspect. This result corroborates the need to run comprehension tests when a new claim is designed to provide consumers/users with information [40].

The reason for choice questions also revealed that, apart from its purpose to provide SI information, the logo claim proved to be a more attractive label, which would explain why consumers preferred the logo- to the text-label.

Bearing in mind the two aforementioned results, i.e., assimilating information and claiming preferences, it would be interesting for future research to approach logo design improvements in order to make their meaning clear for all consumers.

Finally, the WTP results showed that more than 70% of the participants were willing to pay a 15% or higher extra cost for wine produced by SI practices. Despite this study focusing on a specific sustainability aspect (SI), our results corroborate a general trend of consumers' WTP a premium for wine with sustainable production characteristics. This trend was detected by Schäufele and Hamm [2] after reviewing the existing literature that covered studies from different countries.

However, it is worth mentioning that despite this tendency existing, significant differences may arise in specific results among available studies. In the present study, the statistical analysis of the WTP data revealed no significant differences in the results obtained from front- and back-labels. This particular result about the effect of the SI-claim position differs from that reported by Pomorici et al. [11], who found that young Italian consumers were willing to pay 4.4% more for a water-saving wine labeled on the front compared to the back of bottles. Using a different methodology may be the reason for the differences in the results observed between both studies. Moreover, cultural differences among Spanish and Italian consumers and/or participants' age ranges might also have an influence on the WTP results. Despite the existing differences between these two studies, both suggest that providing consumers with information about water management sustainability can help to increase market profits. This could be crucial for preserving farm profitability and, hence, for encouraging growers to adopt sustainable practices. Moreover, in the present study, preference for the SI wine (even for those consumers not willing to pay an extra cost) is *per se* a commercial advantage.

5. Conclusions

This work explores consumers' responses to 'sustainable irrigation' labels for the first time. To this end, a combined approach was followed to evaluate their responses to two SI claims (logo vs. text): the choice task, eye-tracking technology, and the determination of the main reasons for choice, sustainability perception, and WTP.

Our results showed marked consumer interest in SI wines, as reflected in their wine choice and their WTP. More than 70% of the participants stated that they would pay a 15% or higher extra cost for wine produced by SI practices. The eye-tracker technology revealed that both logo- and text-claims captured consumers' attention, and a link between choice probability and paid attention was detected. The logo-label was the preferred one, mainly because consumers found it more attractive than the text-label. Consumers paid more attention to SI-claims when information appeared on front-labels, which was related to lower information density compared to back-labels.

The results of this study have relevant implications for the wine industry because they strongly suggest that producing and marketing SI-labeled wines can be an opportunity for the industry to differentiate the product in markets while taking actions to face the pressing need to preserve the environment. The herein proposed SI-logo proves to be a useful way to draw consumers' attention to the sustainable character of wine, as most consumers adequately assimilate the specific water-saving aspect. However, there is still room to improve logo designs to guarantee that all consumers properly understand their meaning.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12030685/s1, Table S1: Example of how the normalized data was obtained for Fixation Counts parameter (FC) of one participant. Figure S1: Visualization of the front (A) and back (B) labels; Figure S2: AOIs defined on different labels.; Figure S3: Reasons for choice.

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

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

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sustainability

Article

Analysis of Decisive Elements in the Purchase of Alternative Foods Using Bivariate Probit Model

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Abstract: There has been growing attention among major developed countries to alternative food products using vegetable-derived ingredients to help animal welfare and environmental sustainability. The development of ICT technology and awareness of animal welfare, health, and environmental damage have led to a rise in alternative food products. This study explains consumer selection attributes for alternative foods in categories of intrinsic and extrinsic attributes, storage and usage, ethical consumption, awareness of the environment, and vegetarianism. It also intends to clarify the connection between purchase intentions and purchase preferences caused by selection attributes. The bivariate probit model (BPM) was used to quantitatively analyze consumers' selection attributes for alternative foods. Element analysis was conducted on twenty-three variables for alternative food selection attributes to derive five elements: quality and safety, environmental awareness, product specifications, ethical consumption, and storage and usage. Analysis indicated that of the five selection attributes, quality and safety and ethical consumption significantly affected vegetarian or semi-vegetarian purchase intentions and preferences. This study intends to identify the elements that affect consumer purchase intentions for alternative foods introduced from an expanding alternative food market, investigate directions for future food development, and provide useful information for consumption promotion strategies.

Keywords: bivariate probit model; alternative food; selection attributes; purchase intention; purchase preference

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1. Introduction

Food consumers seek better health, hence the increase in eco-friendly food consumption. This is why demand is moving toward a healthier lifestyle and the consumer base increasingly focuses on health. The food industry is grounded in consumer preference diversity, safety, and the culinary culture to create new value in the form of coexisting food, technology, and culture. The government has suggested a new paradigm for the food industry focusing on growth that encompasses citizens' health, food consumption, and sustainability through the Food Industry Invigoration Strategy [1]. The development of ICT technology and awareness of animal welfare, health, and environmental damage have led to a rise in alternative foods. Consumer interest is also leaning toward food safety, health, decrease of animal waste, and other environmental sustainability and bioethical issues. Population increase is expected to lead to higher consumption of meat as a source of protein. Alternative foods can decrease environmental damage and social costs for resource saving. "Alternative food" refers to food that replaces animal protein. They can be categorized into five types: insect protein, vegetable protein, seaweed protein, microorganism protein, and artificial meat [2]. The market has been rapidly formed around plant-based meat, while there are some studies on in vitro meat, but the growth of its market is relatively slowing, and the inset protein is grown around pet food. The level of current skills and the status of the market were examined to show that consumers recognize the plant-based meat as a kind of alternative food, so this study investigated the selection attributes around the plant-based meat. The alternative food market is expected to increase along with the technological innovations in the food industry converging with ICT. The market size is expected to grow at an annual average of 9.5% from 2019 on (Krei, 2020). Convenience, customization, increase in demand for nutritive improvement, and increased awareness of animal welfare and ethics are driving forces in the alternative food market. This has been followed by an increase in corporate investment, thus increasing the alternative food market. Concerns about livestock diseases have been increased due to frequent occurrence of them such as avian influenza, BSE (Bovine spongiform encephalopathy), African swine fever, foot-and-mouth disease, etc. China, Denmark and other countries consider the legislation about charging a tax on meat. Socially, entire conditions such as a surge of interest in the environmental condition of livestock production as well as health and religion, the popularity of diet, the vegetarian declaration of global well-known influencers, and the trend of consumers reflect consumers' needs for alternative food. The development of skills about the alternative food and the extension of consumption has been promoted by the needs of European and American food companies and consumers. In Korea, the demands for the alternative food have been also increased around vegans, and young people give more attention to the social needs for the self-determination right of food and the future food. As such, this study is determined as a timely one, in that it quantitatively analyzes the intention to purchase the alternative food. This study structurally analyzed the selection attributes of alternative food, in line with previous research, and therefore attempted to elucidate the relationship between consumers' purchase intention and purchase preference. It also intends to clarify the connection between purchase intentions and purchase preferences caused by selection attributes. This study intends to investigate directions for government policies on alternative food and other future foods, directions for future food development, and to provide useful information for consumption promotion strategies.

2. Theoretical Background

2.1. Selection Attributes

An attribute is a characteristic that a product has. A selection attribute affects the decision of a consumer when purchasing, and it affects the purchase intention and purchase activity [3–5]. A selection attribute is an important attribute that affects purchase. Active studies to understand and explain the purchase activities of consumers are ongoing [6,7]. The product consists of a variety of attributes, and these attributes provide decisive clues that influence perception and evaluation of the product. In general, consumers evaluate or decide to purchase products based on intrinsic and external attributes among these attributes [8]. According to Zeithaml [9], consumers generally perceive quality by intrinsic and extrinsic attributes. Intrinsic attributes mean functional and physical aspects as objective judgments about consumer quality. It disappears as it consumes and has properties that do not change unless the nature of the product changes [10].

Studies focused on alternative food selection attributes are just beginning. Most studies have centered on food product elements and food reliability and safety in relation to consumer preference. Due to the insufficient number of preceding studies on the selection of alternative foods, the study examined purchase attributes by focusing on new foods, convenience foods, home meal replacements, and genetically modified foods that were determined to be similar.

In a study by Park, M. S. et al. [11], new food products were categorized into characteristic, taste, texture, shape, color, odor, hygiene, health awareness, resource and environmental awareness, ethical consumption and interest in animal welfare, and others. Alternative foods were categorized into vegetable-derived meat, artificial meat, insect foods, and vegetable-derived eggs to be analyzed by both logit and probit methods. The analysis results showed that attributes that affected purchase intentions varied by product. Awareness of animal welfare was the main attribute. Geeroms et al. [12] divided the selection criteria of convenience food into the aspects of reliability (nutrition, ecofriendly, etc.) and those of senses (prices, convenience of use, etc.), and they were found to be significantly varied, depending on individual characteristics. Boer et al. [13] suggested that the prices and nutritional contents of convenience food have significant effects on consumers' purchase behavior. Jiang et al. [14] divided the attributes of genetically modified food into functional and environmental ones. Choi et al. [15] suggested prices and products, health, safety, time, family, convenience and packaging environment as the value of food consumption. Yoo et al. [16] divided selection attributes for convenience foods purchased at online shopping malls into food quality, convenience, homepage configuration, promotion services, and shipment; Yang, S. J and Y. B., Cho [17] named the selection attributes for convenience foods as the five factors of food quality, packaging and brand, accessibility and convenience, preference, and price; and Oh, S. B. [18] offered quality, shopping, convenience, promotion services, informativeness, and the importance of trends as purchase attributes for convenience foods. With regard to purchase attributes in terms of organically processed foods, Chen, M. F. [19] offered expected health effectiveness, sensory characteristics such as taste and texture, as well as the inclusion of artificial additives, price acceptability, product familiarity, and ecofriendly production methods. In a study by Oh, W. K. and J. Y., Hong [20], categories were safety, convenience, taste and quality, economic efficiency, reliability, and others. The study proposed home meal replacement (HMR) significance and satisfaction using the IPA method. The results of the analysis showed that food hygiene was significant and that the freshness, quality, and safety of additives were prioritized in that order. A study by Choi, T. H. et al. [7] categorized selection attributes as taste and quality, convenience, price, and packaging as four subvariables to analyze satisfaction and intention to repurchase. All selection attributes showed a positive effect on purchase intention. Based on a precedent study by Park, H. J. et al. [21], convenience food evaluation criteria were re-categorized for forms of usage and the significance and execution of intrinsic and extrinsic attributes. In this study, intrinsic attributes are categorized as the characteristics of the product itself: a new launch of the product, freshness, price, nutrition, digestibility, safety, and hygiene. Extrinsic attributes are categorized as the hygiene of the packaging, transportation stability of the packaging, safety of the packaging material, color of packaging, expiry date, certifications, place of origin, manufacturer, convenience of opening and closing, and packaging appearance. The selection attributes proposed by prior studies showed that intrinsic attributes of the product, such as quality, taste, texture, and hygiene, as well as extrinsic attributes of price, packaging design, and brand, are significant. Environmental awareness, ethical consumption, and product usage instructions also showed an influence in selecting alternative foods. This study intended to re-categorize and analyze the selection attributes proposed by prior studies to be more appropriate for alternative food characteristics. There has been little research quantitatively analyzing the intention to purchase alternative food in Korea, and the results of this study are determined as important basic data for developing alternative food in the future.

2.2. Purchase Intention and Purchase Preference

Purchase intention is defined as the consumer's personal conviction for repeated purchase based on past experience of a certain product [7]. Purchase intention is the result of being satisfied over a purchase and refers to the subjective condition that leads one's beliefs and attitude to behavior. Furthermore, as the will to do a given behavior, it refers to how much effort one puts forth in carrying out a certain behavior [22,23]. Fishbein [23] said that attitude toward behavior is the strength of belief as an evaluation of previous product use. In terms of consumer behavior, when the attitude of the consumer corresponds with the selection attributes of a product, purchase intention occurs. Blackwell, R. D. et al. [24] claim purchase intention to mean the future behavior of the consumer as well as the potential for the attitude of a belief to carry out behavior, seeing how the purchase intention of the consumer is much related to direct behavior in the decision-making model [25]. Generally, between attitude and behavior, a higher degree of favorable attitude toward certain products leads to a higher possibility of making a purchase [26]. Engel [27] said, with regard to attitude, that because attitude is the subjective possibility of belief becoming behavior, it is highly likely to be converted into the behavior of purchasing an actual product. Baggett [28] argued that attitude forms while reflecting the identity, values, and beliefs of the individual within a complicated mutual relationship between cognitive elements acquired through experience and that, specifically, attitude forms in the process of satisfying needs. In the process of trying to fulfill a need, the individual forms a favorable attitude towards objects that satisfy their needs. Peter and Olson [29] defined it as the recognition-based evaluation. The attitude is defined as the degree to which an individual likes or dislikes a certain behavior. This study set a variable, the purchase preference, as an attitude toward a product.

This study set consumer attitude, noted as one of the selection attributes for alternative foods, as the explanatory variable that affects future purchase intention or preference for alternative foods.

3. Hypothetical Model

This study used the bivariate probit model (BPM) [30] to show both the endogenous types between purchase intention and purchase preference in selection attributes for alternative foods. If the consumer i, in deciding to select an alternative food at the point of purchase, makes an unobservable decision y_1^*, y_2^*, a mutual relation between the two decisions is permitted [31].

$$y_{1i}^* = \beta_1' x_{1i} + u_{1i} y_{1i} = 1\ if\ y_{1i}^* > 0 y_{1i} = otherwise \tag{1}$$

$$y_{2i}^* = \beta_2' x_{2i} + u_{2i} y_{2i} = if\ y_{2i}^* > 0 y_{2i} = otherwise \tag{2}$$

In other words, Equation (1) is composed of a measurable part (y_1, y_2) and immeasurable part (y_1^*, y_2^*), and these refer to the choice where the consumer i chose purchase intention and purchase preference. If the error terms u_1, u_2 hypothesize a bivariate normal distribution, x_i is the purchase intention and purchase preference selection explanation variable vector, and β_1', β_2' are the odds ratio estimate vectors. If the two error terms are independent, the value of becomes $\rho = 0$. In this case, the two error terms do not follow the bivariate normal distribution. In this case, a single probit model can be used. Usually, two models that are mutually related show a consistent covariance, unlike an independent model, such as Equation (3).

$$Cov(u_{1i},\ u_{2i}) = \rho \tag{3}$$

Equation (4) shows the joint probability density function in the case of bivariate normal distribution.

$$\phi_2(u_1, u_2) = \frac{1}{2\pi\sigma_{u1}\sigma_{u2}\sqrt{1-\rho^2}} exp[-\frac{1}{2}\left(\frac{u_1^2 + u_2^2 - 2\rho u_1 u_2}{1-\rho^2}\right)] \tag{4}$$

$$\Phi_2(u_1, u_2, \rho) = \int_{u1}\int_{u2} \phi(u_1, u_2, \rho) du_1 du_2 \tag{5}$$

If two error terms follow bivariate normal distribution, the cumulative density function Φ_2 is assumed as the normal cumulative density function, and the maximum likelihood estimation is hypothesized through the probit model. The maximized likelihood function is as follows.

$$\ln L = \sum_{i=1}^{n} \ln \Phi_2 = (u_{i1}, u_{i2}, \rho_{i*}) \tag{6}$$

4. Research Method

4.1. Data Collection

This study analyzed the purchase intention and purchase preference of consumers caused by selection attributes of alternative foods. The subjects of the survey were consumers from fourteen cities and counties. The survey was conducted for eight days, beginning on 29 June and ending on 6 July 2020. The sampling was done by convenience sampling method of a nonprobable sampling method. Three hundred survey sheets were distributed; of these, three hundred (100.0%) valid sheets were used for analysis.

In Jeollabuk-do, the province surveyed, the food industry and the agriculture and life industry are specialized, so it made a business plan for customized special food, including alternative food. Jeollabuk-do has activated the food plan around its local food, and therefore, it is likely to be developed into the future food consumption city. Hence, this study collected data of 14 cities and counties in Jeollabuk-do. For the sample collection, the quota sampling was conducted in proportion to the number of local populations to properly reflect the characteristics of the whole population. The area of investigation was divided into urban and rural areas, with the investigation carried out at grocery stores—the place where food spending mainly takes place—and data collected by thoroughly trained investigators through face-to-face contact with respondents. Investigators explained the concept and characteristics of alternative foods using example cards as well as the definition for alternative foods in the survey in order to help interviewees understand (Table 1).

Table 1. Survey Time Period and Subjects.

Category	Details
Survey Time Period	29 June 2020~6 July 2020
Survey Subjects	Consumers over the age of 20
Survey Site	Fourteen cities and counties in Jeollabuk-do, Korea
Sampling Method	Convenience Sampling Method
Survey Subjects	Visited and collected in the survey location (professional surveyors employed)

4.2. Data Analysis

In the analysis process of this study, technical statistical analysis was done, including frequency and percentage, to identify the demographics of survey respondents and general status. Second, investigative elemental analysis was conducted to verify the measured variable concept validity and alternative food selection attributes were categorized accordingly. Cronbach's α coefficient was also reviewed to measure the reliability of the survey. Furthermore, a bivariate probit analysis was conducted to analyze the selection attributes of alternative foods.

4.3. Explanation and Measurement Tools for Variables

The measured variables used to infer the suggested research model are as follows.

First, the dependent variables were measured as dummy variables for "yes" and "no" answers to the question asking "whether one will increase the consumption of alternative foods." Purchase preference was measured as dummy variables for "yes" and "no" answers to the question asking "whether one prefers to purchase alternative foods".

Second, the selection attributes for alternative foods were classified into intrinsic and extrinsic attributes and observed for consideration when selecting alternative foods. Intrinsic attributes were set as nutrition, hygiene, place of origin, safety, taste, and quality. Studies by Park. M. S., et al. [11]; Oh, W. K and J. Y., Hong [20]; Choi, T. H. et al. [7]; and other studies were referred to for this. Extrinsic attributes were set as price, packaging design, brand, and product diversity. Multiple categories were measured on a scale of one to five, using the questions proposed by Park, H. J. et al. [21] and Choi, T. H. et al. [7].

Third, the storage and usage of alternative foods were operationally defined from the knowledge used for consumer characteristic analysis in Seo, H. S. and J. H. Hwang [32,33]. The usage purpose, handling, and purchasing knowledge after purchasing alternative foods were measured on a scale of one to five.

Fourth, ethical consumption and environmental awareness were classified into subcategories for the purpose of the study based on the ethical consumption variables used in Park.

M. S. et al. [11]. The vegetarian variables were classified into vegetarian or semi-vegetarian, and nonvegetarian bivariate dummy variables (Table 2).

Table 2. Measurement Subjects for Selection Attribute Measurement.

Composition Concepts	Names of Variables	Measured Subjects
Dependent Variables	Purchase Intention	① Alternative food consumption will increase (=1) ② Alternative food consumption will not increase (=0)
	Purchase Preferences (Attitudes toward alternative foods)	① Alternative food purchase is preferred (=1) ② Alternative food purchase is not preferred (=0)
Intrinsic Attributes	1. Nutrition: nutrition facts on product 2. Hygiene: clean product production and distribution management 3. Place of origin: clear representation of product's place of origin 4. Certification: proven safety and reliability 5. Safety: fresh ingredients, no additives 6. Taste: the savory flavor when the product is consumed 7. Quality: product quality, percentage of domestic ingredients used, easy digestion	Factor score (5-point Likert scale)
Extrinsic Attributes	1. Price: adequate product price 2. Packaging: neat packaging design 3. Brand: brand popularity 4. Variety: a wide range of choices	Factor score (5-point Likert scale)
Storage and Usage	1. Cooking convenience: handling is easy 2. Access to purchase: easy to purchase 3. Storage convenience: storage is easy and convenient 4. Food handling convenience: food is easy to handle	Factor score (5-point Likert scale)
Ethical Purchase	1. Waste such as plastic and excessive packaging are considered when purchasing food. 2. Ecofriendly vegetable foods are preferred. 3. Vegan, ecofriendly, or other certifications are considered. 4. The consumer has relatively high environmental awareness.	Factor score (5-point Likert scale)
Awareness of the Environment	1. It is important to maintain ecological diversity. 2. We must maintain an environment we can pass down to future generations. 3. We must respond to future climate change. 4. It is important to cut down on energy consumption.	Factor score (5-point Likert scale)
Vegetarianism	Vegetarian, semi-vegetarian, nonvegetarian	1 = Vegetarian or semi-vegetarian 0 = nonvegetarian

5. Empirical Analysis Results

5.1. Characteristics of the Sample

The average age of survey respondents was 45.81. Among them, respondents in their 20s and 40s were the largest sample at 22.0%. People in their 50s and 60s followed with 21.7% and 18.0%, respectively. Women made up 61.9% and men were 38.1%. In terms of marriage, 67.4% were married and 32.6% were not. Those who answered that they have children were 66.8%. College graduates (including those with associate degrees) comprised the highest percentage with 42.9%, while high school graduates were 33.7%, and middle school graduates or below were 18.8%. The survey was conducted centered on Jeollabuk-do. The number of answers by city ranged in the order of Gunsan 12.7%, Jeonju 12.0%, Iksan 11.0%, Wanju 10.7%, and Buan 10.3%. Occupations showed that agricultural and fishery was highest at 21.5%. Sales and services were 17.8%, and professional and technical occupations were 14.8%. In the case of vegetarianism, semi-vegetarian was the majority at 64.9%. Nonvegetarian was 29.5%, and vegetarian was 5.6%. By monthly income, the highest number of people had incomes below 2,000,000 won at 29.1%, 2,000,000–2,990,000 won were 20.7%, and 5,000,000–5,990,000 won were 17.6% (Table 3).

Table 3. Distribution of Survey Respondent Characteristics.

Category		N	%	Category		N	%
Sex	Male	114	38.1	Age (45.81)	20s	66	22.0
	Female	185	61.9		30s	34	11.3
Marital Status	Married	188	67.4		40s	66	22.0
	Single	91	32.6		50s	65	21.7
With Children	Yes	169	66.8		60s	54	18.0
	No	84	33.2		70s	11	3.7
Educational Background	Middle School Graduate or Below	53	18.8		80s	4	1.3
	High School Graduate	95	33.7	Occupation	Student	35	11.7
	College Graduate	121	42.9		Professional or Technical	44	14.8
	Master's Degree or Above	13	4.6		Office Work	17	5.7
Region	Jeonju	36	12.0		Public/Education	11	3.7
	Gunsan	38	12.7		Agriculture or Fishery	64	21.5
	Iksan	33	11.0		Housewife	23	7.7
	Jeongeup	25	8.3		Sales or Services	53	17.8
	Namwon	1	0.3		Self-employed/Freelance	35	11.7
	Gimje	29	9.7		Other	16	5.4
	Wanju	32	10.7	Monthly Income (won)	Below 2,000,000	76	29.1
	Imsil	24	8.0		2,000,000–2,990,000	54	20.7
	Sunchang	24	8.0		3,000,000–3,990,000	38	14.6
	Gochang	27	9.0		4,000,000–4,990,000	27	10.3
	Buan	31	10.3		5,000,000–5,990,000	46	17.6
Type	Vegetarian	16	5.6		6,000,000–6,990,000	14	5.4
	Semi-vegetarian	187	64.9		7,000,000–7,990,000	4	1.5
	Nonvegetarian	85	29.5		8,000,000 or above	2	0.8
Subtotal		300	100.0	Subtotal		300	100.0

5.2. Investigative Attribute Analysis and Reliability Verification

The fifteen variables that are selection attributes for alternative foods were summarized into several attributes. Investigative attribute analysis and reliability analysis were conducted to verify the validity and reliability of measurement tools. Attributes were extracted using varimax, a perpendicular rotation method through principal component analysis.

The eigenvalue standard was 1.0 or above. The factor loading was 0.5 or above. The results of the analysis showed that the total variance explanation power was 68.284%. It was above the 60% rate, which is normally accepted in social sciences, and the conformity of KMO to distinguish attribute analysis conformity was 0.878. Bartlett's test of sphericity showed 3809.015, below the significance level of 0.05, and thus it is statistically significant. Attribute analysis was conducted on a total of 25 criteria. As a result of the analysis, five attributes were extracted: quality and safety (intrinsic attribute), environmental awareness, product attributes (extrinsic attribute), ethical consumption, and storage and usage. Reliability analysis showed that all five attributes had a Cronbach's α value of 0.8 or above, showing sufficient reliability (Table 4).

Table 4. Investigative Cause Analysis and Reliability Analysis.

Variable	Factor Loading	Eigenvalue	% of Variance	α	Mean
Factor 1: Quality and safety (intrinsic attributes)		7.886	34.285	0.874	4.19
1. Certification: proven safety and reliability	0.807				
2. Hygiene: clean product production and distribution management	0.779				
3. Nutrition: nutrition facts on product	0.733				
4. Place of origin: clear representation of the product's place of origin	0.654				
5. Quality: product quality, percentage of domestic ingredients used, easy digestion	0.630				
6. Taste: the gustatory sense when the product is consumed	0.614				
7. Safety: fresh ingredients, no additives	0.583				
Factor 2: Environmental awareness		2.586	11.234	0.897	4.41
1. It is important to cut down on energy consumption.	0.820				
2. We must respond to future climate change.	0.819				
3. It is important to maintain ecological diversity.	0.813				
4. We must maintain an environment we can pass down to future generations.	0.792				
5. Disregarding pollution in farming lands or cities can cause higher loss in the future.	0.765				
Factor 3: Product attributes (extrinsic attributes)		2.344	10.191	0.811	3.81
1. Packaging: neat packaging design	0.873				
2. Brand: brand popularity	0.860				
3. Variety: a wide range of choices	0.762				
4. Price: adequate product price	0.578				
Factor 4: Ethical consumption		1.879	8.171	0.834	3.58
1. Ecofriendly vegetable foods are preferred.	0.842				
2. The consumer has relatively high environmental awareness.	0.841				
3. Vegan, ecofriendly, or other certifications are considered.	0.801				
4. Waste such as plastic and excessive packaging are considered when purchasing food.	0.755				
Factor 5: Storage and usage		1.010	4.393	0.830	4.11
1. Food handling convenience: food is easy to handle	0.801				
2. Storage convenience: storage is easy and convenient	0.759				
3. Cooking convenience: easy preparation	0.737				
Cumulative % = 68.284%, KMO = 0.878 Bartlett's test of sphericity χ^2 = 3809.015 (d.f = 253, p = 0.000 ***)					

Note: *** $p < 0.01$.

5.3. Inference Results

First, the BPM with purchase intention and purchase preference as dependent variables was assessed for validity. Dependent variables were set as purchase intention (int_pur) and purchase preference (pur_pre). Independent variables were set as quality and safety (emp_prd), environmental awareness (environ), product attribute (pro_att), ethical consumption (ethics), storage and usage (sto_use), and vegetarian or semi-vegetarian (vegan) for analysis. A likelihood ratio test (LR) was conducted to verify whether the value was identified. Verification statistics showed a value of 196.021, forfeiting the null hypothesis at $p < 0.05$. Therefore, the bivariate probit model (BPM) with dependent variables of purchase intention and purchase preference was confirmed as the appropriate model. In particular, a value of 0.9820 was derived from enabling confirmation that purchase intention and purchase preference had a mutually positive influence through the error term. Therefore, it was decided that the bivariate probit model was a statistically more efficient model compared to the univariate probit model in inferring purchase intention and purchase preference. Parameter estimate results showed that there was little difference in the attributes that influence purchase intention and purchase preference. Quality and safety, ethical consumption, and vegetarian or semi-vegetarian were significant attributes. In reviewing each attribute that influences purchase intention, the following attributes were each significant at the specified rate: quality and safety $p < 0.05$, ethical consumption $p < 0.01$, and vegetarian or semi-vegetarian $p < 0.01$. In reviewing each attribute that influences purchase preference, the following attributes were each significant at the specified rate: hygiene and quality $p < 0.05$, ethical consumption $p < 0.01$, and vegetarian or semi-vegetarian $p < 0.01$ (Table 5).

Table 5. Alternative food selection attribute analysis using BPM.

Division		BPM Estimated Results (y)			
		Purchase Intention (y_1)		Preference for Purchase (y_2)	
		Coef.	S.E.	Coef.	S.E.
x_1	qual_saf	0.453 **	0.228	0.567 **	0.231
x_2	environ	−0.017	0.165	−0.071	0.167
x_3	pro_att	−0.097	0.159	−0.042	0.151
x_4	ethics	0.424 ***	0.127	0.366 ***	0.128
x_5	sto_use	−0.095	0.176	−0.039	0.178
x_6	vegan	0.940 ***	0.176	0.984 ***	0.178
	_cons	−2.933 ***	0.842	−3.624 ***	0.865
					Number of obs = 279
					Wald test of rho (ρ) = 0.9820 ***
					Wald = 196.021 *** ($p = 0.0000$)
					Log pseudo likelihood = −223.96903
					Wald = 58.04 *** ($p = 0.0000$)

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

The odds ratio estimate provides significance and direction in the variables but is irrelevant to the actual amount of influence that each variable has on the dependent variable. Therefore, the marginal effect was measured to confirm the scale of the explanatory variable. The marginal effect refers to the probability change in purchase intention and purchase preference in accordance with a single unit of change in the explanatory variable. Marginal effects were analyzed in the case where purchase intention and purchase preference were simultaneously selected. The results of the marginal effect analysis showed that the attributes that lead to satisfaction of both purchase intention and purchase preference of alternative foods were quality and safety, ethical consumption, and vegetarian and semi-vegetarian. The results indicated that if other variables are consistent, a single unit of increase in the attitude of prioritizing quality and safety leads to an 18.3% increase in the likelihood to choose both purchase intention and purchase preference. For a single unit of increase in significance toward ethical consumption, a 12.6% likelihood was observed in choosing both purchase intention and purchase preference. If the consumer was vegetarian or semi-vegetarian, the likelihood of choosing both purchase intention and purchase preference for alternative food increased by 32.7% in comparison to nonvegetarians (Table 6).

Table 6. Marginal Effects of the BPM.

Division		Marginal Effect (y=Pr[y_1=1, y_2=2])			
		dy/dx	S.E.	z	$P>\|z\|$
x_1	qual_saf	0.183	0.072	2.53 **	0.012
x_2	environ	−0.020	0.054	−0.37	0.708
x_3	pro_att	−0.018	0.049	−0.36	0.720
x_4	ethics	0.126	0.040	3.16 ***	0.002
x_5	sto_use	−0.017	0.058	−0.29	0.772
x_6	vegan	0.327	0.049	6.73 ***	0.000

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

6. Conclusions

This study attempted to infer selection attributes from consumers in fourteen cities and counties in Jeollabuk-do. The bivariate probit model (BPM) was used to quantitatively analyze consumers' selection attributes for alternative foods. Elemental analysis was conducted on twenty-three variables for alternative food selection attributes to derive five elements: quality and safety, environmental awareness, product attributes, ethical consumption, and storage and usage. Analysis showed that of the five selection attributes, quality and safety and ethical consumption significantly affected vegetarian or semi-vegetarian purchase intentions and preferences.

Some implications can be derived in accordance with these analysis results. First, consumers who perceive alternative food quality as high tend to purchase alternative foods. This also positively influences purchase preference. In the case of vegetable-derived meat, the technology to make meat out of vegetable ingredients exists, but most products have a texture that is far from animal meat. In particular, the sensual quality of meat analogue, including tastes and textual characteristics, was lower than that of meat, so skills for enhancing the quality seem to be necessary in order to overcome this problem. Moreover, because consumers of alternative foods have high expectations of quality and safety, food processing and product distribution standards must be systematized to improve the safety and functionality of food. The names and classification system of in vitro meat have been controversial so far; some problems remain to be solved, including GMO and stability. In Korea, the standards of the certification system for the quality of safety of alternative product, so the consumption of it would be able to be increased if the standardization is accomplished. Second, environmental awareness showed an insignificant effect on alternative foods. This means that the environment does not have a direct influence on the decision to consume alternative foods. Previous research, however, demonstrated that persons who pursued the lifestyle of veganism have a tendency to have more interest in health, environmental protection and ethical consumption, which may have an indirect effect on the selection of alternative food. Awareness of the environment and resources is increasing in line with increased consumer interest in food safety, health, and bioethics. By publicizing the environmental pollution, animal welfare, etc., it is necessary to help consumers deeply recognize the ecofriendly image of alternative food. Third, to improve a variety of alternative foods, the field must expand into pet foods, vegan foods, and home meal replacements (HMR). It is also necessary to develop alternative food materials using local resources to help consumers perceive alternative foods as local specialties and to set a purpose in product development for environmental production. Fourth, consumption categories should be specified in line with the increased popularity of veganism and ethical consumption. Products must be developed to reinforce the value of consumption. Safe and healthy foods must be launched in the market so that the consumption of safe alternative foods can lead to the betterment of health and family wellness. Fifth, a recommendation manual should be distributed so that balanced meals with alternative foods are feasible. Information on the food's nutrition and servings should be provided for the consumer to check. Cooking instructions should also be provided, acknowledging digestive abilities and improving masticatory functions. Lastly, a differentiated marketing strategy is needed for demographic characteristics. For vegetarian or semi-vegetarian consumers, a positive influence was observed for alternative food purchase intentions and preferences. The Korean vegan population is assumed to be more than 1,500,000 people (www.vege.or.kr, 2019, accessed on 28 October 2020) and is expected to increase. Vegetarianism can be divided into vegan, lacto, ovo, lacto ovo, polo, pesco, and flexitarian. Products must be developed in line with such types of vegetarianism and consumer preferences and tastes.

This study is significant in that it derived selection attributes through categorization. Further studies are required focusing on consumers and local characteristics. This study was focused on a certain city in which the food industry is specialized, due to limits in the cost of survey and the research period, and a follow-up study reflecting consumers' characteristics by the types of vegetarians, and local ones. Alternative foods continue to grow in popularity with consumer interest in food safety and wellness, as well as environmental sustainability. This study proposed an understanding of selection attributes that affect consumer purchase intentions for alternative foods according to alternative market expansion and suggested a direction for production system improvement, distribution efficiency, and sales promotion in response to the changing food market.

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A Life Cycle Assessment of Organic and Chemical Fertilizers for Coffee Production to Evaluate Sustainability toward the Energy–Environment–Economic Nexus in Indonesia

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Abstract: Coffee is an important agricultural commodity that is branded according to its environmental criteria in the global market. Therefore, Indonesia's coffee production system needs to be investigated to meet the demand for eco-labeling, which has become a consumer preference. This study aims to assess the comprehensive sustainability evaluation of coffee production nurtured by an organic fertilizing system (*OFS*), chemical-organic fertilizing system (*COFS*), and chemical fertilizing system (*CFS*) that focuses on the energy–environment–economic nexus. A life cycle assessment (LCA), life cycle cost analysis (LCC), and energy analysis were performed as methods to evaluate the environmental impact, economic performance, and energy requirement analysis. The results indicated that the *OFS* had superior performance in two sustainability aspects: resulting in the lowest environmental damage and generating the highest economic benefit. Simultaneously, *COFS* shows the highest sustainability performance as it consumes the least energy. In contrast, *CFS* indicated the lowest sustainability performance in all aspects: highest environmental impact, lowest economic benefit, and highest energy consumption. Therefore, *OFS* is strongly recommended to be applied broadly, considering its environmental and economic superiority. Consequently, massive *OFS* application was followed by higher energy consumption. Alternatively, *COFS* can be considered for application due to its higher energy performance, even though it can potentially result in higher environmental damage and lower economic benefit. However, the government should explicitly provide some effort for the broad application of *OFS* in financial and assistance support since the shifting process needs more time to adapt.

Keywords: sustainability assessment; environmental impact; economic performance; energy analysis; coffee cultivation; organic fertilizer; chemical fertilizer

1. Introduction

1.1. Sustainability Issue in the Global Market Demand

The global demand for agricultural commodities has increased with rapid population growth and economic development [1]. This demand has promoted intensive agricultural practices and the development of the agriculture industry. Simultaneously, intensive agriculture substantially depletes the natural resources and causes environmental damage [2–7]. From the global market perspective, environmental issues have become popular, and sustainability guarantees product competitiveness. Due to the increased environmental awareness campaign, the high consumer preferences stimulate business pressure on sustainability concerns [8]. Sustainability issues also challenge production activities: protecting and rejuvenating the environment, promoting and recycling economically, and saving and efficiently utilizing energy [9].

The three sustainability challenges in production activity correspond to the sustainable development goals (SDGs). The SDGs are the way to achieve peace and prosperity for both humans and the earth that are expressed by 17 goals by the United Nations [10]. Eight SDGs are related to agriculture production: zero hunger, economic growth, clean water sanitation, affordable and clean energy, responsible consumption and production, climate action, life below water, and life on land. The SDGs study also reported that SDGs play a central role in producing clean and affordable energy for preserving life both in the sea and on land [11]. Following the SDGs, agricultural production activity should practice methods, processes, and technologies during production activity to protect humans, nature, and resources for the use of future generations [11]. Thus, assessing and promoting the sustainability of agricultural production in environmental, economic, and energy aspects are essential.

1.2. Coffee Production in Indonesia and its Sustainability Issue

According to the International Coffee Organization, the world coffee demand followed an upward trend, with an average increase of 1.4% per year from 2017 to 2020 [12]. Indonesia contributes 7.42% to world coffee demand and is the fourth most significant contributor, with an average annual production of 683.64 million kg y^{-1}. This shows that Indonesia is a potential global coffee producer. Therefore, the coffee industry in Indonesia should consider sustainability concerns for natural responsibility and when competing with the global market. Indonesia's coffee is produced by three different sectors: smallholder communities (95.45%), government companies (2.21%), and private companies (2.44%) [13]. Coffee plantations in Indonesia are predominantly managed by smallholders who apply conventional methods with massive amounts of chemical fertilizer, and only a few practiced organic systems. Massive amounts of fertilizers, pesticides, human labor, electricity, gasoline, and other materials were used during the coffee production process at the farm level. Simultaneously, the environmental damage is predicted to be severely impacted by the conventional practice of coffee production. The study also reported that production activity at the farm level is predicted to be a hotspot for GHG emissions in the coffee supply chain [14]. Shifting into more green coffee cultivation will significantly decrease the environmental damage impacted by coffee production activity. The organic cultivation system that avoids chemical substances represents the green cultivation in progress which is currently broadly practiced in agricultural production [15].

However, some studies have been conducted on coffee in recent years: the environmental study of coffee at different levels of fertilizer input and shade trees in Nicaragua and Costa Rica [14]; the identification of the carbon footprint of coffee beverages in Japan, which evaluated the carbon footprint of the coffee serving technology [16]; the study of shade tree application and its impact on the environment [17]; a cycle of participatory study in Organic coffee [18]; and the study of the environmental profile of green bean coffee in Brazil [19]. However, a specific study on coffee in Indonesia related to fertilizer management during the production of Robusta coffee without evaluating the sustainability profile has been investigated [20]. A study also reported that the coffee industry in Indonesia still provides limited financial benefits to smallholder farmers [21].

Referring to the study reports on coffee, some issues concerning coffee production in Indonesia are highlighted. First, studies on the area of coffee cultivation calculated in multiyear cultivation were limited. As coffee is a multiyear crop, it is essential to calculate the multiyear input-output system during cultivation to obtain a more precise emission result. Second, there is a lack of comprehensive information about the sustainability of coffee production in Indonesia based on fertilizer treatments. Lastly, previous studies only investigate the environmental impacts of coffee cultivation and disregard the economic and energy perspectives.

1.3. Sustainability Measurement

A comprehensive sustainability evaluation on the environment, economy, and energy aspects can be conducted using the life cycle assessment (LCA) approach [22]. In environmental evaluation, LCA specifically estimates the environmental damage over the entire life cycle of a process or product [7]. Some environmental indicators linked to the sustainability performance using an LCA approach, such as carbon footprint which is currently represented by carbon dioxide emissions [2,23,24], acidification potential (AP), eutrophication potential (EP), and global warming potential (GWP) [25,26].

However, economics is one crucial aspect in SDGs which is classified in economic growth development goals in SDGs [10]. Agriculture production activity should include economic sustainability to ensure sustainable production in the future. In coffee production, economic benefits for farmers becomes a concern of the ICO. A recent study conducted by the ICO reported that coffee farmers in selected countries are operating at a loss and that coffee growing is becoming less profitable over time [27]. Additionally, farmers are likely to consider implementing a strategy with a positive economic result. Therefore, economic performance evaluation is essential for coffee production activity. The life cycle cost (LCC) assesses all costs associated with a product's life cycle in economic performance. The LCC can detect the direct and indirect cost factors and estimate improvements in the planned product changes [22,28–30]. The production cost, revenue, and profit were identified during the LCC analysis. Cost and profit were used as indicators of economic performance to determine the relative success of a farm operation in terms of its ability to meet short-term financial obligations [31].

In the energy aspect, promoting affordable and clean energy is one of the goals of SDGs. In modern production, activity was also challenged to achieve energy-saving and efficient utilization. Considering the energy goal of SDGs and energy direction of modern production, analysis of the energy aspect in coffee production is essential. According to energy analysis, the energy requirement is the basis to evaluate the efficient use of energy aspects that become principal requirements of sustainable agriculture [32]. Therefore, measuring the energy requirement can also indicate the sustainability status.

Considering SDGs for agricultural production and the current sustainability issue for coffee in global demand, it is necessary to consider three sustainability aspects comprehensively–environmental impact, economic benefits, and energy–to enhance the sustainability of coffee production. However, the comprehensive evaluation of the environmental, economic, and energy situation at the farm-level potentially has a significant impact on the effective improvement since reported as the hotspot to environmental damage during agriculture production.

1.4. Research Objective

The objective of this study was to comprehensively evaluate the sustainability assessment considering the environmental impact, economic performance, and energy requirements of coffee production nurtured by different fertilizer applications within a multiyear production period. The energy–environment–economic evaluation of coffee production can provide valuable information for all stakeholders to achieve the three sustainable production goals: rejuvenating the environment, promoting economics, and saving and effectively utilizing energy. Additionally, this study can scientifically fill the research gap in coffee production management in Indonesia. Further research is required to encourage farmers to develop a more environmentally and economically viable coffee production system. Moreover, such efforts can also provide considerable insight into the government's decision-making process to support coffee farmers applying the green coffee production method.

This paper consists of five sections. Section 1 is the Introduction; Section 2 is Materials and Methods; Section 3 is study Results; Section 4 is the Discussion; Section 5 is the Conclusion.

2. Materials and Methods

2.1. Research Location and Object Studied

This study was conducted on a farmer's plantation, managing a small-medium coffee industry. Simultaneously, the farmer also practiced intensive maintenance coffee production. The farmer practiced some coffee cultivation systems in 480 ha of chemical-organic fertilizing systems, 25 ha of organic fertilizing systems, and 5 ha of chemical fertilizer fertilizing systems in the central arabica coffee production area sub-district of Sindangkerta, which is located in the West-Bandung District. West Bandung District is located in the specific geographical position at 6°41′–7°19′ S and 107°22′–108°5′ E with 130,577.40 ha of total area. This area is popular as the producer of many agricultural commodities due to the high soil fertility level. This area has the potential to adequately access the hydrological system for agriculture since the main watershed traverses. This region contains evergreen and moist-deciduous forest types. The climate in this location is hot and humid, with the rainfall continuously around four months in a year [33]. Specifically, the Sindangkerta sub-district is more popular with its coffee production and has become one of the coffee production centers in West Java that has produced coffee for domestic and international coffee consumption for more than two decades. The detailed information is presented in the following figure (Figure 1).

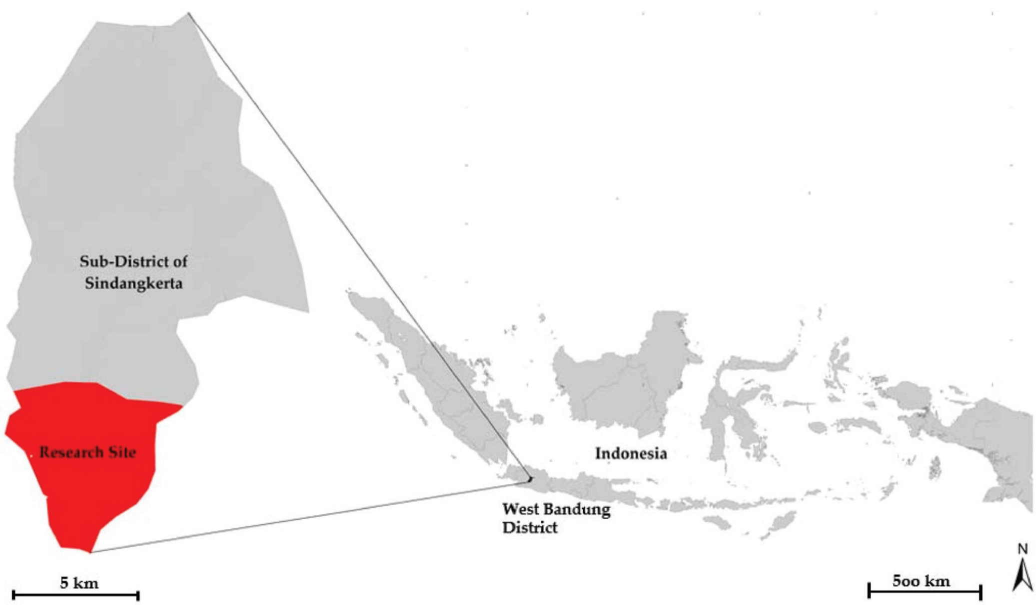

Figure 1. Surveyed coffee plantation area in the sub-district of Sindangkerta, Bandung Barat District, West-Java, Indonesia.

In this study, all coffee cultivation was planted in agroforestry areas. Nowadays, coffee has become more prevalent in agroforestry areas, whereas a few farmers have temporarily planted coffee in open field areas in Indonesia. Table 1 presented detailed geographical information of coffee cultivation studied.

Table 1. General information of the three coffee fertilizing systems.

Particulars	Unit	Fertilizing System		
		Organic (*OFS*)	**Chemical-Organic (*COFS*)**	**Chemical (*CFS*)**
			Geographical information	
Elevation	MSAL *		1200–1300	
Slope	Degree		0–45	
Land area	ha	25	480	5

* MASL is meters above sea level.

According to this study objective, the sustainability assessment will compare the three cultivation systems based on their fertilizer applications. Farmers in Indonesia practice some plantation management systems according to their fertilizer application: organic fertilizing system (*OFS*), chemical-organic fertilizing system (*COFS*), and chemical fertilizing system (*CFS*). *OFS* is still applied in small areas, whereas the *COFS* is extensively applied in Indonesia. However, higher productivity has encouraged farmers to apply the *COFS* continuously. This condition is under some literature and experience in producing other agricultural commodities that suggest that chemical and organic fertilizers can improve production capacity [6], regardless of environmental and economic considerations.

Currently, organic coffee is produced by practicing *OFS* on the farm level to fulfill the demands of specialty coffee export and environmental protection. Farmers used poultry manure, compost, and liquid fertilizer as the main fertilizers in the *OFS*. In *COFS*, organic and chemical fertilizers were combined during the plantation activities. In *COFS* and *CFS*, farmers used NPK as a chemical fertilizer. However, *CFS* is not mainly applied to coffee plantations because of its low productivity. Moreover, the excessive use of chemical fertilizers in the long term reportedly contributes to land degradation and nutrient pollution [34]. Therefore, it seems good progress since the chemical fertilizing system provides severe environmental damage.

2.2. Work Procedure

This study is conducted in four stages. The first stage is the goal and scope definition. In this stage, the objective and the boundary system are also defined. The second stage is data collection and inventory analysis. The data is collected in the research object refers to the boundary system. The third stage is sustainability analysis which evaluates three aspects: environmental impact assessment, economic performance analysis, and energy requirement analysis. The environmental impact analysis of multiyear coffee cherry bean production is performed using the life cycle assessment (LCA) methodology according to ISO 14040:2006. LCA is defined by ISO 14040 as the compilation and evaluation of the input, output, and potential environment of a product system throughout a life cycle [35,36]. Simultaneously, this study performed the life cycle cost method to evaluate the economic performance; and energy requirement analysis is used to evaluate the energy aspect. After conducting the primary analysis in stage 3, result interpretation will be at the end of this study procedure work. Figure 2 expresses the detailed work procedure of this study.

2.2.1. Goal and Scope Definition

The boundary system includes all stages of coffee plantation with multiyear production until replanting as presented in Figure 3. All necessary input-output was calculated following the research scope and boundary in a 1 ha coffee plantation. This study set four and five years as the pre-productive and productive stages, respectively. The pre-productive stage is the period before the coffee tree produces the coffee cherry beans, whereas the productive stage is when the coffee tree yields the coffee cherry bean. Coffee is categorized as an annually harvested plant with a three-month harvesting period per year. The harvesting started from the fourth year after planting and could be harvested until the ninth year of cultivation. The following figure expresses the boundary system of this study.

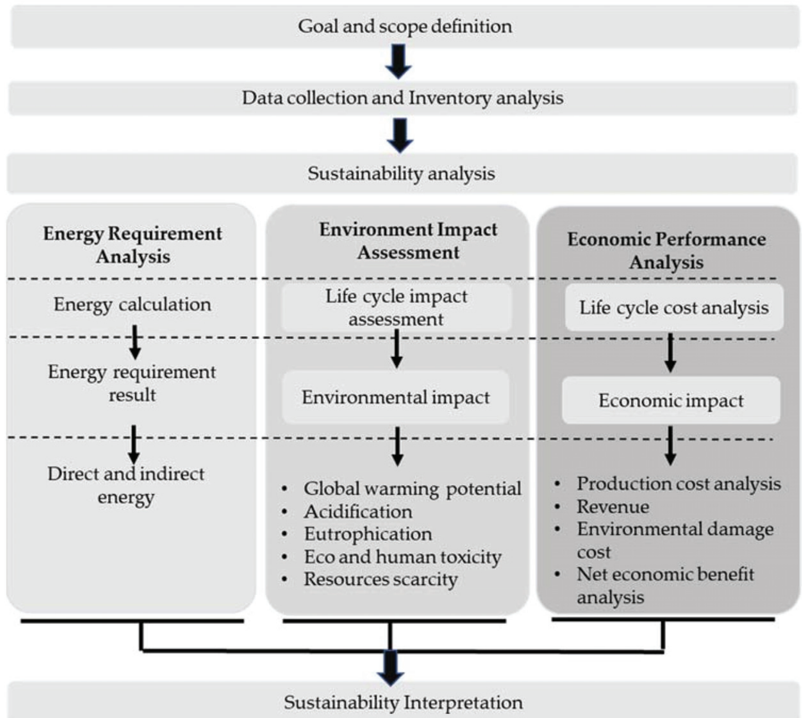

Figure 2. Research stage.

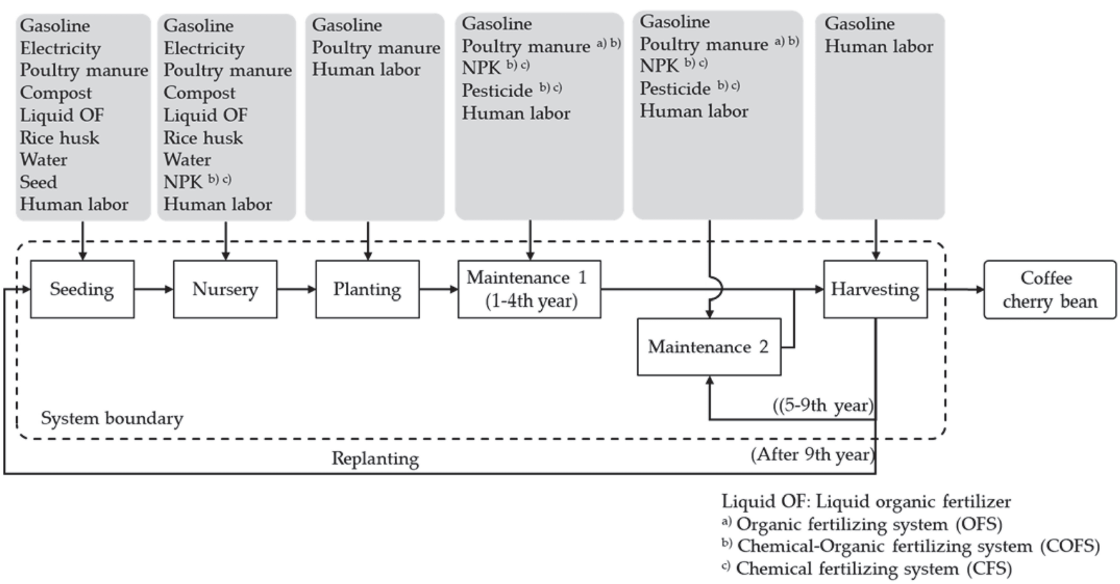

Figure 3. System boundary of the three coffee fertilizing systems.

2.2.2. Data Collection and Life Cycle Inventory Analysis (LCI)

The data was collected by field observation, in-depth interview, and questionnaire based on the coffee farmers with the research scope and boundary. The life cycle inventory (LCI) is an essential phase in the LCA that processes data collected from the farmer. The LCI was conducted based on the material and energy requirements during coffee production. A 1 ha coffee plantation is used as the functional unit during the inventory analysis. Table 2 presented the inventory analysis result of 1 ha coffee cultivation system.

Table 2. Inventory data of the input and output by fertilizing system.

Input and Output		Unit	Fertilizing System: Organic (*OFS*) Quantity	Chemical-Organic (*COFS*) Quantity	Chemical (*CFS*) Quantity
Input					
Seeding	Gasoline	L ha^{-1}	2	2	2
	Electricity	kWh ha^{-1}	0.03	0.03	0.03
	Poultry manure	kg ha^{-1}	100	100	100
	Compost	kg ha^{-1}	100	100	100
	Liquid organic fertilizer	L ha^{-1}	8	8	8
	Rice husk	kg ha^{-1}	100	100	100
	Water	L ha^{-1}	420	420	420
	Seed	kg ha^{-1}	2	2	2
	Human labor	h ha^{-1}	116	116	116
Nursery	Gasoline	L ha^{-1}	5	5	5
	Electricity	kWh ha^{-1}	11.25	11.25	11.25
	Poultry manure	kg ha^{-1}	2400	2400	2400
	Compost	kg ha^{-1}	1200	1200	1200
	Liquid organic fertilizer	L ha^{-1}	96	96	96
	Rice husk	kg ha^{-1}	1200	1200	1200
	Water	L ha^{-1}	48,000	48,000	48,000
	NPK Nitrogen	kg ha^{-1}	-	0.93	1.83
	NPK Phosphorus	kg ha^{-1}	-	0.93	1.83
	NPK Potassium	kg ha^{-1}	-	0.93	1.83
	Human labor	h ha^{-1}	320	320	320
Planting	Gasoline	L ha^{-1}	42	42	42
	Poultry manure	kg ha^{-1}	2500	2500	2500
	Human labor	h ha^{-1}	480	480	480
Maintenance 1 [1] (Pre-productive)	Gasoline	L ha^{-1}	26	20	12
	Poultry manure	kg ha^{-1}	40,000	24,000	-
	NPK Nitrogen	kg ha^{-1}	-	180	266.43
	NPK Phosphorus	kg ha^{-1}	-	180	266.43
	NPK Potassium	kg ha^{-1}	-	180	266.43
	Pesticide	L ha^{-1}	-	3	12
	Human labor	h ha^{-1}	320	192	128
Maintenance 2 [2] (Productive)	Gasoline	L ha^{-1}	78	60	36
	Poultry manure	kg ha^{-1}	137,400	60,000	-
	NPK Nitrogen	kg ha^{-1}	-	750	981
	NPK Phosphorus	kg ha^{-1}	-	750	981
	NPK Potassium	kg ha^{-1}	-	750	981
	Pesticide	L ha^{-1}	-	5	24
	Human labor	h ha^{-1}	960	576	384

Table 2. *Cont.*

Input and Output		Unit	Fertilizing System		
			Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
			Quantity		
Harvesting [3]	Gasoline	L ha^{-1}	288	288	288
	Human labor	h ha^{-1}	4400	5000	2200
Output	Coffee cherry bean	kg ha^{-1}	44,000	50,000	22,000

[1] Maintenance 1 is the maintenance activity in the pre-productive stage; [2] Maintenance 2 is that in the productive stage; and [3] Harvesting indicates the input and output for six years of harvesting.

The inputs for coffee production included gasoline, electricity, fertilizer (poultry manure, compost, liquid organic fertilizer, and NPK), pesticides, rice husks, water, seeds, and labor. Gasoline is used in vehicles to transport labor and materials to the field. Electricity is required for watering during the seeding and nursery stages. Two types of fertilizers were used in this study: organic and non-organic. Compost, poultry manure, and liquid organic fertilizers were used as organic fertilizers, and NPK was used as a chemical fertilizer. Pesticides are conditionally used to control pest attacks. Chemical pesticides are applied in CFSs and COFSs, whereas organic pesticides are used in the *OFS*. The seed is an essential material in the first stage of plantation. Organic seeds were used in all the coffee fertilizing systems. A 1 ha coffee plantation needs 2 kg of organic seed. As the additional material, rice husk is provided as the growth medium during the seeding and nursery stages. Another vital activity during seeding and nursery is watering. The level of water used during seeding and nursery maintenance is different in each stage. As typical of conventional agricultural practice, all the physical activities in plantations are conducted by human labor. Therefore, human labor is an essential input presented by the total labor working hours during coffee production activities. As the output, the total coffee cherry production is generated by six years of harvesting. The following table expresses the inventory analysis results of the input-output system.

2.2.3. Sustainability Analysis

Energy Requirement Analysis

The total energy is calculated as the sum of energy required by each material and energy input during coffee production in energy requirement analysis. The energy of each input system was obtained by multiplying the input consumption (Table 2) and its energy conversion factor (Table 3). This study used the energy conversion factors from scientific literature, as presented in the following table.

Table 3. Energy conversion factor.

Input System		Unit	Energy Conversion Factor (MJ Unit^{-1})	References
	Gasoline	L	34.2	[37]
	Electricity	kWh	11.93	[38]
	Human labor	h	1.96	[39,40]
	Pesticide	L	278	[40]
NPK	Nitrogen	kg	64.4	[41]
	Phosphorus	kg	12.44	[42,43]
	Potassium	kg	11.15	[42,43]
	Compost	kg	6	[44]
	Poultry manure	kg	1.32	[45–47]
	Water	L	1	[43,45]
	Liquid organic fertilizer	L	1.32	[45–47]
	Rice husk	kg	14.6	[48]

Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment is the main stage for assessing the environmental impact. The LCA analysis of coffee cherry bean production performed LCA methodology according to ISO 14040:2006. According to ISO 1440:2006, LCA analysis evaluates the potential environmental impact throughout a product's life cycle [36,49]. The present study adopted the LCA methodology developed by the ReCiPe 2016 v.1.0.4 midpoint method with a hierarchy version created by RIVM, Radboud University, Norwegian University of Science and Technology, and PRé Consultant [49]. The calculation was performed using Simapro v.9.1.1.1® software with the Ecoinvent 3.7.1 database. The environmental impact on this present study considered eleven impact categories: the global warming potential (GWP), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FEc), marine ecotoxicity (MEc), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HnCT), mineral resource scarcity (MRS), and fossil resource scarcity (FRS). The environmental impact of each fertilizing system was calculated using the following equation:

$$EI\ (OFS,\ COFS,\ CFS) = \sum_{k=1}^{n} (EF_{\mathrm{k}} \times material\ or\ energy\ input\ _{\mathrm{k}} \tag{1}$$

The environmental impact indicators for each coffee plantation are expressed as EI (*OFS*, *COFS*, *CFS*). Where *OFS*, *COFS* and *CFS* indicate the organic fertilizing system, chemical-organic fertilizing system, and chemical fertilizing system, respectively. The sum of all emission inputs is calculated in all environmental indicators The emission per input was obtained by multiplying each emission factor (*EF*) by the material or energy input *(n)*. The *EF* indicates the emission impact per unit input. Some studies either used EF from the literature or conducted preliminary calculations. This study conducted a preliminary calculation using SimaPro to obtain the EF and environmental impact results.

Life Cycle Cost Analysis (LCC)

The life cycle costing (LCC) study aimed to fully account for the financial costs of the environmental aspects and impacts of the life cycle [22,48]. The LCC is calculated considering all the input-output inventory costs and the environmental impact costs of the LCA. The LCA input cost is represented by all the expenses required to provide the materials and energy during the plantation. The cost of each specific input was calculated by multiplying the total input used by the standard cost of its input. The environmental impact cost is represented by the CO_2 emission cost, which is calculated as the total CO_2 emissions multiplied by the CO_2 emission tax. This study only calculates the CO_2 emission cost as the primary environmental impact cost considering Indonesia's condition, which is still preparing to implement the CO_2 tax in its environmental policy. The CO_2 emission tax refers to the standard carbon tax for developing countries as the standard carbon tax for Indonesia is still unavailable. According to the OECD Taxing Energy Use (TEU) Database, Indonesia recommends using a moderate emission tax standard emission [50]. As our study considers multiyear production costs, this calculation also assumes the discount rate for the small-to medium-scale sector. Therefore, the following equation is used for the LCC calculation:

$$Total\ life\ cycle\ cost\ (TLCC) = Production\ cost + Emission\ cost \tag{2}$$

$$Production\ cost = Fixed\ cost + Variable\ cost \tag{3}$$

$$Emmision\ cost = Total\ production \times Emission\ tax \tag{4}$$

The total life cycle cost (*TLCC*) is the total cost of the life cycle of coffee, which fully accounts for all the production and emission costs. The production cost indicates all expenses during the coffee production life cycle, which consists of a fixed cost and variable cost. A fixed cost is the initial investment cost, such as the machinery, tools, and rent for the cultivation land. The variable cost included all materials, labor, transportation, distribution, and environmental impact costs during the project's life cycle. The emission cost is the impact of the environmental damage cost. The total production indicates the total coffee cherry bean production. This study considers the multi-year costs following the research boundary.

The economic benefit was also investigated by a subsequent economic analysis using the following equation:

$$Net\ profit = Revenue - TLCC \quad (5)$$

$$Revenue = Total\ production \times selling\ price\ per\ kg \quad (6)$$

Net profit represents the potential profit generated by the farmer which is calculated by the revenue subtracted with the *TLCC*. All currency values are converted into USD from IDR using 14,409 IDR USD^{-1} [51].

2.2.4. Sustainability Interpretation

This stage explains a descriptive interpretation of the study results that compared the sustainability analysis: energy requirement, environmental impact, and economic performance on the three coffee fertilizing systems. By comparing all results, better performance in energy, environmental, and economic aspects will be provided.

3. Result

This section describes the results of the present study: energy requirement analysis, environmental impact assessment, and life cycle cost analysis of coffee production.

3.1. Energy Requirement Analysis

The total energy requirement for managing 1 ha of coffee plantations was dominated by *OFS*, followed by *COFS* and *CFS*. The total energy consumption values in *OFS*, *COFS*, and *CFS* are 344.31 × 10^3, 304.51 × 10^3, and 222.34 × 10^3 MJ ha^{-1}, respectively (Table 4). The fertilizer usage requires the highest energy, wherein manure consumes the highest energy in the *OFS* and*COFS*, and NPK required the most energy in the *CFS*. Poultry manure consumed 240.77 × 10^3 and 117.48 × 10^3 MJ ha^{-1} in the *OFS* and *COFS*, respectively. In comparison, the energy consumption of NPK was 109.92 × 10^3 MJ ha^{-1} in *CFS*. As presented in Table A18, water was the dominant source of energy consumption after fertilizer use, consuming 48.42 × 10^3 MJ ha^{-1} in all the fertilizing systems. Regarding the energy requirement for labor, managing 1 ha of coffee plantations with the *COFS* requires the highest human labor energy at 18.15 × 10^3 MJ ha^{-1}. In contrast, the *OFS* requires lower energy for labor, at 17.23 × 10^3 MJ ha^{-1}. According to Table 4, the highest energy for labor is required for the harvesting activity, which is dominant in the *COFS* at 9.8 × 10^3 MJ ha^{-1}. Regarding the hotspot of energy requirements per stage of the coffee plantation as presented in Table A19, maintenance 2 was the dominant energy source in all coffee fertilizing systems. It consumed 185.92 × 10^3, 149.76 × 10^3, and 94.97 × 10^3 MJ ha^{-1} in the *OFS*, *COFS*, and *CFS*, respectively. The following table presents the energy requirement for managing a 1 ha coffee plantation.

Figure 4 indicates that energy consumption for 1 kg of coffee is dominated by fertilizer application in all fertilizing systems. Specifically, manure consumed the highest energy in the *OFS* and *COFS*. In contrast, NPK predominantly used the energy in the *CFS*. According to Table A1, energy inputs for 1 kg of coffee cherry bean production in the *CFS*, *OFS*, and *COFS* were 10.35, 7.92, and 6.19 MJ kg^{-1}, respectively. The highest energy consumption was identified in all *CFS* inputs. In fertilizers, poultry manure is the highest contributor to energy consumption in the *OFS* and *COFS*. The manure application required 5.47 and 3.35 MJ kg^{-1} in the *OFS* and *COFS*, respectively. In comparison, NPK dominantly consumed energy in the *CFS* which consumed 4.996 MJ kg^{-1}. The second-largest contributor to energy consumption was water, which consumed 1.10, 0.97, and 2.20 MJ kg^{-1} in the *OFS*, *COFS*, and *CFS*, respectively. The domination of energy from fertilizer usage in coffee cherry bean production is similar to the other study in which fertilizer dominated energy consumption in all coffee plantations [32,52]. The water application on managing of 1 ha coffee plantation is at the same level in all fertilizing systems. The differences in energy use related to the water consumption on 1 kg of coffee cherry beans production are caused by the different productivities of each coffee fertilizing system. The following figure presents the energy requirement for 1 kg coffee cherry bean production.

Table 4. Energy requirement for managing of 1 ha coffee plantation.

Stage of Plantation	Input System	Fertilizing System: Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
		Energy Requirement ($\times 10^3$ MJ ha^{-1})		
Seeding	Gasoline	0.068	0.068	0.068
	Electricity	0.0004	0.0004	0.0004
	Poultry manure	0.132	0.132	0.132
	Compost	0.6	0.6	0.6
	Liquid organic fertilizer	0.011	0.011	0.011
	Rice husk	1.46	1.46	1.46
	Water	0.42	0.42	0.42
	Seed	-	-	-
	Human labor	0.23	0.23	0.23
Nursery	Gasoline	0.17	0.17	0.17
	Electricity	0.13	0.13	0.13
	Poultry manure	3.17	3.17	3.17
	Compost	7.2	7.2	7.2
	Liquid organic fertilizer	0.13	0.13	0.13
	Rice husk	17.52	17.52	17.52
	Water	48	48	48
	NPK Nitrogen	-	0.06	0.12
	NPK Phosphorus	-	0.012	0.023
	NPK Potassium	-	0.01	0.02
	Human labor	0.63	0.63	0.63
Planting	Gasoline	1.44	1.44	1.44
	Poultry manure	3.3	3.3	3.3
	Human labor	0.94	0.94	0.94
Maintenance 1 [1]	Gasoline	0.89	0.68	0.41
	Poultry manure	52.8	31.68	-
	NPK Nitrogen	-	11.59	17.16
	NPK Phosphorus	-	2.24	3.31
	NPK Potassium	-	2	2.97
	Pesticide	-	0.83	3.34
	Human labor	0.63	0.38	0.25
Maintenance 2 [2]	Gasoline	2.67	2.05	1.23
	Poultry manure	181.37	79.2	-
	NPK Nitrogen	-	48.3	63.18
	NPK Phosphorus	-	9.33	12.2
	NPK Potassium	-	8.36	10.94
	Pesticide	-	1.39	6.67
	Human labor	1.88	1.13	0.75
Harvesting [3]	Gasoline	9.91	9.91	9.91
	Human labor	8.62	9.8	4.31
Total		344.31	304.51	222.34

[1] Maintenance activity in pre-production stage (four years of maintenance); [2] Maintenance in productive stage (five years of maintenance); and [3] six years of harvesting.

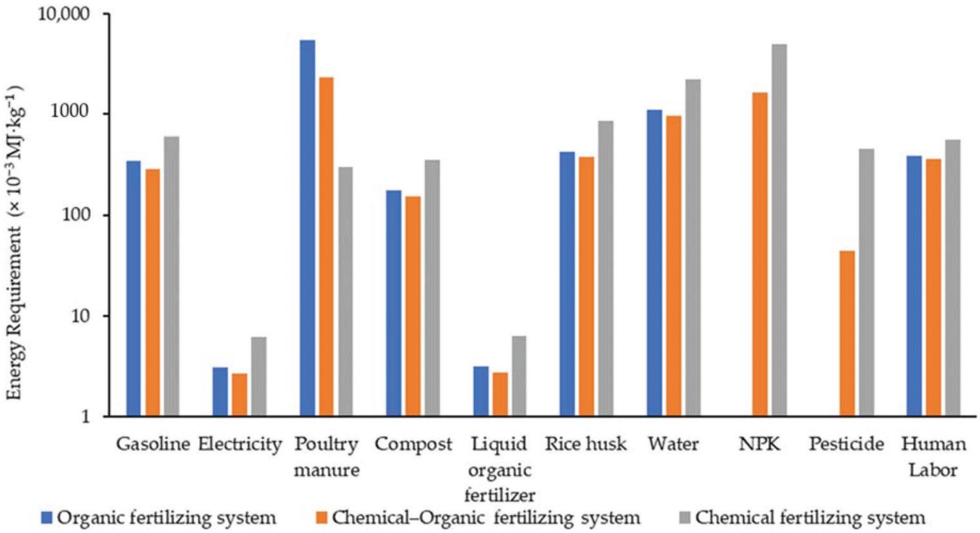

Figure 4. Energy requirement for 1 kg coffee cherry bean.

In developing countries, agricultural production is still predominantly conducted by human labor. Therefore, it is essential to calculate the energy requirement for labor. As presented in Table A1, 1 kg of coffee cherry bean production required about 0.39, 0.36, and 0.57 MJ kg^{-1} in the *OFS*, *COFS*, and *CFS*, respectively. According to Tables A3–A5, harvesting and maintenance activities are the most significant contributors to labor energy. In particular, clearing activities required higher energy than the other maintenance activities in the *OFS*. Simultaneously, fertilizing activity consumed the highest energy in the *COFS*. Although the *OFS* has more clearing activities, it has no significant effect on labor energy consumption because harvesting still dominates the energy consumption. The high energy required for labor indicates that the coffee production system is still conventionally conducted by human labor rather than by machinery. Electricity has the lowest energy requirement. The electricity consumption is on the watering activity. Electricity only contributed 0.038, 0.043, and 0.059% to the total energy requirements in *OFS*, *COFS*, and *CFS*, respectively.

3.2. Environmental Impact Assessment and Its Contributing Factors

3.2.1. Environmental Impact

Figure 5 presents the environmental impact of 1 kg of coffee cherry bean production.

Figure 5 indicates that *OFS* has the lowest environmental impact in all impact categories compared to the *CFS*. The *OFS* presented the lowest impacts on the eight environmental impact categories GWP, TA, FE, TEc, MEc, HCT, MRS, and FRS compared to *COFS*. Simultaneously, *COFS* had the lowest impact in the three environmental impact categories: ME, FEc, and HnCT. In contrast, the *CFS* had the highest environmental impact in all impact categories. The detailed information on the environmental impact of 1 kg of coffee cherry bean production is presented in Table A2. According to Table A2, *OFS* is more environmentally friendly as indicated by the lowest impact, such as in GWP that emitted 0.0678 kg CO_2 eq kg^{-1}, and compared to *COFS* and *CFS*, which have a GWP impact of about 0.182 and 0.496 kg CO_2 eq kg^{-1}, respectively. Comparing *OFS* with *COFS*, seven other environmental indicators were dominant in the *OFS*: TA, FE, TEc, MEc, HCT, FRS, and MRS. In contrast, *CFS* has the highest environmental impact. Thus, shifting the *COFS* or *CFS* to the *OFS* system significantly reduces the environmental impact, as presented in Table A12.

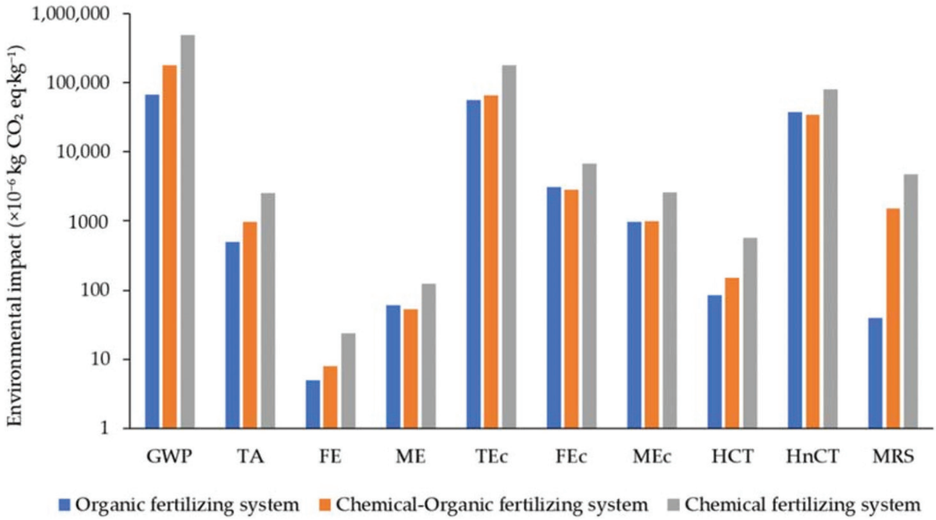

Figure 5. Environmental impact of 1 kg of cherry coffee bean production.

The other study also presented a similar result related to environmental impacts in coffee production as presented by the following table.

According to Table 5, organic coffee plantations has the lowest environmental impact compared with chemical-organic or conventional cultivation in Indonesia and previous research in other countries [14,52]. In previous research, the impact on GWP for organic was at 0.12–0.52 kg CO_2 eq kg^{-1} and 0.27 kg CO_2 eq kg^{-1}, while organic fertilizing system (*OFS*) in Indonesia has an impact at 0.068 kg CO_2 eq kg^{-1}. The lower GWP in Indonesia can potentially be affected by the boundary system that calculates all life cycle coffee production at the farm level from seeding until replanting. The higher productivity in the intensive coffee management system in this study also mainly impacted the lower GWP per kg product compared others. In this study, the farmer applied the intensive coffee cultivation management system with higher production. In the conventional system, Coffee Indonesia also has a lower environmental impact than others. A study also reported that most of the coffee farmers in Indonesia applied the lower chemical fertilizer as suggested [20]. The other study also presented a similar result related to environmental impacts in coffee production as presented by the following table.

Table 5. Comparative environmental impact evaluation with previous coffee study.

Research	Boundary	Scenario	Environmental Impact (kg CO_2 eq kg^{-1})
Martin R.A. Noponen, et al. [14]	Coffee cultivation in Costa Rica and Nicaragua with average annual coffee production since the second year of production	Conventional Organic	0.26–0.67 0.12–0.52
Basavalingaiah, K., et al. [52]	Coffee-pepper in India in general	Conventional Integrated Organic	1.24 1.07 0.27
This study	Coffee cultivation in Indonesia in all life cycle of coffee cultivation from seeding until replanting	Organic (*OFS*) Chemical-Organic (*COFS*) Chemical (*CFS*)	0.068 0.182 0.496

3.2.2. Contribution Factor of Environmental Impact

As presented in Figure 6, rice husk is dominantly contributed to GWP, TA, FE, ME, TEc, FEc, MEc, HTC, and FRS. The second-largest contributor to environmental damage in the *OFS* is gasoline, which is used for transporting materials and labor to the field. In poultry manure application, its effect on the GWP, TA, FE, ME, TEc, FEc, MEc, HTC, HnCT, FRS, and MRS was not noticeable, even though was dominantly contributed to energy consumption. In the *COFS* and *CFS* (Figures 7 and 8), the use of NPK had the most significant environmental impact. The application of NPK in the *COFS* and *CFS* contributed significantly to the GWP, TA, MRS, and FRS. A similar result also presented the domination of chemical fertilizer that contributed to the environmental impact [14,52]. For comparison, the highest contributors to TEc, MEc, FEc, and HnCT were rice husk. Simultaneously, compost contributed significantly to the FE and ME. Pesticides are primarily responsible for human carcinogenic toxicity. This result indicates that the massive NPK application in *COFS* and *CFS* significantly contributes to air, land, and resource scarcity. Simultaneously, rice husk significantly deteriorates water and contributes to ecotoxicity. At the same time, pesticides are the biggest contributing factor affecting human health. The following figure shows the detailed contribution factors of 1 kg coffee cherry bean production.

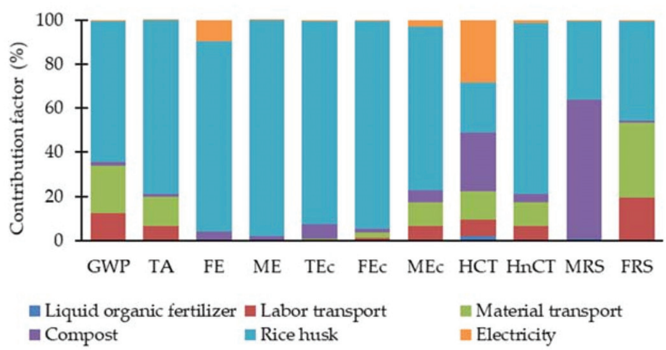

Figure 6. Contributing factors in the Organic Fertilizing System (*OFS*).

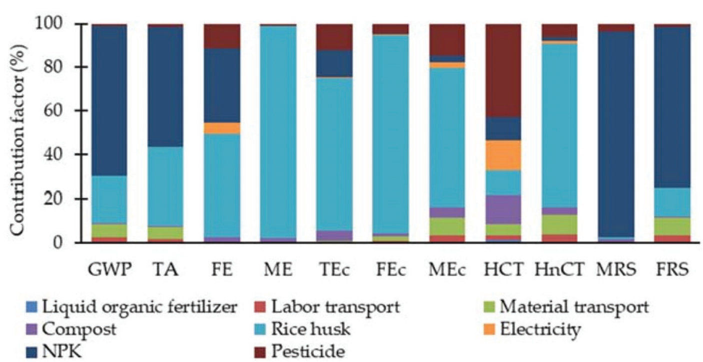

Figure 7. Contributing factors in the Chemical-Organic Fertilizing System (*COFS*).

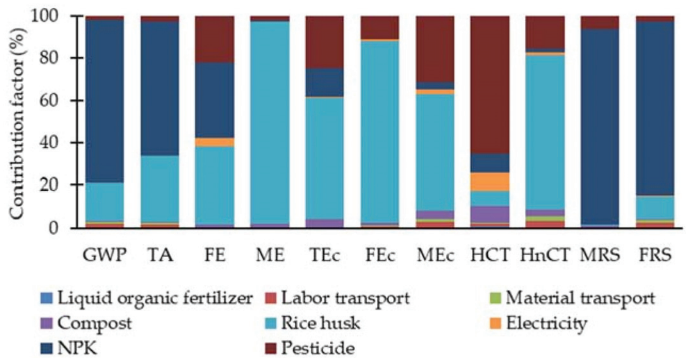

Figure 8. Contributing factors in the Chemical Fertilizing System (*CFS*).

3.2.3. Sensitivity Analysis of Environmental Impact

Figuring the uncertainty on assessing the environmental impact in LCA, the sensitivity analysis is suggested. This method involves calculating different scenarios to analyze the influence of input parameters on either LCIA output result [53]. The present study also performed the environmental impact sensitivity analysis following two variable changes: the change in production capacity and fertilizer use.

As presented in Figure 9, the fertilizer input-level change scenario significantly impacts GWP on *COFS* and *CFS*. In contrast, it has no GWP impact on *OFS* since *OFS* avoided chemical fertilizer. This result indicated that the chemical fertilizer is the hotspot to the GWP. According to system-based fertilization, the change of GWP due to the change of fertilizer input level in *CFS* is more significant than in *COFS*. This result indicated that the level of fertilizer used is sensitive to the GWP impact. The higher the chemical input impacted the higher GWP, and conversely. The impact of scenario changes to GWP was identified as presented by the following figure.

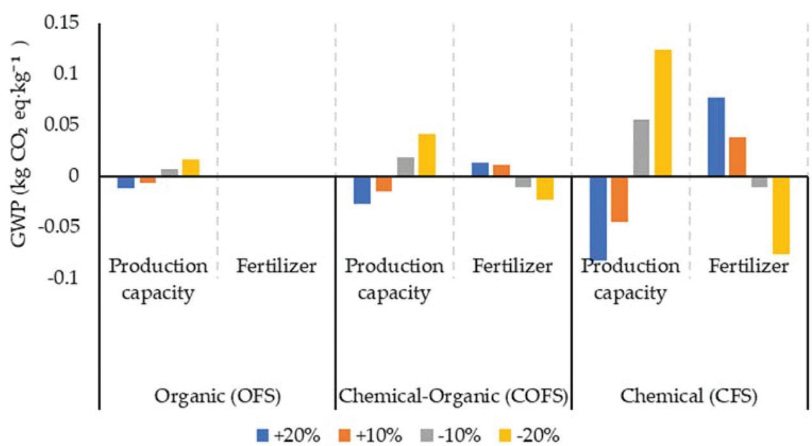

Figure 9. Environmental sensitivity analysis.

This study also conducted the environmental sensitivity analysis related to production capacity change. In this scenario, the GWP change due to the change of production level in *CFS* dominates while the GWP impact in *OFS* is the lowest. This result indicated that *CFS* and *COFS* are vulnerable to the change input and output aspects. Overall, the linear result has been shown following the level change of production and fertilizer used. In this case, it was indicated that the environmental impact result follows the linear trend impact when the uncertainty has occurred in production and fertilizer application.

3.3. Life Cycle Cost Analysis

Table 6 presents the LCC analysis. Overall, *OFS* generates superior performance in the economic aspect, as indicated by the highest value in revenue and net profit as presented by the following figure:

Table 6. Life cycle cost (LCC) analysis.

Indicators	Unit	Fertilizing System		
		Organic (*OFS*)	**Chemical-Organic (*COFS*)**	**Chemical (*CFS*)**
Production Cost	USD ha^{-1}	8936	9084	6176
	USD kg^{-1}	0.2031	0.1816	0.2800
Emission cost	USD ha^{-1}	29.07	88.42	106.02
	USD kg^{-1}	0.0006	0.0017	0.0048
Revenue	USD ha^{-1}	30,537	29,496	12,978
	USD kg^{-1}	0.69	0.59	0.59
Net profit	USD ha^{-1}	21,571	20,330	6720
	USD kg^{-1}	0.49	0.41	0.30

According to Table 6, the result highlights that the highest production cost per hectare coffee plantation is required by *COFS* with total expenses of 9084 USD ha^{-1}. For comparison, the *OFS* and *CFS* required 8936 and 6176 USD ha^{-1}, respectively. The different results showed in production cost per 1 kg coffee cherry bean production, which is the highest required by the *CFS*. The highest cost in *CFS* is caused by its lowest productivity. More detail in production cost, the highest cost was required for human labor in all fertilizing systems. Specifically, human labor for harvesting primarily contributed to the cost. This result indicates that human labor cost is a hotspot regarding economic expenditure (Tables A3–A5, A13 and A14).

The *OFS* had the lowest emission cost with a significant margin compared to the other fertilizing systems in terms of emission cost. Therefore, applying the *OFS* to the *COFS* will reduce the emission cost by approximately 0.0011 USD kg^{-1} (62.63%), and shifting the *CFS* to the *OFS* can potentially reduce the production cost by 0.0042 USD kg^{-1} (86.29%). *OFS* is also dominantly providing the highest revenue and net profit performance. The results revealed that although the *OFS* generates a lower production capacity than the *COFS*, the *OFS* provides the highest profit for the farmer due to the higher selling price and lower production cost compared with the other systems. For example, a farmer earned 21,571 USD after managing a 1 ha coffee plantation as well as 0.49 USD earned from 1 kg of coffee cherry bean production. For comparison, managing a 1 ha coffee plantation nurtured by the *COFS* generated 20,330 USD; the *CFS* provided the lowest profit of 6720 USD ha^{-1}, which is approximately 31.1% of the total profit in a hectare of the *OFS*. Therefore, according to the net profit result, the *OFS* is more profitable than the other systems. However, the current situation in farmers, is that the higher productivity resulting from *COFS* has attracted farmers to manage their plantations by practicing its system. Fortunately, this result finds essential information for other farmers that managing coffee using the intensive *OFS* will attain a higher economic benefit.

3.4. Sustainability Interpretation

Table 7 presents the three of sustainability assessment: Environmental-Economic-Energy aspect. *OFS* provided better performance in environmental and economic aspects. The *OFS* had the lowest environmental impact in eight environmental indicators compared to the *CFS*. Simultaneously, in economic benefit, 1 kg of organic coffee cherry beans generated the highest net profit at 0.49 USD kg^{-1}. In energy aspect, *COFS* provided the high performance that consumed the lowest energy compared to *OFS* and *CFS*. Even though *OFS* requires more energy than the *COFS*, but still less than the *CFS*. The following table summarizes all the results of the sustainability assessment in this study.

Table 7. Results of the sustainability assessment.

Category	Indicators	Unit	Fertilizing System		
			Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
Environmental Impact	GWP	kg CO_2 eq kg^{-1}	0.068 Lowest (++)	0.182 Modest (+−)	0.496 Highest (−−)
	TA	kg SO_2 eq kg^{-1}	0.0005 Lowest (++)	0.001 Modest (+−)	0.0025 Highest (−−)
	FE	kg P eq kg^{-1}	0.000005 Lowest (++)	0.000008 Modest (+−)	0.000023 Highest (−−)
	Mec	kg N eq kg^{-1}	0.00006 Modest (+−)	0.00005 Lowest (++)	0.00012 Highest (−−)
	TEc	kg 1,4-DCB kg^{-1}	0.056 Lowest (++)	0.066 Modest (+−)	0.182 Highest (−−)
	Fec	kg 1,4-DCB kg^{-1}	0.0031 Modest (+−)	0.0028 Lowest (++)	0.0068 Highest (−−)
	MEc	kg 1,4-DCB kg^{-1}	0.00096 Lowest (++)	0.00098 Modest (+−)	0.0026 Highest (−−)
	HCT	kg 1,4-DCB kg^{-1}	0.00008 Lowest (++)	0.00015 Modest (+−)	0.00057 Highest (−−)
	HnCT	kg 1,4-DCB kg^{-1}	0.038 Modest (+−)	0.034 Lowest (++)	0.08 Highest (−−)
	MRS	kg 1,4-DCB kg^{-1}	0.00004 Lowest (++)	0.0015 Modest (+−)	0.0047 Highest (−−)
	FRS	kg 1,4-DCB kg^{-1}	0.0139 Lowest (++)	0.043 Modest (+−)	0.1178 Highest (−−)
Economic benefit	Net profit	USD kg^{-1}	0.49 Highest (++)	0.41 Modest (+−)	0.31 Lowest (−−)
Energy Requirement	Total energy	MJ kg^{-1}	7.92 Modest (+−)	6.19 Lowest (++)	10.35 Highest (−−)

Considering the three aspects of sustainability, *OFS* provided superior performance in two sustainability aspects as indicated by the lowest environmental impact and the highest economic benefit. Therefore, it indicated that *OFS* is more environmentally sustainable and economically viable.

4. Discussion

4.1. Energy, Environment, and Economic Hotspots and Its Strategies on Reducing the Negative Impact Factor

Identifying the hotspots in energy, environmental, and economic aspects will provide proper insights and strategies to effectively reduce energy usage, environmental damage, and production expenses. For example, the inputs of fertilizer, water, rice husk, and labor required higher energy during the coffee plantation. In particular, considering the fertilizer input, manure needs the highest energy in the *OFS* and *COFS*, whereas the NPK predominantly uses the energy in the *CFS*. Thus, our results highlight that fertilizer is a hotspot in terms of the energy requirements of the life cycle of coffee plantations. A similar study also revealed the most significant amount of energy contributed by fertilizer at 32–38% [52]. Therefore, Reducing the chemical input and managing the fertilizer can potentially reduce the energy used.

In environmental impact results, NPK most contributed to the environmental damage in *COFS* and *CFS*. At the same time, rice husk contributes significantly to the environmental impact in the *OFS*. These findings indicated that chemical fertilizer is the hotspot contributing to the environmental damage during coffee production. A similar study in agriculture commodity also reported that fertilizer mainly contributed to the environmental damage [34,52]. Therefore, some strategies can significantly reduce the environmental impact, such as reducing the NPK application, switching the chemical substances into organic ones, and substituting the rice husk with a more environmentally friendly material.

According to the net profit result, our economic analysis identified that *OFS* is more profitable than the other systems. In production cost, labor and fertilizer usage were the hotspots of production cost. In particular, approximately 60.7–75.88% of the labor cost is used for the harvesting activity. Manure predominantly accounted for 22.6% and 11.36% of the fertilizer cost in the *OFS* and *COFS*, respectively. Simultaneously, NPK accounted for 21.61% of the fertilizer cost in the *CFS*. Therefore, the following scenarios can predictively reduce the production cost: (1) reducing the labor during harvesting using appropriate technology and tools; and (2) reducing the NPK application in the *COFS* and *CFS*, and substituting it with the *OFS*.

4.2. Future Challenges of the Green Coffee Plantation System

Developing the green industry from the upstream to downstream in the agricultural sector is essential for promoting sustainable agriculture [27]. Thus, the business framework warrants a transformation [22]. To adopt the most environmentally and economically viable approach, coffee production must be evaluated and improved. This study suggests that practicing the *OFS* should be extended to sustainable coffee production in Indonesia. However, there are several challenges in implementing such green coffee plantation systems. First, most coffee farmers employed conventional practices using a large amount of chemical fertilizer and still depended on labor for all activities [13,20]. Second, most farmers practiced a low-intensity coffee management system. However, only a few farmers practiced intensive coffee plantation systems. Low maintenance in managing the plantations will inevitably result in low productivity. Lower productivity resulted in more serious environmental damage and had lower economic performance per 1 ha of coffee plantation. Third, although this research recommends that the *OFS* be extensively applied, the higher energy requirements for providing manure are an important challenge. Therefore, research should be conducted to determine the optimum sustainable coffee plantation management system, considering the energy requirement, environmental impact, and economic performance.

5. Conclusions

The comprehensive sustainability evaluation of coffee production systems in Indonesia was conducted considering three sustainability aspects: energy requirement, environmental impact, and economic performance. From the energy perspective, managing 1 kg of coffee cherry bean using *CFS* is not recommended due to its higher energy requirements. Conversely, *COFS* and *OFS* were recommended because of the lower energy consumption. Our results highlight that fertilizer is a hotspot in terms of the energy requirements of the life cycle of coffee plantations. From an environmental perspective, the *OFS* is recommended for managing coffee plantations. The *OFS* provides the lowest environmental impact compared to those managed by the *COFS* and *CFS*. Due to the lower environmental impact provided by the *OFS*, the potential reduction of emissions was also a significant result. Chemical fertilizer was identified as the most significant contributing factor to all emissions in the *COFS* and *CFS* and followed by the rice husk. Therefore, our result findings that NPK and rice husk are the hotspot contributing to the environmental damage during coffee production. From the economic perspective, managing 1 ha of coffee plantations nurtured by the *OFS* generated the highest revenue and net profit for farmers compared with those of the *COFS* and *CFS*. In terms of energy perspective, the *COFS* and *OFS* are recommended due to the lower energy consumption compared to *CFS*. Considering the environmental impact and economic analysis results, the *OFS* is recommended due to its lower impact on environmental damage and the highest net profit for farmers. The massive *OFS* practice will be followed by higher energy consumption. From an energy requirement perspective, *COFS* can be the second alternative to be applied.

This study result provided a positive implication and valuable information related to managing organic coffee cultivation (*OFS*) as suggested by this result. As *OFS* provided more benefit not only for the environmental but also to the higher economic benefit, farmers are becoming more attracted to practicing *OFS* which represents green coffee cultivation. As the majority of farmers are still applying *COFS* with a significant level of chemical substances, shifting to the *OFS* will significantly impact the environmental and economic sustainability of coffee production in Indonesia. Practically, this research contributed a practical method of how to reduce environmental impact through the hotspots in environmental, economic, ad energy impacts that are found in this research. The hotspots of emission, cost, and energy will help farmers reduce the negative impact on environmental, economic, and energy aspects. This research also contributes to the academic purposes of providing scientific literature to fulfill the research gap and limited information related to comprehensive sustainability assessment in Indonesia.

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Abbreviations

COFS	Chemical-Organic fertilizing system	kg	Kilogram
CFS	Chemical fertilizing system	LCA	Life cycle assessment
d	day	LCC	Life cycle costing
DCB	Dichlorobenzene	ME	Marine eutrophication
EF	Energy factor	MEc	Marine ecotoxicity
EI	Environmental impact	MRS	Mineral resource scarcity
FE	Freshwater eutrophication	*n*	Number of input system
FEc	Freshwater ecotoxicity	*OFS*	Organic fertilizing system
FRS	Fossil resource scarcity	TA	Terrestrial acidification
GWP	Global warming potential	TE	Terrestrial ecotoxicity
h	hour	TLCC	Total life cycle cost
HCT	Human carcinogenic toxicity	USD	United States Dollar
HnCT	Human non-carcinogenic toxicity	y	year
IDR	Indonesia Rupiah		

Appendix A

Table A1. Energy requirement for 1 kg coffee cherry bean production.

Input Energy	Fertilizing System		
	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
	Energy Requirement (MJ kg^{-1})		
	Direct energy		
Gasoline	0.34	0.29	0.6
Electricity	0.0031	0.0027	0.006
	Indirect energy		
Poultry manure	5.47	2.35	0.3
Compost	0.16	0.16	0.35
Liquid organic fertilizer	0.003	0.003	0.006
Rice husk	0.43	0.38	0.86
Water	1.1	0.97	2.2
NPK	-	1.64	4.97
Pesticide	-	0.044	0.455
Human Labor	0.39	0.36	0.57
Total	7.92	6.19	10.35

Table A2. Environmental impact for 1 kg of coffee cherry bean.

Impact Category	Unit	Fertilizing System		
		Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
Global warming potential (GWP)	kg CO_2 eq kg^{-1}	0.0678	0.182	0.496
Terrestrial acidification (TA)	kg SO_2 eq kg^{-1}	0.0005	0.00096	0.00254
Freshwater eutrophication (FE)	kg P eq kg^{-1}	0.0000049	0.000008	0.000023
Marine eutrophication (ME)	kg N eq kg^{-1}	0.000059	0.000053	0.00012
Terrestrial ecotoxicity (TEc)	kg 1,4-DCB kg^{-1}	0.0564	0.0655	0.1819
Freshwater ecotoxicity (FEc)	kg 1,4-DCB kg^{-1}	0.0031	0.0028	0.00678
Marine ecotoxicity (MEc)	kg 1,4-DCB kg^{-1}	0.00096	0.00098	0.0026
Human carcinogenic toxicity (HCT)	kg 1,4-DCB kg^{-1}	0.000085	0.00015	0.00056
Human non-carcinogenic toxicity (HnCT)	kg 1,4-DCB kg^{-1}	0.0378	0.0345	0.0804
Mineral resource scarcity (MRS)	kg Cu eq kg^{-1}	0.000039	0.00149	0.0046
Fossil resource scarcity (FRS)	kg oil eq kg^{-1}	0.014	0.043	0.118

Table A3. Working hour on managing 1 ha of Organic fertilizing system (*OFS*).

Activities	Detail Activities	Working Days (d)	Working Hour per Day (h)	Total Labor (Person)	Subtotal (h y^{-1})	Total Working Hour (h)	Contribution Percentage (%)
Seeding	Preparation	2	8	2	32	32	0.47
	Maintenance	42	1	2	84	84	1.23
Nursery	Preparation	5	8	2	80	80	1.18
	Maintenance	240	1	1	240	240	3.53
Planting	Planting	30	8	2	480	480	7.05
Subtotal at 1st year					916	916	13.46
Maintenance in pre-productive stage	Clearing	6	8	2	96	192	2.82
	Pruning	1	8	2	16	32	0.47
	Fertilizing	3	8	2	48	96	1.41
Subtotal 2nd–3rd year					160	320	4.70
Maintenance in productive stage and harvesting	Clearing	6	8	2	96	576	8.47
	Pruning	1	8	2	16	96	1.41
	Fertilizing	3	8	2	48	288	4.23
	Harvesting	24	4	8	768	4608	67.72
Subtotal at the 4–9th year					928	5568	81.83
Total working hour						6804	100

Table A4. Working hour on managing 1 ha of Chemical-Organic fertilizing system (*COFS*).

Activities	Detail Activities	Working Days (d)	Working Hour per Day (h)	Total Labor (Person)	Sub Total (h y^{-1})	Total Hour (h)	Contribution Percentage (%)
Seeding	Preparation	2	8	2	32	32	0.47
	Maintenance	42	1	2	84	84	1.22
Nursery	Preparation	5	8	2	80	80	1.16
	Maintenance	240	1	1	240	240	3.49
Planting	Planting	30	8	2	480	480	6.99
Subtotal at the 1st year					916	916	13.34
Maintenance in pre-productive stage	Clearing	1	8	2	16	32	0.47
	Pruning	1	8	2	16	32	0.47
	Fertilizing	4	8	2	64	128	1.86
Subtotal at the 2nd–3rd year					96	192	2.8
Maintenance in productive stage and harvesting	Clearing	1	8	2	16	96	1.4
	Pruning	1	8	2	16	96	1.4
	Fertilizing	4	8	2	64	384	5.59
	harvesting	24	4	9	864	5184	75.48
Subtotal 4–9th					960	5760	83.87
Total working hour						6868	100

Table A5. Working hour on managing 1 ha of Chemical fertilizing system (*CFS*).

Activities	Detail Activities	Working Days (d)	Working Hour per Day (h)	Total Labor (Person)	Sub Total (h y^{-1})	Total Hour (h)	Contribution Percentage (%)
Seeding	Preparation	2	8	2	32	32	0.84
	Maintenance	42	1	2	84	84	2.21
Nursery	Preparation	5	8	2	80	80	2.11
	Maintenance	240	1	1	240	240	6.32
Planting	Planting	30	8	2	480	480	12.64
Subtotal at the 1st year					916	916	24.13
Maintenance in pre-productive stage	Clearing	1	8	2	16	32	0.84
	Pruning	1	8	2	16	32	0.84
	Fertilizing	4	8	2	64	128	3.37
Subtotal at the 2nd–3rd year					96	192	5.06
Maintenance in productive stage and harvesting	Clearing	1	8	2	16	96	2.53
	Pruning	1	8	2	16	96	2.53
	Fertilizing	2	8	2	32	192	5.06
	Harvesting	24	4	4	384	2304	60.7
Subtotal at the 4–9th year					448	2688	70.81
Total working hour						3796	100

Table A6. Environmental impact contributor factor in Organic fertilizing system (*OFS*).

Impact Category	Unit ($\times 10^{-6}$)	Liquid Organic Fertilizer	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	kg CO_2 eq	130.11	8328.0	14,280	1,290	43,071	299.92
TA	kg SO_2 eq	0.89	31.99	65.87	7.08	387.10	1.04
FE	kg P eq	0.02	-	-	0.19	4.24	0.47
ME	kg N eq	0.14	0.04	0.07	1.08	58.02	0.03
TEc	kg 1,4-DCB	223.21	149.31	252.90	3598	51,293	369.36
FEc	kg 1,4-DCB	3.48	45.41	76.91	42.14	2880.05	20.68
MEc	kg 1,4-DCB	4.29	61.19	103.64	50.78	704.53	27.11
HCT	kg 1,4-DCB	2.02	6.31	10.68	21.98	19.40	23.88
HnCT	kg 1,4-DCB	60.83	2447	4145	1328	28,977	509.04
MRS	kg Cu eq	0.36	-	-	24.90	14.09	0.16
FRS	kg oil eq	9.17	2736.9	4635.8	125.7	6256.3	76.46

Table A7. Environmental impact contributor factor in Chemical-Organic fertilizing system (*COFS*).

Impact Category	Unit ($\times 10^{-6}$)	NPK	Liquid Organic Fertilizer	Pesticide	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	kg CO_2 eq	125,102	114.89	1694	4092	10,915	1146	38,260	264.05
TA	kg SO_2 eq	528.26	0.78	12.74	15.72	50.35	6.29	343.85	0.92
FE	kg P eq	2.72	0.02	0.91	-	-	0.16	3.77	0.41
ME	kg N eq	0.13	0.12	0.51	0.02	0.06	0.96	51.53	0.03
TEc	kg 1,4-DCB	7999	197.10	7965	73.36	193.32	3196	45,563	325.18
FEc	kg 1,4-DCB	2.93	3.07	130.96	22.31	58.79	37.43	2558	18.20
MEc	kg 1,4-DCB	29.54	3.79	144.59	30.06	79.22	45.11	625.82	23.87
HCT	kg 1,4-DCB	16.19	1.78	65.07	3.10	8.17	19.52	17.23	21.02
HnCT	kg 1,4-DCB	506.23	53.71	2188	1202	3168	1179	25,740	448.16
MRS	kg Cu eq	1412	0.32	52.50	-	-	22.12	12.51	0.14
FRS	kg oil eq	31,746	8.10	578.41	1345	3544	111.66	5557	67.32

Table A8. Environmental impact contributor factor in Chemical-Organic fertilizing system (*COFS*).

Impact Category	Unit ($\times 10^{-6}$)	NPK	Liquid Organic Fertilizer	Pesticide	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	kg CO_2 eq	381,541	261.04	9627	9299	5368	2602	86,886	599.61
TA	kg SO_2 eq	1611	1.78	72.37	35.72	24.76	14.29	780.87	2.09
FE	kg P eq	8.30	0.05	5.19	-	-	0.37	8.56	0.94
ME	kg N eq	0.39	0.28	2.88	0.05	0.03	2.17	117.03	0.06
TEc	kg 1,4-DCB	24,394	447.83	45,255	166.72	95.07	7257	103,472	738.43
FEc	kg 1,4-DCB	8.93	6.98	744.08	50.70	28.91	85.01	5810	41.34
MEc	kg 1,4-DCB	90.08	8.61	821.56	68.32	38.96	102.43	1421	54.20
HCT	kg 1,4-DCB	49.38	4.05	369.72	7.04	4.02	44.34	39.13	47.74
HnCT	kg 1,4-DCB	1544	122.04	12,430	2732	1558	2678	58,455	1018
MRS	kg Cu eq	4306	0.73	298.27	-	-	50.23	28.42	0.33
FRS	kg oil eq	96,821	18.40	3286	3056	1743	253.58	12,621	152.86

Table A9. Environmental impact contributor factor in Chemical-Organic fertilizing system (*COFS*).

Impact Category	Liquid Organic Fertilizer	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	0.19	12.6	21.19	1.91	63.90	0.44
TA	0.18	6.48	13.33	1.43	78.37	0.21
FE	0.48	-	-	3.77	86.19	9.56
ME	0.23	0.07	0.12	1.81	97.71	0.05
TEc	0.40	0.27	0.45	6.44	91.78	0.66
FEc	0.11	1.48	2.51	1.37	93.85	0.67
MEc	0.45	6.43	10.9	5.34	74.04	2.85
HCT	2.39	7.48	12.7	26.1	23.02	28.3
HnCT	0.16	6.53	11.1	3.54	77.34	1.36
MRS	0.92	-	-	63.0	35.65	0.42
FRS	0.07	19.7	33.5	0.91	45.20	0.55

Table A10. Percentage of contribution factor in Chemical-Organic fertilizing system (*COFS*) (%).

Impact Category	NPK	Liquid Organic Fertilizer	Pesticide	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	68.89	0.06	0.93	2.25	6.01	0.63	21.07	0.15
TA	55.09	0.08	1.33	1.64	5.25	0.66	35.86	0.10
FE	34.00	0.26	11.40	-	-	2.06	47.09	5.18
ME	0.24	0.23	0.95	0.04	0.10	1.79	96.60	0.05
TEc	12.21	0.30	12.16	0.11	0.30	4.88	69.55	0.50
FEc	0.10	0.11	4.62	0.79	2.08	1.32	90.34	0.64
MEc	3.01	0.39	14.72	3.06	8.07	4.59	63.73	2.43
HCT	10.65	1.17	42.79	2.04	5.37	12.84	11.33	13.82
HnCT	1.47	0.16	6.34	3.49	9.19	3.42	74.64	1.30
MRS	94.16	0.02	3.50	-	-	1.48	0.83	0.01
FRS	73.90	0.02	1.35	3.13	8.25	0.26	12.94	0.16

Table A11. Percentage of contribution factor in Chemical fertilizing system (*CFS*) (%).

Impact Category	NPK	Liquid Organic Fertilizer	Pesticide	Labor Transport	Material Transport	Compost	Rice Husk	Electricity
GWP	76.89	0.053	1.94	1.87	1.08	0.52	17.51	0.12
TA	63.35	-	2.85	1.405	0.97	0.56	30.7	0.08
FE	35.45	0.2	22.15	-	-	1.59	36.56	4.02
ME	0.32	0.225	2.34	0.039	0.02	1.76	95.23	0.047
TEc	13.41	0.24	24.89	0.09	0.05	3.99	56.9	0.4
FEc	0.13	0.1	10.98	0.75	0.43	1.25	85.74	0.61
MEc	3.45	0.33	31.53	2.62	1.49	3.93	54.55	2.08
HCT	8.73	0.71	65.39	1.246	0.71	7.84	6.92	8.44
HnCT	1.91	0.15	15.43	3.39	1.93	3.32	72.58	1.26
MRS	91.93	0.015	6.37	-	-	1.07	0.607	0.007
FRS	82.08	0.016	2.78	2.59	1.47	0.21	10.7	0.13

Table A12. Potential increase or decrease of applying the Organic fertilizing system (*OFS*).

Impact Category	Unit	Potential Decrease or Increase			Percentage Decrease or Increase (%)		
		OFS vs. *CFS*	*OFS* vs. *CFS*	*COFS* vs. *CFS*	*OFS* vs. *COFS*	*OFS* vs. *COFS*	*COFS* vs. *CFS*
GWP	kg CO_2 eq	−0.114	−0.428	−0.314	−62.6	−86.3	−63.4
TA	kg SO_2 eq	−0.00046	−0.00204	−0.00158	−48.1	−80.4	−62.3
FE	kg P eq	−3.1E-06	−0.000018	−0.000015	−38.8	−78.7	−65.2
ME	kg N eq	0.000006	−0.000064	−0.00007	11.3	−52	−56.9
TEc	kg 1,4-DCB	−0.009	−0.126	−0.116	−13.9	−69	−64
FEc	kg 1,4-DCB	0.0003	−0.0037	−0.0039	9.3	−54.3	−58.2
MEc	kg 1,4-DCB	−0.00002	−0.00164	−0.00162	−2.4	−63.2	−62.3
HCT	kg 1,4-DCB	−0.000067	−0.00048	−0.00041	−44.4	−85	−73.1
HnCT	kg 1,4-DCB	0.0033	−0.0427	−0.046	9.5	−53.1	−57.1
MRS	kg Cu eq	−0.0015	−0.0046	−0.0032	−97.4	−99.2	−68
FRS	kg oil eq	−0.029	−0.104	−0.075	−67.6	−88.2	−63.5

According to Table A12, the minus value indicates the shifting from organic fertilizing system to chemical fertilizing system will decrease its environment impact; and the positive value indicates the shifting from organic fertilizing system to chemical fertilizing system will increase its environment impact. The potential decrease or increase and its percentage were obtained using the Equations (A1)–(A3):

$$\%\ decrease\ or\ increase\ OFS\ vs.\ COFS = \frac{potential\ reduction\ OFS\ vs.\ COFS}{impact\ in\ COFS} \times 100\% \quad (A1)$$

$$\%\ decrease\ or\ increase\ OFS\ vs.\ CFS = \frac{potential\ reduction\ OFS\ vs.CFS}{impact\ in\ CFS} \times 100\% \quad (A2)$$

$$\%\ decrease\ or\ increase\ COFS\ vs.\ CFS = \frac{potential\ reduction\ COFS\ vs.CFS}{impact\ in\ CFS} \times 100\% \quad (A3)$$

Table A13. Production cost per 1 ha coffee plantation (USD).

Item of Cost	Fertilizing System		
	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
	Fixed cost		
Equipment	17.35	17.35	17.35
Device maintenance	249.85	249.85	249.85
	Variable cost		
Human labor cost	4577.79	4638.87	2517.92
NPK	-	990.64	1329
Rent transportation	1811.41	1894.69	1728.12
Compost	180.45	180.45	180.45
Manure	2025.44	1031.60	54.41
Polybag	19.09	19.09	19.09
Rice Husk	45.11	45.11	45.11
Seed	10.41	10.41	10.41
Pesticide	-	6.25	24.98
Total cost	8936.90	9084.31	6176.69

Table A14. Production cost per 1 kg coffee cherry bean (USD kg^{-1}) and its percentage (%).

Item of Cost	Cost per kg (USD)			Percentage (%)		
	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
Fixed cost						
Equipment	0.0004	0.0003	0.0008	0.19	0.19	0.28
Device maintenance	0.006	0.005	0.011	2.8	2.75	4.05
Variable cost						
Labor	0.104	0.093	0.114	51.22	51.06	40.76
NPK	-	0.02	0.06	-	10.9	21.52
Transportation	0.04	0.04	0.08	20.27	20.86	27.98
Compost	0.004	0.004	0.008	2.02	1.99	2.92
Manure	0.046	0.021	0.002	22.66	11.36	0.88
Polybag	0.0004	0.0004	0.001	0.21	0.21	0.31
Rice Husk	0.001	0.001	0.002	0.5	0.5	0.73
Seed	0.0002	0.0002	0.0005	0.12	0.11	0.17
Pesticide	-	0.0001	0.0011	0	0.07	0.4
Total cost	0.203	0.182	0.28	100	100	100

The Production cost per kilogram coffee cherry bean is obtained by Equations (A4) and (A5).

$$Production\ cost\ per\ kg = \frac{cost\ per\ hectar}{coffee\ production\ per\ hectar} \times 100 \quad (A4)$$

$$Cost\ percentage\ per\ item\ input = \frac{cost\ per\ item\ input}{total\ life\ cycle\ cost} \times 100 \quad (A5)$$

Table A15. Emission cost.

Fertilizing Systems	Coffee Cherry Bean Production (kg)	Emission per Kilogram Coffee Cherry Bean (kg CO_2 eq kg^{-1})	Emission Tax (USD t^{-1})	Total Emission (USD ha^{-1})
Organic (*OFS*)	44,000	0.068	9.7	29.07
Chemical-Organic (*COFS*)	50,000	0.182	9.7	88.42
Chemical (*CFS*)	22,000	0.496	9.7	106.03

Table A16. Revenue and Net profit.

Fertilizing Systems	Coffee Cherry Bean Production (kg ha^{-1})	Selling Price (USD kg^{-1})	Revenue (USD ha^{-1})	Net Profit (USD ha^{-1})
Organic (*OFS*)	44,000	0.69	30,537	21,571
Chemical-Organic (*COFS*)	50,000	0.59	29,496	20,323
Chemical (*CFS*)	22,000	0.59	12,978	6695

Table A17. Percentage contribution of life cycle cost.

Item of Cost	Fertilizing System		
	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
	Percentage (%)		
Fixed cost			
Equipment	0.19	0.19	0.28
Device maintenance	2.8	2.75	4.05
Variable cost			
Human labor cost	51.22	51.06	40.76
Fertilizer (NPK)	-	10.9	21.52
Rent transportation	20.27	20.86	27.98
Compost	2.02	1.99	2.92
Manure	22.66	11.36	0.88
Polybag	0.21	0.21	0.31
Rice Husk	0.5	0.5	0.73
Seed	0.12	0.11	0.17
Pesticide	-	0.07	0.4
Total	100	100	100

The percentage cost is calculated using the Equation (A6).

$$Cost\ percentage\ per\ item\ input \tag{A6}$$

Table A18. Cumulative energy requirement per 1 ha coffee plantation.

Input Energy	Fertilizing System		
	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
	Energy Requirement ($\times 10^3$ MJ ha^{-1})		
Direct energy			
Electricity	0.13	0.13	0.13
Gasoline	15.14	14.32	13.22
Direct energy			
Poultry manure	240.77	117.48	6.6
Compost	7.8	7.8	7.8
Liquid organic fertilizer	0.14	0.14	0.14
Rice husk	18.98	18.98	18.98
Water	48.42	48.42	48.42
NPK	-	81.91	109.92
Pesticide	-	2.22	10.01
HUman labor	12.93	13.1	7.11
Total	344.31	304.51	222.34

Table A19. Energy requirement per stage of coffee plantation.

Stage	Fertilizing System		
	Organic (*OFS*)	Chemical-Organic (*COFS*)	Chemical (*CFS*)
	Energy per Hectare ($\times 10^3$ MJ ha^{-1})		
Seeding	2.92	2.92	2.92
Nursery	76.95	77.03	77.11
Planting	5.68	5.68	5.68
Maintenance 1	54.32	49.41	27.44
Maintenance 2	185.92	149.76	94.97
Harvesting	18.53	19.71	14.22
Total	344.31	304.51	222.34

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Article

Short-Term Speculation Effects on Agricultural Commodity Returns and Volatility in the European Market Prior to and during the Pandemic

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Abstract: Motivated by increased agricultural commodity price volatility and surges during the past decade, we investigated whether financial speculation is to blame. The aim of this paper is to build on prior research about to what extent and in which ways financial speculation undermines agricultural commodity prices. In our analysis, we utilized the daily returns on milling wheat, corn, and soybean futures from the Euronext Commodities Paris market (MATIF) as well as the short-term speculation index. To quantify this impact, we apply Granger noncausality tests as well as the GARCH (generalized autoregressive conditional heteroskedasticity) technique. We also propose a model using seasonal dummy variables to examine whether financial speculation has a greater impact on price volatility during more volatile months. According to our results, financial speculation, as an external factor, in most cases has no effect or reduces the volatility of the underlying futures prices. The opposite is observed in the corn market, where volatility has risen in the post-2020 period and has been pushed up even more by speculation in April. However, since the influence on other commodities is limited or nonexistent, more emphasis should be focused on speculation in the European corn futures market or its interdependence with energy markets.

Keywords: short-term speculation; agricultural commodity futures; return volatility; commodity futures markets

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1. Introduction

Speculative activity is common among many markets, especially those where transactional costs are minimal and goods traded are standardized and liquid, such as financial markets, including agricultural futures markets. Futures contracts are standardized agreements between two parties to acquire or sell a standardized asset of a certain quantity and quality at a fixed price at a future date. Agricultural commodity producers and consumers, also known as "commercial market participants," employ them to protect themselves against price movements and volatility. Typically, there is a different amount of demand to hedge against increasing or decreasing prices. This results in a difference between commercial long and commercial short positions, and therefore creates risk premium opportunities, also known as hedging pressure, because commercial hedgers are frequently net short [1]. Futures market speculators seek to earn these risk premiums. In other words, they take over this price risk in exchange for earning profits. Speculators can also correct price drifts from their fundamental values, as explained by supply and demand factors. For example, according to Du and Dong [2], who investigated US dairy futures markets, the volatility of both price and trade volume can be explained by flows of new market information. Consequently, it may be argued that some speculative activity is both common and necessary in these markets to make them more efficient and liquid. However, the number of speculators in major international commodity markets has increased considerably in the last two decades because of the market liberalization and financialization of many agricultural commodities, as well as the ability to make cash settlements. However, in some cases, speculative activity can get out of hand when the number of positions held by speculators exceeds the number of positions held by commercial long and short positions. In many cases, even traditional commercial participants engage in speculative activities [3].

Traditional economic theories that investigate the role and impact of speculation on the price of assets on markets are effective market theories and behavioral finance. Even though speculators bring liquidity and new information, they have, on the other hand, different objectives than typical business users seeking to protect themselves from price risk, and their behavior patterns may result in commodity prices that are not representative of their genuine worth, therefore creating opportunities for price booms and spikes. Recent empirical work on commodity futures has extensively explored futures market volatility and what factors cause it. The cost-of-storage model, which examines inventory quantities, interest rates, and desired profitability to explain price volatility and differences between spot and futures prices, is often used to investigate speculators' participation in futures markets [4]. In many studies, it is found that speculation in derivatives markets has no or limited statistically significant effect on price or return volatility and instead benefits the stability of these markets [5,6]. Several methodological approaches are used to study the influence of speculation on commodity prices. Granger causality tests and price volatility models (such as the GARCH, stochastic volatility modeling, and others) are used to see if speculation measured by trade volume, commercial-to-noncommercial ratios, or other indicators causes commodity prices or volatility. Researchers are also investigating if speculative comovement across markets is related to product and asset links [7,8]. Speculation in the energy market could lead to price spikes and other problems in the grain market because it takes a lot of fuel to make grain.

Typically, less liquid markets, such as livestock products or cotton, have a larger and more statistically significant impact from short-term speculation on return volatility [9]. In addition, Bohl et al. [10] observed a short-term speculation impact on return volatility on rapeseed oil, cotton, sugar, and corn traded on Chinese markets. It can be argued that the inclusion of more speculative indicators and more frequent data can better explain prices. Speculation and its price-distorting effects may be especially common in products heavily impacted by global energy prices and utilized as biofuel. This is particularly true when analyzing markets outside of the United States. For example, according to research conducted by Bandyopadhyay et al. [11], excessive futures market speculation in Indian commodity exchanges increases spot market volatility. Another thing that the results show is that too many short-term investors in the futures market could have a destabilizing impact on these markets.

However, there is less research on European commodity markets that are smaller in size and less liquid or transparent compared to US markets. European agriculture commodity markets, such as the Paris exchange MATIF (Paris, France) and the London exchange LIFFE (London, UK), trade mainly in rapeseed, corn, and milling wheat. Prices in these markets are heavily influenced by commodity prices in the main US markets, but they also attract speculative activity, which may distort pricing during economic turmoil. In their research on products traded on the Paris exchange MATIF, Statnik and Verstraete [12] argue that exogenous factors influence the behavior of agricultural product prices, as reference markets, market depth, and market regulation may all have an impact on market behavior, pointing out short-term memory effects in return volatility. Other, older studies, such as one conducted by Busse et al. [13], argue that the increased European rapeseed price is influenced by speculation, characterized by market over-reactions and high volatilities, and increased correlation with crude oil. On the other hand, more recent studies focus more on structural changes in these markets when trading activity has grown dramatically. Price-shock amplification (period-to-period shock transmission) increased in the Paris and London wheat futures markets after 2006 as trade volume increased [6]. Authors argue that noncommercial positions have been found to stabilize the market during stressful periods. When investigating the London wheat market, Dawson [14] points out a structural change in these markets as the increase in volatility since June 2007 appears not to be short-lived. Futures prices significantly determine volatility, and volatility is stable and highly persistent. Other studies on the European grain futures market focus on relationships between commodities and other financial markets. For example, Makkonen et al. [15] observed that the stock market interacts more with the rapeseed futures market during extreme conditions; moreover, when the economy recovers and the rapeseed market is strong, investors' positive expectations raise the returns even further. According to Zuppiroli and Revoredo–Giha [16], the US wheat market outperforms European wheat markets in terms of short-term hedging against price movements, making smaller markets more vulnerable to speculative activity and other distortions. This is particularly significant considering the current pandemic-outbreak-caused economic shock.

In the scholarly literature, the influence of the pandemic on agricultural markets has been extensively studied. It has an impact on economic performance, sustainability, and development processes in general [17]. More specifically, health crises such as these have a detrimental impact on the global economy, globalization, food and job security, supply chains, or even food fraud [18]. Stricter government rules and lockdowns, for example, raise concerns about food security as a health and economic well-being problem [19]. Changes in consumer buying behavior, transportation network disruptions, workforce absenteeism, and the closure of major food production businesses have all posed challenges to the food supply chain. [18]. Authors Falkendal et al. [20] point out that production losses have only a modest influence on worldwide pricing and supplies; but trade restrictions and precautionary purchases by a few important players might result in global food price increases and catastrophic local food shortages. Consumer purchase behavior shifted as well and was influenced by income impacts, the opportunity cost of time, and longer planning horizons during the COVID-19 pandemic [18]. According to Coyne [21], negative externalities are caused by infectious illnesses. Market pricing will not represent the social cost of individual activity if these externalities exist, and as a result, market imbalances are probable. Most recent studies on commodity markets during the pandemic period highlight increases in cross-correlations between commodities and increases in hedging and speculative pressures [22,23].

The current COVID-19 situation has had a significant detrimental impact on the European economy in general. In the first quarter of 2020, almost all EU nations saw a drop in exports compared to the previous year [24]. Furthermore, since Western Europe's agricultural sector is primarily reliant on Eastern European seasonal laborers who work for low rates, the epidemic is driving companies to consider whether this is a sustainable model and if they should instead seek local people [25]. Negative impacts were seen across the board in the agricultural commodities trade, although industries and sectors were affected differently according to their size and kind of product [18]. For example, some farmers who produce particular items (such as grapes and flowers) destroy their unsold supply due to market access issues [26]. As a result, one of the long-term consequences of any crisis is predicted to be a reduction in farmers' income. COVID-19 also has an influence on how farmers behave. As a result of the drop in agricultural revenue, farmers lowered their crop-related costs [26]. Greater opportunities to hedge against price risks in financial markets may have resulted in better options for dealing with falling prices and income instability.

The COVID-19 pandemic was a shock to present agricultural production and distribution systems, food security, and unemployment rates because of company limitations, and it also resulted in economic instability because of business restrictions [26]. Demand, production, and overall economic activity must be increased to avoid economic stagnation. Therefore, fiscal and monetary policies implemented stimulus packages and announced emergency assistance that were unprecedented in scope and volume, both at the national and European levels [25,27]. A drop in wheat production, together with export restrictions in Russian and Ukrainian wheat markets, is especially important to European agricultural markets. The world's wheat market is controlled by oligopolistic relationships, with eight nations accounting for 95.6 percent of global exports [28]. Grain prices, on the other hand, remained stable in 2020 due to relatively low energy costs. Researchers on European commodity markets such as Ahmed and Adjemian [29] claim that following 2015, wheat market leadership shifted from the United States to Europe, implying that the French (MATIF) futures market is the primary source of price discovery and therefore leads other markets [29]. Farmers, traders, and other market participants have begun to base their decisions and budgeting on European futures markets rather than US futures markets as a result of changes in the trade map, resulting in the United States losing market leadership in wheat to the former Soviet Union and EU countries [30]. Additional research also indicates that the global wheat market price discovery leadership has shifted from the United States to the French MATIF futures market [31].

To summarize, European markets are utilized in research on occasion, but they may be explored further by adding extra factors to better understand speculation and its influence on agricultural commodity prices or returns. To begin with, these studies lack concrete measures of speculation, such as short-term or long-term speculation indices and their influence on commodity returns. Second, unlike in energy or metal markets, the models provided do not account for seasonality, which is typical in agriculture markets. Finally, greater focus should be placed on the post-2020 era (the COVID-19 pandemic period) when comovement among different commodity types has risen and prices in major commodities markets have become more volatile. The COVID-19 pandemic, which is still ongoing, has had an unprecedentedly huge impact on the lives, societies, economies, and markets of the affected countries [32]. Therefore, the primary goal of this study is to strengthen the other authors' research into the impact of speculation on agricultural prices and return volatility. Using theoretical and empirical derivatives speculation theories, we study the influence of derivatives speculation on European commodity prices. We also emphasize that in the pandemic period, short-term speculation makes these prices even more volatile.

2. Materials and Methods

2.1. Methods

Besides descriptive statistics, we also employ the Granger noncausality test to study causal linkages between price and returns and speculation, as well as the Augmented Dickey–Fueller test for time series stationarity and the generalized autoregressive conditional heteroskedasticity approach (GARCH) to model price/return volatility. The dependent variable is the continuous futures price or, more specifically, the returns from these futures. We choose, as an independent variable, the short-term speculation index, which is derived as a ratio of total trade volume to open interest.

We begin by defining the variables used in our models. We use the natural log of futures prices to generate a price return series. In futures markets, price indices such as the lowest, highest, opening, and closing prices can be evaluated. We have decided to go with the closing price of the day. Returns on agricultural product futures are calculated using the logarithmic difference between the prices of futures contracts in periods t and $t-1$ (Formula (1)). This volatility metric is a logarithmic difference between the futures prices on the futures exchanges used in other authors' studies, as typically full-time price data is not stationary as compared to futures returns [33–35]. The dependent variable returns on the futures contract, represented by R_t, will be used for our research. To show returns as a percentage of change, we multiply them by 100:

$$R_t = \ln\left(\frac{P_t}{P_{t-1}}\right) * 100. \tag{1}$$

where: R_t is the return on agricultural futures, P_t is the futures price, t is the time, and ln is the natural logarithm.

TV/OI is a speculation index that measures short-term speculation (Formula (2)). The main advantage of this speculative index is that it is based on real-time data and is applicable to futures exchanges that do not disclose information on exposure structures, such as European commodity markets. Trade volume shows the intensity of speculative activity, whilst open positions reflect the total amount of hedging activity in commodity markets [10]. As Shear [35] claims, because speculators have a short trading horizon and trade daily, the volume of speculation influences the volume of daily trade. Because this ratio is simple and easy to use, it is often used to show speculative behavior in futures markets.

$$S_t = \frac{TV_t}{OI_t}. \tag{2}$$

where: S_t is the short-term speculation index, TV_t is the futures contract trade volume, OI_t is futures contract open interest, and t is the time.

Before we go over the details of our suggested model, it is necessary to assess the stationarity of time series. We then run a test to see if the time series for price, returns, and short-term speculation index TV/OI are stationary. A unit root test is used, both with and without a time trend. When evaluating time series, it is critical that their statistical features and distribution remain constant—especially regarding autocorrelation, mean, and variance. Stationary processes are those that have a constant mean and variation. When conducting causality tests, nonstatistical trends, which are commonly defined by time series in financial markets, may mislead statistical conclusions. To determine whether future variable time series are stationary, the Augmented Dickey–Fuller (ADF) test will be utilized. This approach includes a single-root test to see if time series have a single root that describes nonstationary processes and whether time series have a stochastic trend [36]. An autoregressive time series model (Formula (3)) is the foundation of the ADF test [37]. In this situation, the parameter φ should be equal to 0 for it to be described as having a unit root:

$$\Delta Y_t = \varphi Y_{t-1} + u_t. \tag{3}$$

where: Y_t is the dependent variable return on a futures contracts, φ is a parameter of the model, u_t is the residual error, Δ is the change in the first order, and t is the time.

The supplemented Augmented Dickey–Fueller (ADF) test (Formula (4)) likewise employs a constant, a trend, and a greater number of time lags [38]. This makes it possible to assess whether the time series is stationary by considering (by adjusting the data accordingly) the long-term determinative trend. In this regard, it is assumed that prices will continue to rise over time; therefore, long-term economic growth and pricing changes are removed as a result:

$$\Delta Y_t = \alpha + \beta t + \varphi Y_{t-1} + \sum_{i=1}^{j} \theta_i \Delta Y_{t-i} + u_t. \tag{4}$$

where: Y_t is the dependent variable return on futures contracts; α, β, φ, and θ are model parameters; u_t is the residual error; Δ is the change in the first order; i is the time lag; j is the number of time lags; and t is the time.

A third-degree root from the sample size will be used to select the number of time lags $j = \sqrt[3]{n}$. Hypotheses for the ADF test can be described as H0: $\varphi = 0$, time series have a unit root; H1: $\varphi < 0$, time series do not have a unit root.

If the time series in absolute terms of prices does not fit the condition of stationarity, the Granger Causation Test is used to analyze the causal relationship between the specified speculative index and the returns on futures contracts for selected agricultural products. Despite the substantial correlation between the variables, this test will allow the direction of causality to be discovered and assessed to determine whether short-term speculation leads price/returns or vice versa. The Granger Causation Test is expressed as two autoregressive equations (Formulas (5) and (6)). The model's first equation allows one to check if speculation is not driving prices or returns on a product's futures contracts (Formula (5)). The model's second equation allows one to determine whether prices or futures returns do not cause speculation (Formula (6)). Then, it is assessed which time series can better explain the other one under a given number of time lags using the methodology presented by Granger [39]. However, there are times when statistically significant effects with respect to both time series are not detected, or when statistically significant impacts are identified for both time series and the variables are characterized by feedback relationships.

$$Y_t = \alpha_0 + \sum_{i=1}^{j} \alpha_{1i} Y_{t-i} + \sum_{i=1}^{j} \alpha_{2i} X_{t-i} + \varepsilon_t. \quad (5)$$

$$X_t = \beta_0 + \sum_{i=1}^{j} \beta_{1i} X_{t-i} + \sum_{i=1}^{j} \beta_{2i} Y_{t-i} + \omega_t. \quad (6)$$

where: Y_t is the dependent variable return on futures contracts, X_t is an independent variable index of short-term speculative activities, $\alpha_{0,1,2}$ and $\beta_{0,1,2}$ are model parameters, ε_t, ω_t are residual errors, i is the time lag, j is the number of time lags, t is the time.

Next, we define our research hypotheses for the causality test:

- H0: $\alpha_{21} = \alpha_{22} = 0$. Speculation does not cause the return on futures contracts.
- H0: $\partial_{21} = \partial_{22} = 0$. The return on futures contracts does not cause speculation.

Then we use GARCH modeling to see how short-term speculation affects price or return conditional volatility. To obtain consistent parameter estimations in GARCH modeling, stationary time series are also necessary [40]. As a result, if the price is not stationary, we employ returns, which are first-order logarithmical price differences. The model consists of mean and variation equations (Formulas (7) and (8)). An autoregressive equation of return from futures contracts is included in the mean equation (Formula (8)). The second equation in the model is called the equation of variation (Formula (8)). It lets us see how the autoregressive link between price/return variability and external (external) variables, such as short-term speculation described by the TV/OI index, affects price/return variability.

This methodology was first described by Engle [41], who proposed ARCH models, and Bollerslev [42], who developed the generalized GARCH methodology. This approach is well suited for financial markets where return volatility is typically clustered and can be split into periods of high or low volatility. The residual error from the mean equation represents innovation and its impact on price and return volatility. Additional exogenous variables that explain agricultural commodity returns can be added into the mean equation. The model's variance equation also allows us to evaluate the impact of historical variables on the estimated conditional volatility. The residual effect shows if volatility can be explained by its lagging values. Unlike ordinary ARCH, the generalized model GARCH also uses a generalized volatility effect that incorporates multiple lagged residual values from earlier periods. Therefore, it is more user-friendly because it requires a smaller number of parameters to be calculated and taken into consideration. This makes them easier to read and makes the results more explanatory from an economic perspective. In most studies, one autoregressive conditional volatility lag and one generalized conditional volatility lag effect on conditional volatility are used, and therefore such models are named as GARCH (1,1). In our study, we use one-day residuals and volatility lag.

As an extension to our previously published GARCH model, we also use a Threshold Autoregressive Conditional Heteroskedasticity (TGARCH) technique developed by Zakoian [43] for our main model. Using this technique, a binary variable is added to the variance equation to measure the negative return impact on volatility and if the relationship between returns and volatility is asymmetric [44]. This shows that if negative news has a destabilizing effect on markets, it will increase return volatility. Then, we define our preliminary model with one-period AR lags TGARCH (1,1):

Mean equation:

$$R_t = \alpha_0 + \alpha_1 R_{t-1} + u_t. \quad (7)$$

Variance equation:

$$h_t^2 = \beta_0 + \beta_1 u_{t-1}^2 + \beta_2 h_{t-1}^2 + \beta_3 u_{t-1}^2 d_{t-1} + \beta_4 S_{t-1}. \quad (8)$$

where: the mean equation consists of returns R_t as an autoregressive process with parameters α_0 and α_1, and an error term u_t with a variance of h^2. The conditional variance h_t^2 is provided in the variance equation, where β_0 is the constant, $\beta_1 u_{t-1}^2$ is the residual (ARCH) effect, $\beta_2 h_{t-1}^2$ is the variance (GARCH) effect, $\beta_3 u_{t-1}^2 d_{t-1}$ is the asymmetric component, and the parameter $d_t = 1$ if $u_{t-1} < 0$ and $d_t = 0$ otherwise. If $\beta_3 \neq 0$, then a threshold effect exists; when $\beta_3 > 0$, the return impact on volatility is asymmetrical. We also use an external variable $\beta_4 S_{t-1}$ in the variance equation to assess the direct effect of the speculation on conditional volatility.

Even though spring can be assumed to be the most volatile season for agricultural futures markets, we apply an additional GARCH model to investigate these relationships in more detail for commodities traded in European commodity markets. We then select the exact month for each commodity when their returns are most volatile. To examine seasonal volatility, time seasons described by dummy variables are also included in the GARCH model variance computation. We only utilize 11 months from January to November, to avoid multicollinearity, assuming that agricultural prices are less volatile during winter. The following formulae describe our suggested month-selection model:

Mean equation:

$$R_t = \alpha_0 + \alpha_1 R_{t-1} + u_t. \tag{9}$$

Variance equation:

$$h_t^2 = \beta_0 + \beta_1 u_{t-1}^2 + \beta_2 h_{t-1}^2 + \sum_{i=1}^{n} \gamma_i D_{it.} \tag{10}$$

where: the mean equation consists of returns R_t as an autoregressive process with parameters α_0 and α_1, and an error term u_t with a variance of h^2. The conditional variance h_t^2 is provided in the variance equation, where β_0 is the constant, $\beta_1 u_{t-1}^2$ is the residual (ARCH) effect, and $\beta_2 h_{t-1}^2$ is the variance (GARCH) effect. We also use an external variable $\gamma_i D_{it}$ in the variance equation to assess the direct effect of a month on conditional volatility, where i is the month, and n is the number of months.

Then, using GARCH modeling, we examine how speculative variables influence price or return conditional volatility during the most volatile months. We focus if short-term speculation amplifies this month-related increase in return volatility. For this purpose, we describe how to model short-term speculation as a multiple component with a seasonal dummy variable using a TGARCH model with an extra variable (Formulas (11) and (12)). The impact of seasonally weighted speculation on return volatility can be determined using a similar model but with two additional variables in the variance equation: season effect and season effect multiplied by short-term speculation. This enables us to evaluate the influence and direction of short-term speculation on volatility during the month with the highest volatility after we select the most volatile month for each commodity using our month-selection model (Formulas (9) and (10)). Aside from short-term speculation and seasonality, we employ a one-day lag for autoregressive residual and volatility effects, as well as the dummy variable for asymmetry between returns and conditional volatility, as in the prior example. For clarity, the models are referred to as "Framework I" and "Framework II." Framework I only examines short-term speculation, but Framework II considers both short-term speculation and seasonal effects. Both Framework I and II use GARCH and TGARCH variants, so there are a total of four models:

Mean equation:

$$R_t = \alpha_0 + \alpha_1 R_{t-1} + u_t. \tag{11}$$

Variance equation:

$$h_t^2 = \beta_0 + \beta_1 u_{t-1}^2 + \beta_2 h_{t-1}^2 + \beta_3 u_{t-1}^2 d_{t-1} + \beta_4 S_{t-1} + \beta_5 D_{t-1} + \beta_6 D_{t-1} S_{t-1}. \tag{12}$$

where: $\beta_6 D_{t-1} S_{t-1}$ is the combined effect of the speculation index $\beta_4 S_{t-1}$ and the season's effect $\beta_5 D_{t-1}$. Other parameters are described in the preliminary and main models (Formulas (7)–(10)).

Then, we check if the GARCH/TGARCH model parameters' p-values are less than 0.05, suggesting statistically significant volatility clustering, effects of exogenous variables, and so on. The following are hypotheses about the effect of speculation on return volatility:

- H0: $\beta_4 = 0$. Speculation has no impact on the volatility of the return.
- H0: $\beta_6 = 0$. Speculation does not amplify return volatility during the most volatile month.

The final step is to compare these models with one another. Therefore, the following information criteria are used to select the best model: the Hannan–Quinn information criterion, the Akaike information criterion, and the Schwartz information criterion (Bayesian). To choose the best model, the information criteria values must be the lowest.

2.2. Data

Using three EU agricultural commodities futures contracts, we study the relationship between changes in commodity prices and speculative activity. More specifically, we investigate how futures speculation measured by a short-term speculative index affects returns and return volatility in milling wheat, corn, and rapeseed futures markets. These futures contracts are traded on the Paris Euronext exchange MATIF. Bloomberg and Barchart provide us with daily closing prices, total open interest, and trading volume through their data platforms [45–47]. To measure long-term dynamics in European commodity markets, we use continuous closing prices, which are prices of nearby future contracts, which change on the first trading day of each contract month. Trade volume is the total number of contracts traded during each trading day, whereas open interest shows the total amount of hedging activity in the underlying market. For all three variables, we collected daily data from 23 April 2003, to 1 September 2021. This period saw large price changes as well as considerable increases in open interest throughout our analysis. Commodity prices have risen steadily throughout time, becoming more volatile in recent years (see Figure A1). The rise in commodity prices and volatility has resulted in a significant increase in speculators' market share in the commodity futures market. Therefore, the rise in commodity prices and volatility has been ascribed to an increase in speculators' market share. The sample is then separated into two subsamples: the full sample, and after 2020. In the post-2020 period, changes in price patterns and epidemic-induced shocks can be observed. Using these data, we calculate the short-term speculation ratio for each commodity market using trade volume and open interest.

3. Results

We begin with descriptive statistics for rapeseed, corn, and milling wheat futures traded on the Euronext exchange in Paris (MATIF) (see Table 1). First, we analyze the full sample data for 2003–2021. The volatility of returns as measured by standard deviation is highest for milling wheat futures (1.299) and lowest for rapeseed futures (1.019). Milling wheat futures have the highest short-term speculative index values (the mean is 0.095), while corn futures have the lowest (0.068).

Next, if we look at the pandemic years of 2020 and after, we can see that the standard deviation of returns is highest for rapeseed (1.317), and it has changed dramatically if compared to full sample results. The standard deviation of returns for corn has remained nearly constant, while it has decreased in milling wheat markets (to 1.206). Short-term speculation index values increased for milling wheat (to 0.128) and rapeseed (to 0.101). However, short-term speculation decreased in the corn market (to 0.066). Mean values of prices are higher in all three commodities during the pandemic years of 2020–2021.

It is also worth noticing that returns do not follow a well-shaped normal distribution. For example, kurtosis is high (>3) for all three commodities using both samples, indicating that many return values are close to the mean or zero. Return skewness is negative for all three commodities in both samples, implying that there are more positive-but-small returns and fewer-but-larger negative returns. To sum up, milling wheat has the highest variation of returns and is the most volatile and risky commodity with the highest short-speculative activity. However, rapeseed futures have changed dramatically in terms of return volatility during the pandemic period, becoming more volatile than milling wheat and having almost the same amount of short-term speculation.

Table 1. Descriptive statistics of agricultural commodity futures.

Variable	Milling Wheat		Corn		Rapeseed	
	Full Sample	Post-2020	Full Sample	Post-2020	Full Sample	Post-2020
Price						
Mean	174.470	203.860	170.060	188.600	353.220	431.590
Minimum	103.750	175.250	105.000	160.000	190.500	335.500
Maximum	286.000	254.250	265.000	241.250	577.250	577.250
St. deviation	39.605	17.449	32.642	21.852	80.992	63.571
St. deviation, % mean	22.700	8.559	19.194	11.586	22.930	14.729
Skewnees	0.095	0.572	0.395	0.303	−0.017	0.765
Kurtosis	−0.508	−0.432	−0.172	−1.408	−0.616	−0.809
Return						
Mean	0.016	0.060	0.012	0.055	0.019	0.078
Minimum	−18.697	−8.722	−15.553	−15.553	−13.608	−13.608
Maximum	12.507	3.685	7.925	3.390	5.318	3.671
St. deviation	1.299	1.206	1.181	1.192	1.019	1.317
Skewnees	−1.324	−0.861	−1.325	−5.214	−1.674	−2.913
Kurtosis	23.805	6.902	24.338	67.510	17.939	27.195
Speculation index						
Mean	0.095	0.128	0.068	0.066	0.085	0.101
Minimum	0.000	0.013	0.000	0.003	0.000	0.017
Maximum	0.396	0.329	0.492	0.249	0.346	0.285
St. deviation	0.054	0.044	0.045	0.035	0.048	0.040
Skewnees	0.960	0.536	1.751	1.315	1.004	0.870
Kurtosis	1.793	0.760	7.044	2.432	1.447	1.385

Source: author's calculations based on Euronext Commodities (MATIF) data, 2021.

Following that, we present the results of the Augmented Dickey–Fuller (ADF) test using two models: one with only constant and the other with both constant and trend (see Table 2). The *p*-value of price for all three commodities and both ADF models is more than 0.05, indicating that these time series have a unit-root and are nonstationary. However, returns from futures (specified in Formula (1)), which are the first logarithmical difference in price values, have a *p*-value for all three commodities smaller than 0.05 using both time samples. With a *p*-value of less than 0.05, the short-term speculation index is also stationary for all three commodities in both time samples. To sum up, all of the time series except for prices are stationary; thus, returns can be properly used for further Granger noncausality investigation. Another thing to keep in mind when using a time–trend model is that the returns are more stationary and the *p*-values are lower, suggesting that the returns have a time trend throughout this period.

We then present the results of the Granger noncausality test (Table 3). In most cases, the *p*-value of the underlying AR model is greater than 0.05 for all three commodities. Corn and rapeseed futures are the only two exceptions.

Using a one-day lag, we can reject the hypothesis that returns do not cause speculation in rapeseed futures (*p*-value is 0.0405). This shows that returns better explain speculation than vice versa. Using a two-day lag, we can reject the hypothesis that speculation does not cause the return in the instance of corn futures (*p*-value is 0.0418), but we cannot reject the opposite hypothesis (*p*-value is 0.6065). If we look at the total lag one-directional effect, it is only significant in the corn market (*p*-value is 0.0053), where returns are better explained by speculation than vice-versa. This shows some evidence of speculation having an impact on returns in corn markets. It is also worth noting that in this scenario, the coefficient values are positive, indicating that speculation increases returns. In the case of the milling wheat market, none of the *p*-values are above 0.05. This demonstrates that time series are only loosely related to one another. However, the second hypothesis, that speculation does not cause returns, has higher *p*-values. Other observations are that the *p*-value is smaller when using a one-day lag, except for corn futures, so more time lags can be added for further investigation.

Table 2. Augmented Dickey–Fuller test results.

Time Period	Milling Wheat		Corn		Rapeseed	
	Full Sample	Post-2020	Full Sample	Post-2020	Full Sample	Post-2020
Price of commodity						
test with constant	0.1133	0.8312	0.0813	0.7778	0.7341	0.9793
with constant and trend	0.1484	0.3689	0.1886	0.3225	0.6749	0.4079
Return of commodity						
test with constant	<0.0001	<0.0001	<0.0001	<0.0001	0.0001	<0.0001
with constant and trend	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Speculation index of commodity						
test with constant	<0.0001	<0.0001	<0.0001	0.0006	<0.0001	<0.0001
with constant and trend	<0.0001	0.0001	<0.0001	0.0046	<0.0001	0.0003

Source: author's calculations based on Euronext Commodities (MATIF) data, 2021.

When using pandemic period *p*-values for all commodities and time lags, they are all above 0.05. This shows that there is no statistically significant direction from speculation to returns or vice versa. However, *p*-values during the pandemic period are higher for speculation than returns, showing that returns explain speculation better than vice versa. Even though returns better explain speculation, in the case of corn futures, the opposite is true.

Table 3. Estimates of Granger's noncausality test using one-day, two-day, and combined lags.

Variable/Hypotheses	Full Sample			Post-2020		
	Coefficient	*p*-Value	Result	Coefficient	*p*-Value	Result
Milling Wheat						
H0: the return does not cause speculation:						
The return lag (-1) is equal to zero, $\alpha_{21} = 0$.	0.0007	0.1144	Accept	0.0007	0.1152	Accept
The return lag (-2) is equal to zero, $\alpha_{22} = 0$.	0.0005	0.2805	Accept	0.0005	0.2852	Accept
Return lags (-1) and (-2) are equal to zero, $\alpha_{21} = \alpha_{22} = 0$	-	0.1447	Accept	-	0.1473	Accept
H0: speculation does not cause the return:						
The speculation index lag (-1) is equal to zero, $\beta_{21} = 0$.	0.4628	0.2986	Accept	0.4607	0.3015	Accept
The speculation index lag (-2) is equal to zero, $\beta_{22} = 0$.	0.1891	0.6706	Accept	0.1865	0.6752	Accept
The speculation index lags (-1) and (-2) equal to zero, $\beta_{21} = \beta_{22} = 0$	-	0.2369	Accept	-	0.2427	Accept
Corn						
H0: the return does not cause speculation:						
The return lag (-1) is equal to zero, $\alpha_{21} = 0$.	0.0003	0.5462	Accept	0.0020	0.0852	Accept
The return lag (-2) is equal to zero, $\alpha_{22} = 0$.	0.0003	0.6065	Accept	−0.0003	0.7629	Accept
Return lags (-1) and (-2) are equal to zero, $\alpha_{21} = \alpha_{22} = 0$.	-	0.7136	Accept	-	0.2068	Accept
H0: speculation does not cause the return:						
The speculation index lag (-1) is equal to zero, $\beta_{21} = 0$.	0.6232	0.1328	Accept	2.3764	0.2374	Accept
The speculation index lag (-2) is equal to zero, $\beta_{22} = 0$.	0.8441	0.0418	Reject	−1.3586	0.4977	Accept
The speculation index lags (-1) and (-2) equal to zero, $\beta_{21} = \beta_{22} = 0$.	-	0.0053	Reject	-	0.4925	Accept
Rapeseed						
H0: the return does not cause speculation:						
The return lag (-1) is equal to zero, $\alpha_{21} = 0$.	−0.0011	0.0405	Reject	−0.0008	0.5374	Accept

Table 3. *Cont.*

Variable/Hypotheses	Full Sample			Post-2020		
	Coefficient	*p*-Value	Result	Coefficient	*p*-Value	Result
The return lag (-2) is equal to zero, $\alpha_{22} = 0$.	−0.0001	0.9377	Accept	0.0013	0.3117	Accept
Return lags (-1) and (-2) are equal to zero, $\alpha_{21} = \alpha_{22} = 0$.	-	0.1178	Accept	-	0.5182	Accept
H0: speculation does not cause the return:						
The speculation index lag (-1) is equal to zero, $\beta_{21} = 0$.	−0.5440	0.1758	Accept	−1.4491	0.4281	Accept
The speculation index lag (-2) is equal to zero, $\beta_{22} = 0$.	0.2808	0.4843	Accept	0.2249	0.9019	Accept
The speculation index lags (-1) and (-2) equal to zero, $\beta_{21} = \beta_{22} = 0$.	-	0.3886	Accept	-	0.6939	Accept

Source: author's calculations based on Euronext Commodities (MATIF) data, 2021.

Following that, we investigate the GARCH month-selection model using time dummy variables for months (Table 4). We look at when these markets are the most volatile. We also take note of cases when *p*-values are above 0.05 but below 0.10. We are concerned about the *p*-values for models and their coefficients.

Milling wheat and corn both have a statistically significant effect in January, with a *p*-value between 0.05 and 0.10 (parameter γ_1 estimations are 0.0312 and 0.0398). However, this effect is relatively small compared to other months. Milling wheat also has a statistically significant impact in June (estimated value is 0.0257) and in August (estimated value is −0.0051, with a *p*-value below 0.05). However, during April, this effect is estimated to be 0.2950 even though its *p*-value is higher than 0.10.

On the other hand, corn has a statistically significant and stronger (compared to milling wheat) month's impact in May (estimated value is 0.1609), July (estimated value is 0.0857), and October (estimated value is 0.1747, with a *p*-value below 0.05). However, the strongest effect in this market is during April, estimated to be 0.1919, with a *p*-value above 0.10.

In the rapeseed market, only August (coefficient estimated to be −0.0137) and October (coefficient estimated to be −0.0125) are statistically significant, with *p*-values below 0.10. However, these values are negative, showing that returns from these futures contracts are less volatile during these months. Rapeseed markets are found to be most volatile in March (coefficient estimated to be 0.0649), but this effect is smaller than it is in milling wheat and corn markets during April and with a *p*-value above 0.10.

Table 4. Estimates from the GARCH month selection model for agricultural commodities.

Month	Milling Wheat	Corn	Rapeseed
January, γ_1	0.0312 *	0.0398 *	−0.0138
February, γ_2	0.0063	0.0333	0.0419
March, γ_3	0.1157	0.0108	0.0649
April, γ_4	0.2950	0.1919	−0.0432
May, γ_5	−0.0187	0.1609 *	−0.0117
June, γ_6	0.0257 *	0.0699	0.0035
July, γ_7	0.0135	0.0857 *	−0.0079
August, γ_8	−0.0051 **	0.0073	−0.0137 **
September, γ_9	0.0042	0.0190	0.0040
October, γ_{10}	0.0131	0.1747 **	−0.0125 *
November, γ_{11}	0.0025	−0.0094	−0.0054

Notes: Estimates with a *p*-value of less than 0.1 are flagged with one asterisk (*), and those with a *p*-value of less than 0.05 are flagged with two asterisks (**).

It is evident that all three agricultural commodities have increased return volatility during sowing and before harvest, mostly in the spring months: March–April for milling wheat, April–July for corn, and February–March for rapeseed futures. For further analysis, we select April for milling wheat and corn, and March for rapeseed futures. Even though the *p*-values are above 0.10 for these months, we will revisit the *p*-values in our revisited Framework II.

Then, we examine the outcomes of the basic GARCH and threshold TGARCH models to see if speculation has an impact on return conditional volatility as described in our methodology (Table 5). The TGARCH model shares the same characteristics as the GARCH model, except that it also includes an asymmetry factor (a dummy variable d_{t-1}). In this table, we only show GARCH and TGARCH models that are based on Framework I, with only short-term speculation as an exogenous element.

When analyzing full sample data, mean equation parameter values for all three commodities are statistically insignificant or close to zero, which can reflect the fact that these time series are stationary and previous returns do not explain the further ones. Next, we can look further into the variance equation where we put the speculation index as an exogenous factor. Residual volatility is statistically significant (*p*-value is below 0.05), so we can reject the hypothesis that this parameter is equal to zero. This is present in all cases except for rapeseed when using the TGARCH model (estimated value of lagged residual volatility to current volatility is 0.1149). This shows that volatility closely reflects its lagged values, as evidenced by residuals. The volatility effect is statistically significant for all three commodities, indicating that their return volatility is clustered. In other words, the market activity timeline can be grouped into high and low volatility periods. For all three commodities, the asymmetry coefficient is nonsignificant, indicating that there is no asymmetry for positive or negative return to increase volatility. Constants are close to zero or statistically insignificant in both mean and variance equations. When using the GARCH model in the milling wheat market and both the GARCH and TGARCH models in the corn market, the speculation effect on volatility is statistically significant and increases volatility. This effect is higher in the corn market than in milling wheat; it is especially high when using the basic GARCH model (estimated value is 2.2663). In the milling wheat market, this effect is only significant under a *p*-value greater than 0.05 and lower than 0.10. When modeling rapeseed returns, the information criteria are discovered to be the lowest. When modeling the milling wheat market, the information criteria are found to be the highest. The information criteria are smaller for TGARCH estimates.

When using the post-2020 data, we see that only TGARCH model estimates show statistically significant mean equation estimations (*p*-values are below 0.05) in the mean equation for both milling wheat and rapeseed futures. The residual is statistically significant only when using the TGARCH model and for all three commodities. Volatility is statistically significant for all three commodities using both models. The asymmetry factor, unlike in full sample data, is statistically significant in the milling wheat futures market but is negative (-0.3229), indicating that positive returns are followed by increased volatility. The speculation index is only statistically significant in the corn market using both models (estimations are 3.4420 and 1.8786). As we see, this effect is stronger than compared to full sample results. The information criteria for the corn market are the smallest, while those for milling wheat are the largest. Information criteria for GARCH and TGARCH models are similar, but are smaller in TGARCH models. To sum up, speculation increases volatility in the corn market using both models, and this effect has become stronger during the post-2020 era.

Table 5. Estimates of GARCH agricultural commodity-return models using Framework I without a month's effect.

Time Period	Milling Wheat				Corn				Rapeseed			
	GARCH		TGARCH		GARCH		TGARCH		GARCH		TGARCH	
	Full Sample	Post-2020	Full Sample	Post-2020	Full Sample	Post-2020	Full Sample	Post-2020	Full Sample	Post-2020	Full Sample	Post-2020
Mean equation:												
Constant	−0.0123	0.0154	0.0127 **	0.0584 **	0.0268	0.0310	0.0355 **	0.0906 *	0.0230	0.0696 *	0.0148	0.0381 **
Return	0.0273	0.0407	0.0369 **	0.0797 **	0.1047 **	0.0509	0.0830 **	0.0474	0.1160 **	0.0665	0.0909 **	0.0665 **
Variance equation:												
Constant	−0.0083	0.1536	0.0084 *	0.1717	−0.0213 **	−0.0858 *	0.0096	−0.0166	0.0516	0.1035	0.0319	0.0966
Residual	0.2881 **	0.2273	0.0701 **	0.2270 **	0.2072 **	0.1825	0.1678 **	0.0915 **	0.1513 *	0.3547	0.1149	0.2967 **
Volatility	0.7672 **	0.7041 **	0.9493 **	0.7002 **	0.7399 **	0.7600 **	0.8317 **	0.8552 **	0.8040 **	0.6866 **	0.8859 **	0.7553 **
Asymmetry	-	-	−0.1271	−0.3229 *	-	-	0.1966	−0.7400	-	-	0.0839	0.1982
Speculation	0.6645 *	−0.1562	−0.0393	0.0836	2.2663 **	3.4420 **	0.9461 **	1.8786 **	0.1295	−0.5183	−0.0132	−0.4463
Information criteria:												
L-lik	−7362	−661	−7265	−658	−6888	−618	−6797	−602	−6344	−645	−6285	−644
BIC	14,775	1358	14,590	1359	13,826	1272	13,653	1247	12,739	1327	12,628	1330
AIC	14,736	1334	14,544	1330	13,787	1248	13,608	1218	12,701	1302	12,583	1301
HQC	14,750	1344	14,560	1341	13,801	1258	13,624	1229	12,714	1312	12,599	1312

Source: author's calculations based on Euronext Commodities (MATIF) data, 2021. Notes: Estimates with a p-value of less than 0.1 are flagged with one asterisk (*), and those with a p-value of less than 0.05 are flagged with two asterisks (**).

Following that, we provide further estimates with extra exogenous variables put into the mean equation, which may better explain movements of agricultural commodity returns (see Table A1). We employ log differences of the S&P 500, GSCI Energy, Euro Stoxx 50, and 3-month Eurodollar indexes to depict the economic environment, namely, economic growth and energy prices. This leads to some important observations. The GSCI energy index exhibits a statistically significant influence with p-values of less than 0.05 for all three products when considering the whole sample and for rapeseed futures when analyzing post-2020 data as well. Coefficient values are positive, indicating that rising energy prices enhance agricultural futures returns and vice versa. This demonstrates that energy costs have a significant impact on agricultural commodity returns. In more cases than the S&P 500 index, the Euro Stoxx 50 is statistically significant and has positive coefficients. In all circumstances, the Euro Stoxx 50 index is statistically significant in the rapeseed market. This demonstrates that the Eurozone stock market has a greater influence on agricultural prices than the S&P 500, which is composed of companies based in the United States. This suggests that rising European stock market returns are correlated with rising agricultural commodity prices traded on the MATIF. The 3-month Eurodollar index is statistically significant and has negative coefficients except for the corn market when analyzing full sample data. The higher the implied 3-month U.S. dollar LIBOR interest rate, the lower this index value. Therefore, when interest rates grow, returns from agricultural commodity futures grow as well, and vice versa. Other estimates are comparable to those in models where there are no extra variables in the mean equation. Even though all models indicate statistically significant volatility effects, a statistically significant asymmetry component is detected in the corn market (the coefficient is 0.1591 when analyzing the full sample and -0.659 when analyzing post-2020 data). However, in the corn market, short-run speculation is merely statistically significant. When both techniques and time samples are used, the information criterion for all three commodities is slightly smaller.

Then, we examine the outcomes of the GARCH and TGARCH models to see if speculation has an impact on price conditional volatility when the month is also taken into consideration (Table 6). These models have an additional two exogenous variables: a dummy variable D_{t-1} representing the most volatile month, and speculation multiplied by this dummy variable $D_{t-1} \times S_{t-1}$. As the month-selection model shows, milling wheat and corn futures returns are the most volatile in April, and rapeseed futures returns are the most volatile in March.

As in our previous models based on Framework I, mean equation parameters are close to zero, yet here they are more statistically significant. The residual and volatility effects from the variance equation are statistically significant in all cases, including rapeseed. This again shows that return volatility is clustered in these markets and that current volatility closely follows its previous values. Then again, constants are close to zero or statistically insignificant in both mean and variance equations. The asymmetry factor is only significant in the corn market (estimated to be 0.2031), showing that negative returns are followed by increased volatility. Negative news affects corn futures volatility when using this improved model. Next, we analyze the impact of exogenous factors on return volatility. Neither speculation nor month had a statistically significant effect on milling wheat returns, even though milling wheat, when analyzing descriptive statistics, was found to be the most volatile and had the highest speculation-index mean value. Speculation increases return volatility throughout the year in the corn market using both the GARCH model (parameter estimation is 0.9835) and the TGARCH model (parameter estimation is 0.6988). Month and combined effect are statistically significant only in TGARCH estimates, and season speculation amplifies return volatility (parameter estimation is 4.1949) while month alone reduces volatility (parameter estimation is -0.1679). In the rapeseed market, speculation reduces volatility throughout the years, but this effect is only statistically significant in the TGARCH model (which is estimated to be negative -0.0899). Month reduces volatility (effects are estimated to be -0.1364 and -0.0575) and the combined effect increases volatility (effects are estimated to be 2.8548 and 1.1661) in both models.

Information criteria are estimated to be the smallest when modelling corn returns with the GARCH approach and rapeseed returns with the TGARCH approach, and largest when modelling the milling wheat market. GARCH estimates have a lower information value only in the corn market. The information criteria are smaller than in the previous model for all three commodities. We focus on these results because the GARCH model for corn has a lower information criterion. In the rapeseed market, there is evidence that during more volatile time periods, speculation increases volatility. Seasonal volatility is amplified in the corn market as well as the rapeseed market.

Table 6. Estimates of GARCH commodity-return models using Framework II with a month's effect.

Time Period	Milling Wheat		Corn		Rapeseed	
	GARCH	TGARCH	GARCH	TGARCH	GARCH	TGARCH
Mean equation:						
Constant	−0.0071	0.0016	−0.0016	0.0329 **	0.0231	0.0208 **
Return	0.0621 **	0.0580 **	0.1121 **	0.0919 **	0.1077 **	0.0943 **
Variance equation:						
Constant	−0.0029	0.0150	−0.0024	0.0111	0.0309	0.0223 *
Residual	0.1546 **	0.1113 **	0.1972 **	0.1398 **	0.0753 **	0.0795 **
Volatility	0.8541 **	0.9094 **	0.7878 **	0.8547 **	0.9035 **	0.9236 **
Asymmetry coefficient	-	−0.0963	-	0.2031 **	-	0.0278
Speculation index (1)	0.2508	−0.0212	0.9835 **	0.6988 **	−0.1326	−0.0899 *
Month (2)	0.3982	0.1495	−0.0351	−0.1679 **	−0.1364 **	−0.0575 *
1 × 2	−0.6940	−0.4433	0.4559	4.1949 **	2.8548 **	1.1661 **
L-lik	−7234	−7139	−6180	−6720	−6262	−6200
BIC	14,535	14,354	12,436	13,515	12,591	12,475
AIC	14,483	14,295	12,378	13,457	12,540	12,417
HQC	14,501	14,316	12,398	13,478	12,558	12,438

Source: author's calculations based on Euronext Commodities (MATIF) data, 2021. Notes: Estimates with a p-value of less than 0.1 are flagged with one asterisk (*), and those with a p-value of less than 0.05 are flagged with two asterisks (**).

Following that, we present estimates for Framework II models that integrate economic variables such as the S&P 500, GSCI Energy, Euro Stoxx 50, and 3-month Eurodollar indices into the mean equation (see Table A2). The GSCI energy index was statistically significant for all three items except wheat when using the GARCH model, with a p-value of less than 0.10. Positive coefficient values indicate that increasing energy prices improve agriculture futures returns and vice versa. When using the GARCH approach and having positive coefficients, the Euro Stoxx 50 is statistically significant in all cases except the wheat market. When employing the TGARCH technique, the S&P 500 index is only statistically significant in the corn market but has a negative coefficient. Only in the maize and rapeseed markets, particularly when using the TGARCH model, is the 3-month Eurodollar index statistically significant. The coefficient value in the corn market is positive, but it is negative in the rapeseed market. Other estimates are comparable to those in models where there are no extra variables in the mean equation. However, when employing the TGARCH technique in the wheat market, there is a statistically significant influence from short-run speculation multiplied by month on returns (−0.4103). Short-run speculation, in this sense, lessens volatility during the more volatile month of April. Asymmetry may also be seen in the wheat market. However, it has a negative coefficient (−0.1192). Most of the time, when both methodologies and time samples are used, the information criteria values are slightly smaller.

We conclude in the following section that GARCH approaches can be effectively used to analyze realized futures returns in European commodity markets. Time series are stationary and, in most cases, residual and volatility effects are present under a *p*-value of 0.05. This shows that returns are clustered, and volatility follows its lagged values. Therefore, European agricultural futures trading activity can be split into periods of high and low volatility. The asymmetry factor has no or mixed results, as it is only statistically significant when using a month-based model for the corn market or a basic model for milling wheat during the pandemic period. This shows that negative information is not necessarily destabilizing these markets. Corn markets, on the other hand, showed good evidence that speculation was having a significant and growing effect on return volatility.

4. Discussion

4.1. Contextualization with Previous Research

These GARCH-modeling findings, when combined with the Granger noncausality test, provide a compelling case. Even though similar methods were applied by other authors, they used either the US markets or different dummy variables [48–50]. As a result, our study came up with three major results:

First, not all products investigated in this paper are statistically significantly affected by short-term speculation. Many other authors came up with similar results. Typically, neither or only some of the commodities used in research have shown some form of relationship [5,51,52]. Thus, our research results show that the price bubble cannot be blamed directly on speculative factors. This is opposed to, for example, Adämmer and Bohl [53], who proposed that speculative bubbles were frequent in the wheat markets in 2006–2008. Furthermore, increased speculation may have explained some of the price increases in the soybean markets [54]. However, this impact is mostly related to data analysis up to 2010. Therefore, similarly to Etienne et al. [55], we cannot agree that during the present time, agricultural futures markets were characterized by price bubbles that were driven by speculative forces. On the other hand, speculative influences are debated, in much research, to have at least a minimal impact on prices. According to [56,57], it has been demonstrated that having a higher number of speculative variables increases the accuracy of price volatility predictions. In our study, even though corn futures were not the most volatile or had the highest mean value of speculative index, they are the only product where speculation can explain both return and return volatility.

Second, in our research, corn futures returns are found to be partially driven by short-term speculation. However, in much of the research conducted by other authors, opposing or insignificant effects are observed, and agricultural returns are better explained by returns [36,52,58,59]. However, similar effects from speculation on corn returns were observed in some studies, but these studies are typically older. For example, in the years 2006–2008, speculative price bubbles were discovered in the wheat and corn futures markets [53]. According to a study conducted by Shanmugah and Armah [60], except in the corn and cattle markets, index fund holdings cannot be considered to influence prices. However, when evaluating the influence of speculation on price fluctuations, the wheat markets may be regarded as an exception since it cannot be ruled out that speculation drives prices rather than the other way around [3]. However, as noticed in our research, this effect on corn markets is not true when analyzing the post-2020 period. The current research on the pandemic period highlights the importance of energy markets and their relationships with the corn market, which is used as biofuel. Speculation in energy and precious metal futures is more prevalent during crisis periods and even more so during the COVID-19 pandemic. In contrast, agricultural futures attract more hedging pressure [22]. The cross-correlations of multifractality between crude oil and the sugar future market are the strongest, and the cross-correlations of all the agricultural futures increased after the emergence of COVID-19, except for the orange juice future market [23].

And finally, corn return volatility is also driven by short-term speculation, whereas other commodities have mixed or no results. These results are similar to research conducted by Bohl et al. [10], where the return from corn futures in non-US markets was found to be driven by short-term speculation. In addition, research conducted by Bandyopadhyay et al. [11] also provides evidence that excessive speculation in futures markets increases spot market volatility, therefore suggesting that the excess presence of short-term investors can destabilize the futures market. On the other hand, some researchers point out that commodities such as corn may have had a stabilizing effect on return volatility. For example, speculation in soybean futures markets, which are likewise less liquid, has stabilized prices since 2003 [50]. In corn markets, a stabilizing impact of speculation on price volatility has been established, as has been shown in prior research by other authors [5,48]. When it comes to prices, except for corn after 2006, speculation cannot be said to influence them [60]. In our research, only the rapeseed futures market showed some evidence of a stabilizing effect. Our research also provides indications that the effect of speculation on return volatility is amplified in the corn market during the more volatile month of April. In other writers' research, seasonality has a substantial influence on the volatility of agricultural commodity prices, and the highest volatility is often in the month before harvest, with US maize futures swinging at their peak in May and lowest in November [61,62]. Karali and Power [63] propose that individual product price volatility and structural components are better explained by specific causes than by macroeconomic variables, which they observed during the period of 2006–2009 for different agricultural products. Financial turmoil during periods of crisis may well amplify return volatility. For example, during the 2008–2009 crisis, goods prices, especially metals and energy items, were highly intertwined, and speculation in this area might have resulted in price synchronization across various items [64]. During the 2008–2011 crisis, the total volatility of energy and maize prices reached up to 45 percent [65]. Similar effects can be observed during the pandemic period of 2020–2021.

4.2. Research Limitations and Further Research Guidelines

This leads to the conclusion that corn futures are mostly affected by short-term speculation and that the destabilizing effect can only be argued in the corn market. Therefore, future research should also emphasize its comovement with energy prices if both short-term speculation and return volatility are driven by changes in energy prices. Energy price movements are analyzed, especially in contemporary research. For example, Hung [66] finds a strong comovement between crude oil prices and agricultural commodity markets predominantly during the COVID-19 outbreak compared to the preCOVID-19 period. According to Wen et al. [67] during the outbreak of COVID-19, the spillover effect of the stock market on the commodity market has been significantly enhanced. The effect of biofuel, together with speculation on European corn prices, should be analyzed as well, as there are many fewer studies on this subject in European markets compared to the US. Even though, according to older studies [68], energy market speculation stabilizes prices more than maize speculation, according to Etienne et al. [51], because maize is used as a biofuel to produce ethanol, corn prices have grown increasingly tightly related to energy product prices, and this external influence accounts for more than 30% of the variance. However, according to Cao and Cheng [69], the food-oil market system has the strongest spillover effect in the short term, and the spillovers during the pandemic are significantly weaker than those during the financial crisis. According to Fan et al. [70], the cross-speculative pressure remains relatively low, and the increased speculation does not cause seemingly unrelated commodities to become correlated. Further research shows that when crude oil futures prices go down, speculation helps to lessen the negative effects of positive macroeconomic uncertainty changes on futures returns [71].

Most studies on EU markets are relatively dated [12,13]. Price shock amplification rose in the Paris and London wheat futures markets in 2006 when these markets grew, resulting in market over-reactions and excessive volatility, as well as a stronger link with crude oil [6]. Dawson [14] points out that the rise in volatility since June 2007 looks to reflect a long-term structural shift in these markets. Studies may as well employ other commodities, such as rapeseed oil or meal. For example, the findings of Lawson [72] reveals that the impact of speculation on product prices varies depending on the commodity (rice and wheat prices are less responsive than maize and soybean prices) and the variable used to represent speculation. For example, according to Živkov [73], oil and soybean futures are the best diversification tools since their prices are least reliant on oil prices and their natural volatility and surges. Furthermore, more emphasis should be put on factors that describe long-term speculation and compare them to short-term speculation. Long-term speculation indices are analyzed by many other authors, but not in the EU markets. According to Manera et al. [74], long-term speculation increases volatility, whereas short-term speculation decreases it. Ludwig [75] notes that long-term speculation, which includes a positioning structure, gives liquidity to markets over time, but short-term speculative consumption depletes liquidity, necessitating more study using daily trade volume data. Short-term fluctuations in open interest might be primarily driven by speculators' demand for liquidity. Therefore, speculators, as identified by the money managers category of the CFTC, may be responsible for increasing volatility in several markets (corn, wheat, soybean oil, coffee, and cotton) [76]. Except for the wheat markets, the volatility of the noncommercial position in corn markets has decreased. In research of the wheat and maize markets, a similar influence on volatility was discovered by Borin and Di Nino [77].

Once more information becomes available on noncommercial positions on the Euronext exchange in Paris (MATIF), excessive speculation measured by the Working T index can be calculated. This index is usually used in studies on US markets [78], and it can be used to improve our proposed model and better explain speculation in European corn markets. A speculation index based on the most popular and extensively used Working T Index by other authors, which demonstrates excessive speculating, was employed in an empirical investigation [79]. In addition, the GARCH model can employ more dummy variables, such as ones explaining shock moments or structural breaks. An important observation is that in the post-2003 period, when financialization processes developed and interactions between financial markets intensified, the effect of seasonality on return volatility was weaker than in previous periods. Various writers looked at negative and positive return effects, as well as asymmetric connections [74,80,81]. Baur and Dimpfl [80] found that agricultural commodity futures markets showed similar asymmetric relationships when using the TGARCH approach: positive asymmetry factors were seen mostly in maize markets, and in wheat markets they were generally negative. As a result, a good return is more likely to increase price volatility than the other way around. Other authors employed the GARCH (DCC) approach and observed that nonfundamental factors, such as commodity market financialization and market sentiment, play important roles in driving return comovement over the sample period, though their impacts vary over time [82]. More sophisticated GARCHs such as EGARCH or APGARCH can be included for long-term memory effects in return volatility similarly to studies by Czudaj [49]. On the other hand, the GARCH-M model for predicting risk premiums might be used to further characterize these relationships [83]. Continuous Granger causality tests may be employed as well [84]. The fact that the residual errors of the models are correlated shows that these interactions are nonlinear, allowing the Granger causal test findings to be used in more advanced approaches, such as that conducted by Dick and Panchenko [85]. Finally, more observations during the pandemic and postpandemic periods can be added to the calculations once more time passes.

Another important observation is that GARCH modeling occasionally produces contradictory findings between the complete sample and the post-2020 data. This might be related to GARCH and TGARCH's failure to detect abrupt changes in regimes. As a result, in future research, a more dedicated tool, such as Regime-Switching or more sophisticated structural break models, can be used to see how short-run speculation affects agricultural commodity returns in response to changing regimes reflecting major shifts in the economic environment, not just in the pandemic period. Improved models may also provide a more exact definition of the duration of these modes and when exactly these structural changes happen.

4.3. The Practical Significance of the Study

Many researchers investigate the impacts of trade restrictions on commodity pricing and price volatility and how to quantify these effects [49,86,87]. Producers and dealers who are more sensitive to price risk and are willing to face uncontrollable financial losses are the ones that choose product futures [88]. Another important consideration is that commodity traders who are more vulnerable to price shocks may require more stringent restrictions on speculative activity in commodity markets [89]. Even those scholars who have documented specific instances in which speculative factors have destabilized pricing believe that bans or other limitations would be harmful to market growth at this stage of product market creation [35]. For example, Acharya et al. [9] developed a model that permitted the evaluation that noncommercial market players' capital limits impose restraints on commercial market participants' ability to manage price risk, affecting futures and product prices. Others argue that hedging pressures, price volatility, liquidity, and the risk premium will be more distorted by position limits [90]. On the other hand, there is a great significance of providing market players and policymakers with accurate information on the different categories of traders and their relevance to the market's and pricing mechanism's effective operation [75].

Therefore, active and passive measures should be distinguished. Active mechanisms include position limitations in US and EU product markets, trading day limits for market price fluctuations, extra transaction fees for trading transactions, marginal account requirements, and other marginal requirements. Passive measures include tougher reporting requirements, more product market transparency, and tighter regulation of over-the-counter trade. Active measures, according to empirical research, would not accomplish the stated purpose and would further destabilize pricing. Therefore, the use of passive measures, on the other hand, is more reasonable considering our work and the findings of other empirical investigations [5,87].

Commodity exchanges should completely segment market participants into commercial and noncommercial players, as well as give higher frequency data, more thorough data on trade processes, and market concentration indicators. Increased product financial market openness and a clearer legal architecture would go a long way toward lowering product market uncertainty and pricing volatility [78,91]. This is especially true for commodity exchanges in other countries, where, owing to a lack of data and the inability to detect all markers of speculative behavior, only a small number of academics have employed these marketplaces in their empirical study. Market participants and regulators should be informed of the results.

A well-functioning commodities market with liquid futures contracts may help in resolving the various problems caused by pandemics and other exogenous shocks. A well-performing commodity futures market, for example, provides an opportunity to hedge against price risks that are common in agriculture, especially during epidemic periods marked by considerable price volatility and farmers' income uncertainty. Second, commodity futures markets benefit not only farmers but also agricultural producers who hold long positions to hedge against rising prices, thereby preserving supply chains of agricultural goods, which, as others have noted, are vulnerable to health crises such as these and contribute to food security. Finally, futures contracts may be used during times of uncertainty, such as rising energy prices, so their use is still beneficial when the epidemic period is over.

5. Conclusions

This research investigates the above-mentioned connection for the Paris Exchange MATIF, which is motivated by disagreement among empirical results in the literature concerning the stabilizing or destabilizing influence of speculative activity in futures markets. We used realized, daily returns on rapeseed, milling wheat, and corn futures traded on the European commodity exchange MATIF. We investigated data from 2003 to 2021. This time encompasses various events connected to financialization and commodities market globalization, as well as more than a year of the pandemic period. We observed that these commodities have increased in their return volatility, or speculative activity, over this time. The speculation index, which is calculated by dividing trade volume by open interest, is a proxy for speculative behavior in our research. We, like many other authors, use this speculation measure based on the assumption that speculators engage in short-term trading activity attempting to gain profits from price changes. In our research, we analyze the volatility of three agricultural commodities using extended autoregressive conditional heteroskedasticity GARCH models as well as Granger noncausality testing. Seasonal effects, and whether speculation makes returns more volatile during volatile months, were added to the GARCH model. Dummy variables were also added to the model.

Our study provides three important findings. First, we uncover evidence that short-term speculation drives corn market returns; moreover, speculation causes these markets to be more volatile. Corn markets, on the other hand, are neither more volatile nor have higher levels of short-term speculation than milling wheat or rapeseed. Second, the influence of short-term speculation on return volatility in the corn market has risen over the pandemic era, indicating that speculation may have skewed this market during the COVID-19-induced economic shock. Finally, there are insights that this influence is exacerbated in the corn market during the more volatile month of April since this month is known to be the most volatile, and more new information enters these markets considering that season's crop. However, according to our study, there is not enough data to back up the destabilizing hypothesis for all agricultural commodities.

Our study's results have important policy implications. Because of financial speculation, futures commodity exchange regulators have proposed limiting trading activities. Our results, like those of other authors, indicate that financial speculation has a limited influence on price levels and volatility in agricultural markets and that, in certain cases, speculators help to bring new information and correct prices. Another thing to take into consideration is that restrictions on commodity trading can make these markets less liquid and prevent them from effectively hedging against price risks. However, we demonstrate that if short-term speculation is destabilizing these markets, this effect is only observable in corn markets. Therefore, it should be investigated whether energy costs impact not just corn prices, but also encourage speculation, and whether the connectivity of the corn and oil markets makes them more vulnerable to adverse speculative repercussions. Future studies should focus more on long-term speculation and its effects on the return volatility on European agricultural commodity markets once more information about noncommercial traders' positions becomes available.

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Appendix A

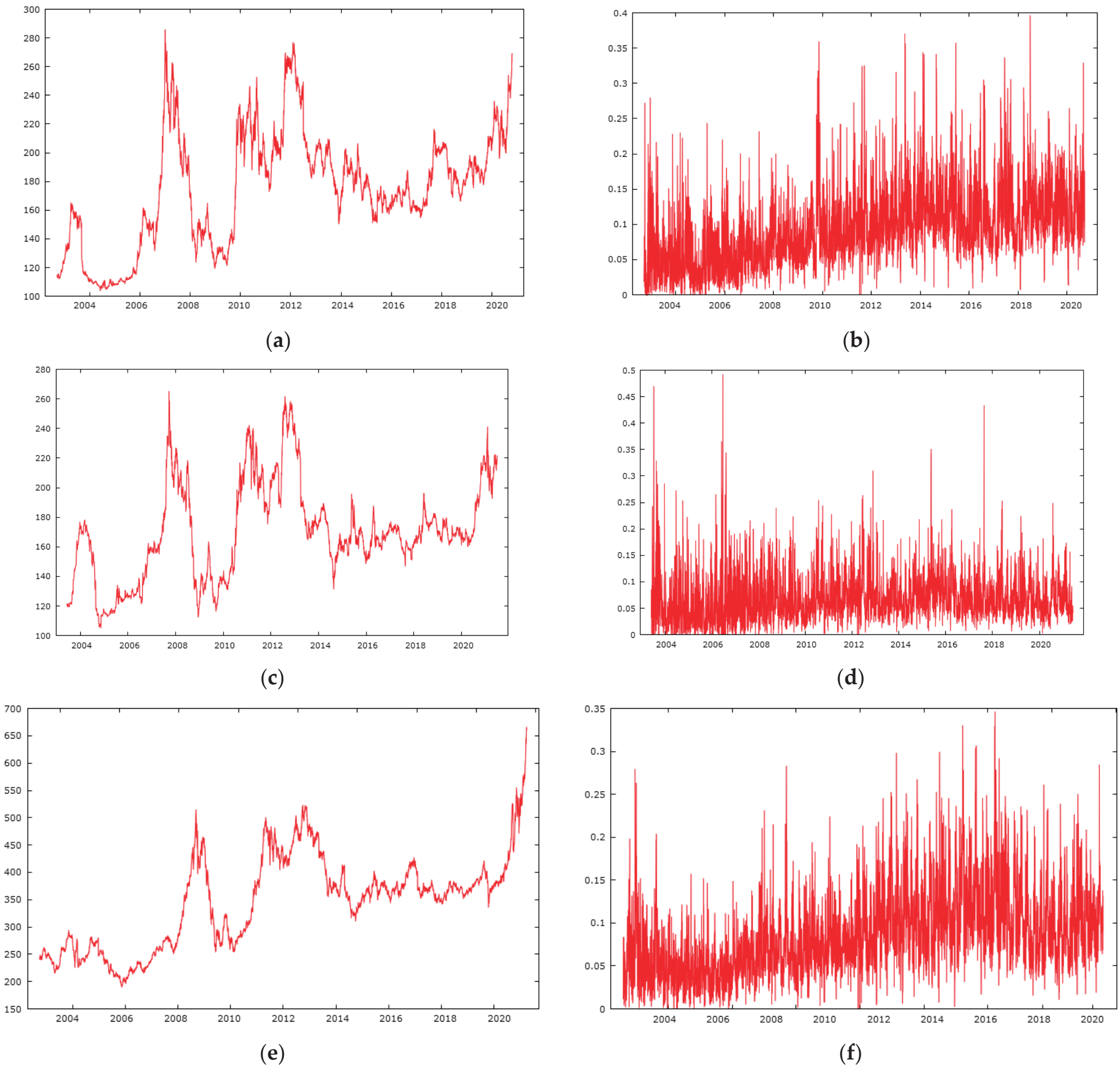

Figure A1. Price and short-term speculation index for selected commodity futures (April 2003–September 2021): (**a**) Price of milling wheat in Euros per metric ton; (**b**) Short-term speculation in the milling wheat market; (**c**) Price of corn in Euros per metric ton; (**d**) Short-term speculation in the corn market; (**e**) Price of rapeseed in Euros per metric ton; (**f**) Short-term speculation in the rapeseed market. Source: author's calculations based on Euronext Commodities (MATIF) data, 2021.

Appendix B

Table A1. Estimates of GARCH agricultural commodity-return models with additional variables using Framework I without a month's effect.

Time Period	**Milling Wheat**				**Corn**				**Rapeseed**			
	GARCH		**TGARCH**		**GARCH**		**TGARCH**		**GARCH**		**TGARCH**	
	Full Sample	**Post-2020**	**Full Sample**	**Post-2020**	**Full Sample**	**Post-2020**	**Full Sample**	**Post-2020**	**Full Sample**	**Post-2020**	**Full Sample**	**Post-2020**
Mean equation:												
Constant	−0.0169	0.0536	0.0181	0.0999 *	−0.0049	0.0768	0.0260 **	0.1159 **	0.0167	0.0540	0.0150 **	0.0274
Return	0.0315	0.0205	0.0446	0.0644	0.1141 **	0.0760	0.0957 **	0.0332	0.1129 **	0.0785	0.0892 **	0.1016 **
GSCI Energy	0.0288 **	0.0204	0.0240 **	0.0135	0.0235 **	0.0180	0.0284 **	0.0189	0.0503 **	0.0338 **	0.0539 **	0.0355 **
S&P 500	0.0221	−0.0152	−0.0153	−0.0043	−0.0152	0.0357	−0.0152	0.0510	0.0033	0.0291	−0.012 **	0.0248
Euro Stoxx 50	0.0144	0.0351	0.0558 **	0.0315	0.0656 **	0.0550	0.1028 **	0.0239	0.1085 **	0.1007 **	0.1148 **	0.1078 **
3M Eurodollar	−0.0384	−5.968 **	−0.1255	−5.102 **	0.2310	−3.390 **	0.8789 **	−2.5027	−0.3647	−4.378 **	−0.420 **	−4.181 **
Variance equation:												
Constant	−0.0079	0.0611	0.0068	0.1840 **	−0.0025	0.0658	0.0052	−0.0049	0.0501	0.0715	0.0115	0.0530
Residual	0.2866 **	0.0627	0.0653 **	0.2156 **	0.2078 **	0.9183	0.1882 **	0.1081 **	0.1548 **	0.3633	0.0790	0.2878 **
Volatility	0.7643 **	0.9104 **	0.9529 **	0.7227 **	0.7732 **	0.2345	0.8202 **	0.8538 **	0.8050 **	0.6988 **	0.9324 **	0.7761 **
Asymmetry	-	-	−0.1673	−0.433 **	-	-	0.1591 **	−0.659 **	-	-	−0.0210	0.1934
Speculation	0.7092	−0.1677	−0.0295	−0.1725	1.0773 **	3.4771	0.9572 **	1.4974 **	0.0852	−0.4008	−0.0164	−0.2087
Information criteria:												
L-lik	−7344	−640	−7247	−650	−6134	−600	−6725	−592	−6215	−612	−6144	−611
BIC	14,774	1346	14,586	1367	12,373	1260	13,543	1250	12,515	1285	12,380	1289
AIC	14,709	1302	14,515	1323	12,302	1219	13,472	1206	12,451	1244	12,309	1244
HQC	14,732	1319	14,540	1340	12,327	1235	13,497	1223	12,473	1260	12,334	1262

Source: author's calculations based on Euronext Commodities (MATIF) data, 2021. Notes: Estimates with a p-value of less than 0.1 are flagged with one asterisk (*), and those with a p-value of less than 0.05 are flagged with two asterisks (**). S&P500, GSCI Energy, Euro Stoxx 50, 3-month Eurodollar indices are used as Δlog by subtracting the index value logarithms.

Appendix C

Table A2. Estimates of GARCH commodity-return models with additional variables using Framework II with a month's effect.

Time Period	Milling Wheat		Corn		Rapeseed	
	GARCH	**TGARCH**	**GARCH**	**TGARCH**	**GARCH**	**TGARCH**
Mean equation:						
Constant	−0.0115	−0.0038	−0.0048	0.0245 **	0.0186	0.0229 **
Return	0.0615 **	0.0621 **	0.1143 **	0.0966	0.1044 **	0.0948 **
Δlog GSCI-Energy	0.0214 *	0.0191 **	0.0233 **	0.0297 **	0.0515 **	0.0546 **
Δlog S&P 500	0.0159	−0.0002	−0.0150	−0.0043 **	−0.0001	−0.0057
Δlog Euro Stoxx 50	0.0178	0.0373 **	0.0652 **	0.0777 **	0.1091 **	0.1110 **
Δlog 3 m Eurodollar	−0.0593	−0.0473	0.2271	0.8577 **	−0.4183	−0.3880 **
Variance equation:						
Constant	−0.0018	0.0137 **	−0.0017	0.0090 **	0.0296 *	0.0162 **
Residual	0.1575 **	0.1078 **	0.2080 **	0.1527 **	0.0709 **	0.0697 **
Volatility	0.8501 **	0.9125 **	0.7725 **	0.8442 **	0.9086 **	0.9360 **
Asymmetry coefficient	-	−0.1192 **	-	0.1859 **	-	−0.0501
Speculation index (1)	0.2618	−0.0179	1.0834 **	0.7572 **	−0.1387	−0.0783 **
Month (2)	0.3903	0.1424 **	−0.0220	−0.1720 **	−0.1257 **	−0.0467 *
1 × 2	−0.5673	−0.4103 **	0.2579	4.1686 **	2.5993 **	0.9439 **
L-lik	−7223	−7126	−6134	−6668	−6131	−6057
BIC	14,548	14,362	12,389	13,445	12,363	12,225
AIC	14,470	14,278	12,305	13,362	12,286	12,141
HQC	14,498	14,307	12,335	13,391	12,313	12,170

Source: author's calculations based on Euronext Commodities (MATIF) data, 2021. Notes: Estimates with a *p*-value of less than 0.1 are flagged with one asterisk (*), and those with a *p*-value of less than 0.05 are flagged with two asterisks (**).

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How High Is High Enough? Assessing Financial Risk for Vertical Farms Using Imprecise Probability

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Abstract: Vertical farming (VF) is a method of indoor agricultural production, involving stacked layers of crops, utilising technologies to increase yields per unit area. However, this emerging sector has struggled with profitability and a high failure rate. Practitioners and academics call for a comprehensive economic analysis of vertical farming, but efforts have been stifled by a lack of valid and available data as existing studies are unable to address risks and uncertainty that may support risk-empowered business planning. An adaptable economic analysis is necessary that considers imprecise variables and risks. The financial risk analysis presented uses with a first-hitting-time model with probability bounds to evaluate quasi-insolvency for two unique vertical farms. The UK farm results show that capital injection, robust data collection, frequent cleaning, efficient distribution and cheaper packaging are pathways to profitability and have a safer risk profile. For the Japanese farm, diversification of revenue streams like tours or education reduce financial risk associated with yield and sales. This is the first instance of applying risk and uncertainty quantification for VF business models and it can support wider agricultural projects. Enabling this complex sector to compute with uncertainty to estimate financials could improve access to funding and help other nascent industries.

Keywords: financial risk assessment; vertical farming; urban agriculture; probability bounds analysis; economic viability

1. Introduction

Agriculture faces a plethora of threats including unusual weather phenomena, water shortages and ageing rural populations [1]. These combined challenges require innovation in resilient farming methods to meet the demands of a growing population. Vertical farming (VF) is one such method that may contribute towards food and nutritional security.

VF is a novel form of agriculture, defined as multi-layer indoor crop production systems with artificial lighting, in which growth conditions are controlled [2]. Plants can be stacked vertically (in towers) or horizontally (in trays or gullies) [2]. The goal is simple, to produce more food with less land. It utilises controlled-environment agriculture (CEA) techniques, such as hydroponics with growing-specific light-emitting diodes (LEDs). Figure 1 maps the spectrum of agricultural systems across two gradients in technology and exposure to nature.

Indoor vertical farms, otherwise known as plant factories with artificial lighting (PFALs) [1], are typically the most technology-intensive and expensive. Consequently, they can control most growing parameters independently of external environment factors. This unprecedented level of control has enabled research to optimise production by fine-tuning variables, including light spectrum, temperature, and irrigation [3,4]. With such control, VF offers a host of advantages when appropriately managed, including higher yields all year round, quicker feedback cycles, longer shelf-life, and zero pesticide usage [1]. This form of agriculture can utilise the internet-of-things and big data to achieve smart factory performance [5]. The most popular crops to farm vertically are leafy greens, herbs, and microgreens due to high energy conversion to edible matter. Technically it is possible to grow any crop; however, economics and growing complexity constrain crop choice.

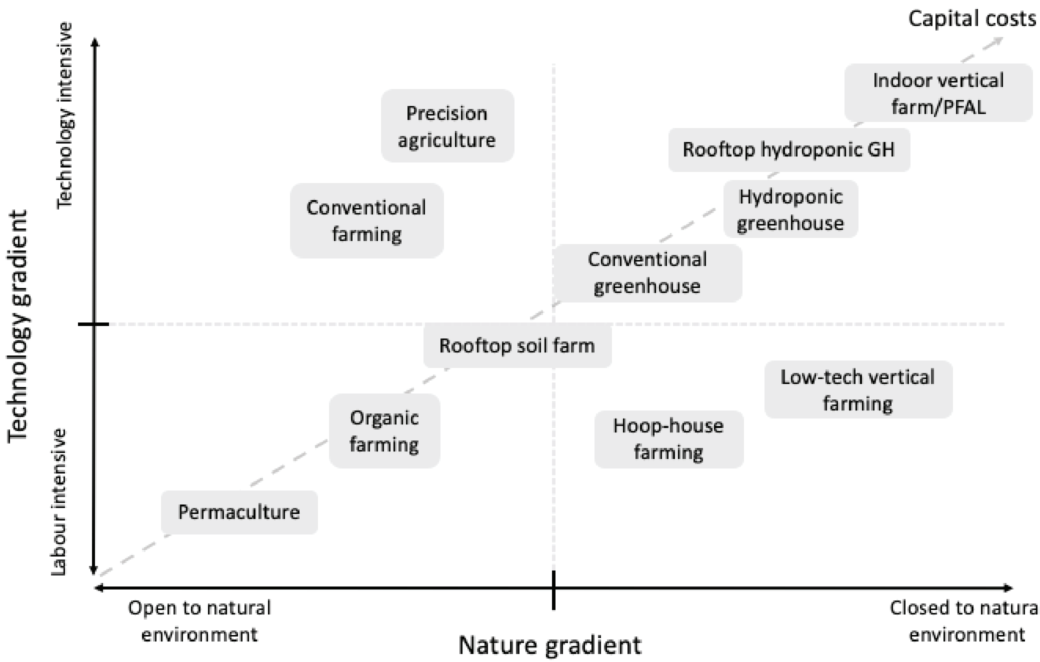

Figure 1. Spectrum of farm types (adapted with permission from C. Peterson & S. Valle de Souza [6]). Capital costs increase the further away a farm type is from the bottom left.

The industry has seen a surge of interest and significant investments in recent years [7–9], driven by advances in light-emitting diode (LED) technologies over the past decade. As a result, vertical farms are sprouting up worldwide, particularly in locations that make strategic sense (environments hostile to crops, regions with cheap electricity and markets for premium-quality food). The practice is not widespread and attracts scepticism. Criticism is focused on high capital and operational costs due to expensive equipment and the high-level expertise required to operate it, and high energy demands, which can result in low profit margins [2,10,11]. The learning curve is steep as the market, expertise, and technology begin to mature.

Market drivers are in VF's favour; however, there have been numerous failures over the past decade [12]. Continued investment is usually needed to sustain vertical farms; otherwise, they may bleed dry from negative cash flow [13,14]. Therefore, there remains hesitance to invest in VF [12,15]. A recurring complaint from investors, researchers, and practitioners is the scarcity of peer-reviewed research investigating economics underlying the construction and operation of VF [6,16–18]. Despite vertical farms operating in controlled environments and utilising data to optimise growing conditions, there is a lack of production, yield, and economic data available in the literature [12,18]. This is amplified by the absence of any standardised data framework and benchmarking. Variations in data quality due to complex climate controls and differing technologies, sensors, and yield measurement practices mean that data are not always applicable across farms. There are industry working groups now working towards standardisation [19,20]. The void of validated and peer-reviewed economic and risk data in the literature highlights a vital need for addressing the economics of VF so that it can be improved. One way to circumvent this is the utilisation of risk and uncertainty quantification techniques. In principle, risk management would reduce profit fluctuations and increase investments whilst raising farmers' income. As a consequence, improved access to finance could help with achieving sustainable development goals [21].

VF is a high-risk business, yet no efforts have been made to quantify and evaluate financial risk in the literature. There is a need to factor risk and uncertainty into business models for a more accurate assessment and to increase accessibility to funding [22]. This article explores whether VF economics can be analysed through a novel economic risk methodology, allowing imprecise random variables to assist farm owners and investors in making financially sensitive decisions. It aims to address the following research questions:

- How can farm economics be modelled with an absence of available production, risk and financial data to conduct economic viability and risk assessment?
- What is the risk profile for two case study farms, one of which benefits from a synergistic partnership with a landlord and cost deductions?
- How might a risk assessment tool be used to inform a profitable business model?
- The article is structured as follows:
- In Section 2, related works and their inability to accurately assess the economic viability of VF projects are discussed alongside potential risks;
- In Section 3, the model is proposed alongside the risk and uncertainty quantification methods, as well as the two case study farms;
- In Section 4, the results from the analysis are presented for financial metrics;
- In Section 5, the results are discussed alongside possible interventions to de-risk one case study, the implications of using the methods proposed in the broader industry, and the limitations of the analysis are discussed; and
- In Section 6, the conclusions are presented.

2. Related Works

In this section, the related works on the economics and risks of VF is investigated. Economic models on VF are grouped and then examined for their insights and challenges. Typical risks of the sector from VF and CEA are described.

2.1. Economic Analyses

There are 16 disparate economic analyses from academic and commercial sources detailed in Table 1. The literature reflects the nascence of the industry.

Table 1. Vertical farming economic analyses alongside their characteristics.

Type	Source	Objective	Results
Cost analyses	[23]	Simulate the economics for a hypothetical 37-storey (167.5 m) vertical farm hybrid in Berlin, Germany.	Cost of production presented through probability distributions. Costs lie between €3.5–4 per kg in 44% of cases. No validation.
	[24]	Simulate life cycle costing for a hypothetical 50 m^2 apartment to study small and inexpensive VF.	Sensitivity analysis results indicate added value crops such as herbs and pharmaceutical ingredients are necessary for economic viability. No validation.
	[22]	Provide a business planning spreadsheet developed for a hypothetical 1000 m^2 PFAL based on expert's and industry practitioners' insights. Most comprehensive data set in the literature.	Cashflow projections for a profitable farm with a 7.8 payback period.

Table 1. *Cont.*

Type	Source	Objective	Results
	[25]	Conduct feasibility study using central limit theorem to assess ROI for a hypothetical 5000 m^2 VF serving 24 canteens in Wuhan, China.	The breakeven on investment in this VF analysis is 11.5 years. Unviable crops are selected.
	[26]	Perform cost analysis for a hypothetical ZipGrow VF in São Paulo, Brazil comparing to Denver, North America, assessing its economic viability using vendor's data.	São Paulo provides a cheaper scenario in comparison to Denver, but possesses market conditions where low costs cannot compete with traditional farming product prices. Analysis predicts Denver as 14.17% IRR compared to −19.12% in Sao Paulo.
	[27]	Analyse the economics of a hypothetical six-story VF in Delhi, India, with a footprint of 200 m^2 and 3 stacked layers in each story.	Payback period calculated to be 64 years. Unviable crops are selected.
	[18]	Draw from hypothetical Japanese PFAL data [22] and substitute modern data in various scenarios (changes to scale, operations and market context).	Significant decline in capital costs, especially equipment (45%), make profitability increase substantially (ROI rose from 1.8% to 14.3%). Scale of operation is critical to profit as well and depends on the proportion of fixed costs in the operating structure. Doubling the size of the PFAL results in the enhancement of ROI from 14.3% to 22%.
Software systems	[28]	A flexible system for predicting costs and return-on the investment of a VF, with results shown for several hypothetical scenarios and sensitivity analysis.	Return on investment is sensitive to price of electricity, crop price and CO_2 concentrations. Software not publicly available.
	[29]	A commercial and flexible digital platform for economic estimation of farms, greenhouses and VF.	Capital expenditure, operating costs and yield estimates alongside 15-year projection. Not peer-reviewed or academically validated.
	[12]	Evaluate business sustainability using imprecise data techniques using ideas from [28]. The economic modelling contained within "How High is High Enough?" builds upon the framework and executes the first passage time risk analysis on two case studies.	N/A—No results presented.
Greenhouse vs. VF	[30]	Simulate a hypothetical scenario comparing profitability of growing lettuce in a semiclosed VF and semiclosed GH farm near Quebec City.	Results show that the costs to equip and run the two facilities are similar with higher gross profit for VF.
	[31]	Simulate scenarios to compare hypothetical VF and GH facilities under various financing schemes in Denmark.	Results show that regardless of financing scheme, the VF facility was much more profitable compared to the GH, with high IRR rates and a payback period between 2–6 years.
Industry surveys and reports	[32]	Present results of a self-reported survey of 56 indoor VFs (primarily in the USA).	Aggregated data for OpEx breakdowns per and profitable crops
	[11]	Present results of the government census of a number of profitable Japanese plant factories with typical production costs.	Aggregated data for production costs and percentage of profitable farms in Japan.
	[33]	Present results of a self-reported survey of 190 indoor VFs.	Aggregated and self-reported data on profitability and revenue.
	[34]	Design and cost an economically feasible next-generation VF concept. A workshop of experts design and cost five hypothetical food modules with margins to account for uncertainty.	The resulting concept is broken down into estimated capital expenditure and running costs.

Records and financial data on vertical farms are scarce, and this is demonstrated by the fact that most of the analyses are based on hypothetical case studies. The farms in these studies range from skyscrapers [23,25,27] to more realistic warehouses [35] and small-scale operations [24,31]. The sector has been notorious for being closed, yet it is starting to shift due to the immense complexity of combining elements of lighting, plant science, engineering, policy, architecture, and sustainability [19,36]. Currently, VF studies commonly extrapolate data from greenhouse literature [28,30,31], estimate values [23] or utilise projections from vendors [26,37].

Cost Analyses and Scenario Simulation

These analyses discuss the categories of capital expenditure (CapEx) and operational expenditure (OpEx) alongside the methods used to compute productivity and profitability [22–27,34]. Most of these struggle to provide a balanced assessment of feasibility of the VF projects due to an absence of empirical data. The complex nature of combining architecture, agriculture and digital technologies in an urban food-water-energy nexus context makes accounting difficult. The most comprehensive dataset of a vertical farm is a hypothetical PFAL in Japan [22]. One recent study expands on this dataset to test various scenarios with an updated capital cost reduced by 45% due reduction in equipment costs (changes to scale, operations and market contexts) [18]. It reveals that doubling the production scale with the same fixed costs can increase the return on investment from 14.3% to 21.7% [18]. Moreover, profitability hinges on commanding a premium price point whilst reducing costs (such as electricity through LED efficiency) without sacrificing produce quality [18]. It concludes that scale of operation, reduction in capital cost, and innovations in improving yield and produce quality are critical to profitability [18].

Economic Estimation Software

Customisable analyses are necessary to accommodate various scenarios and user inputs, especially as datasets are hard to come by. Tools exist that aim to help entrepreneurs compare different locations, systems, and business models [12,28], but only one is available for commercial use [29]. As a commercial tool, it lacks the rigour of peer-reviewed yield values and does not currently allow the user to consider any uncertainty or risks. Moreover, it is a black box and is therefore challenging to critique; [28] is not fully functional but the model informed [12], which provides the framework executed within this study.

Greenhouses vs. Vertical Farms

There are mistakes that can easily result from hypothetical data. Two studies conclude that vertical farms are more profitable than greenhouses in certain conditions [30,31]. Upon closer examination, the values for space utilisations (defined as floor space dedicated to growing divided by facility area) are unfairly skewed in favour of VF for both studies. Space utilisations are typically 50% for VF [11] and 60–90% for greenhouses [38]. Thus, the studies are misrepresentative of real farms. If an analyst adjusts the space utilisations to realistic values, then greenhouses are more competitive then the results suggest. If it were possible to compute with uncertainty about these assumptions, then perhaps false conclusions could be avoided. Neglecting depreciation is another critical mistake, as a comparison study claims that vertical farms are more profitable [30] without consideration for depreciation of vertical farming equipment like lighting. Greenhouses may use supplemental lighting but they are not in-use for up to 16 h a day all year, and therefore depreciation will happen at a much slower rate compared to VF.

Industry Surveys and Reports

These are the three analyses utilising real-life farm data, albeit two are self-reported surveys without auditing and are aggregated across different farm types, making them difficult to compare [32,33]. Nevertheless, they collectively cover a dataset of 461 vertical farms and provide some overview statistics including the percentage of profitable vertical farms increasing each year [37]. Some also include the percentages of cost components [11,32] and a snapshot of the average labour (0.0155–0.03 people per square metre) and water required (an average of 1.69 litres per square metre) [32].

2.1.1. Cost Components

Three elements primarily drive CapEx comprising 80–90% of costs: lighting, racking and grow system, and building [37]. The production costs consist of three major constituents that account for 75–80%: electricity, labour and depreciation [35,37]. There is no analysis whereby all cost components are considered. To highlight the disparity between both the real-life and hypothetical data for OpEx and CapEx, [37] collates all the available information for fixed and variable costs. This collation shows that researchers frequently omit heating, ventilation and air-cooling (HVAC), depreciation and CO_2 enrichment. Resource data are speculative in most cases.

2.1.2. Uncertainty

To date, most of the analyses rely upon deterministic models to predict cash-flows [26,27,29,30,34,35,39,40]. Scarce data have forced researchers to utilise uncertainty quantification techniques in order to bolster analyses and improve accuracy [24,25,28]. World-leading researchers in plant factories claim that a risk scenario approach would benefit the sector but would require industry-wide research and cooperation (involving horticultural scientists, farm operators, equipment manufacturers, etc.) [35]

Stochastic methods are utilised in several models, such as central limit theorem [25], scenario analysis [23,31], sensitivity analysis [24,28] and probability bounds analysis [12]. Sensitivity analyses determine that profitability is sensitive to electricity price, crop price, sunlight contribution, photosynthetic photon flux density, and LED fixture efficacy [24,28]. These factors highlight the importance of electrical efficiency and suitable sales models.

2.1.3. Limitations

The primary source of error is that many of these analyses utilise speculative assumptions without accommodating uncertain inputs. An attempt to calculate uncertainty would represent more realistic cash flow predictions, especially as projected yields and costs can be misrepresentative [14]. Researchers often overlook HVAC costs in most economic analyses due to their complexity. Additionally, labour is costly, and automation solutions like seeding machines, packaging machines, and nutrient delivery systems are popular solutions, yet no analyses consider automated systems in their cost breakdowns. Researchers and industry practitioners recognise the need for more detailed economic analysis that model all the variable costs to inform business models and financial investment [18,23,28,41]. Without this and the lack of proven business models, there is insufficient evidence to address criticisms regarding profitability. Moreover, all of the analyses are for unique farms and production systems with differing levels of technology and operating with different economies, making performance not directly comparable.

The learning curve is a vital element considered in only two cases [12,29]. Farms can experience an improvement in yield and produce quality depending on growing experience, wastage and the optimisation of parameters [29]. This improvement should be tracked in future studies for validation.

No studies have addressed the fundamentals of microeconomics, such as maximising profit and average cost curves. This would enable the assessment of economies of scale and finding the ‘sweet-spot’ in terms of facility sizing. Access to real data would reduce epistemic uncertainty in analyses. A credible foundation for literature will then develop. Computational uncertainty quantification could compensate for lack of available data. Lastly, risks and opportunities can be applied. A tool that could achieve this can inform decision-makers of VF viability with confidence and avoid costly failures. Other limitations are discussed within a review [37].

2.2. Risks and Opportunities

The VF sector is littered with failed start-ups, some of which have been spoken about publicly [42,43] and many that go unreported. Reasons for ceasing trading include:

1. cash flow problems [14,44];
2. underestimated labour costs due to operational complexity [14,42,45];
3. lack of adequate knowledge and accessible education about the integration and operation of vertical farming systems (irrigation, lighting, plant science, HVAC and manufacturing systems) [14,42];

4. inefficient workflow and inadequate ergonomic design consideration [14,42,46];
5. low profitability margins [46];
6. sources of capital investment and the misalignment of support and expectations from funders [42];
7. zoning codes and regulatory obstacles [14,47];
8. equipment failures and associated repair costs [42,48]; and
9. poor early decisions around pricing, crop selection and location [12,42,49,50].

These failures are acute because of the high CapEx investments required. The economic analyses omit all these risks that may influence crop productivity, sales, and profitability [14]. No empirical data exists for the frequency and impact of such events in VF except for anecdotal reports [14]. On the other hand, the literature on risk analysis in greenhouses and field-grown agriculture is more mature [51–59]. The sources of risk range widely. As indoor farming climbs the technology and nature gradient (see Figure 1) its risks shift away from external environmental factors and towards production risks associated with technology. Table 2 identifies and ranks the likelihood for risks for field-grown produce, greenhouses from the literature and compares against vertical farms based on anecdotal reports [14,42].

Table 2. Risk identification and corresponding likelihood for vertical farm, greenhouse and field-grown produce (cf. [14,51,57,60–62].)

Risk Parameters	Risk Source	Indoor Vertical Farm	Greenhouse	Field-Grown
Yield risk	Weather conditions	Low	Medium	High
	Pest outbreak	Low	Medium	High
	Pathogen outbreak	Medium	Low	High
Production risk	Environmental control (malfunctioning HVAC)	High	Medium	Low
	Electrical outage	Medium	Low	Low
	Incorrect nutrient/pH dosage	Medium	Low-Medium	Low
	Irrigation (flooding, clogs)	High	Medium	Low
	Equipment failure	High	Medium	Low
Cost risk	Energy expense variability	Very High	High	Low
	Underestimated labour costs	High	Medium	Low
	Technology advances	High	Medium	Low
Labour risk	Poaching of staff/Loss of expertise	High	Medium	Low
	Accidental damage	High	Medium	Low
Safety risk	Fire	Low	Low	Low
Planning risk	Zoning codes	High	Medium	Low
	Change of lease agreement	High	Medium	Low
Market risk	Market competition	Medium	Medium	Low
	Local supply/demand situation	Low-Medium	Low	High

Economists model such risks according to probability distribution functions known to decision-makers [57]. However, in empirical analyses, researchers almost never know the true probability distributions [57]. Economists assume that decision-makers hold beliefs consistent with known probability distribution functions. Rather than assuming the exact distribution whilst lacking adequate data, imprecise data techniques are better suited for estimating this.

Innovations in the VF sector have arisen to address the challenges and improve unit economics in an increasingly competitive market. Therefore integrating opportunities are equally important to consider. PFALs in Japan report that cost performance can be radically improved by reducing production costs and increasing annual sales [35]:

- A 50% increase in sales is achievable within five years by adjusting environmental control setpoints, selecting better cultivars, improving the cultivation system and reducing waste [35].
- A 50% reduction in production cost is possible through improving labour and electrical efficiency [35]
  - Automation, process flow and human resource development can reduce labour costs.
  - A 50% reduction in electrical cost is attainable within several years through the intelligent operation of electrical systems, insulation, LED efficiency advancements [35] and load shifting [63].

Other opportunities such as new customer contracts, introducing new technologies and scaling plans are out of the scope of this article.

3. Methodology

This methodology is broken down into several sections:

1. The economic model containing its framework and assumptions to calculate cashflow forecasts and return on investment (ROI);
2. The risk and uncertainty analysis, which describes the methods used, why they were used, the risk profiling results and the risks that will be considered within this analysis;
3. The case studies and associated data for a real-life and hypothetical farm.

3.1. Economic Model

The economic survivability model is a flexible and robust means to conduct financial risk assessment by combining historical data with risk and uncertainty quantification to fill gaps in knowledge. This method is based on previous work [12]. The model functions through a series of modules that interprets inputs based on the local market, selected crops, farm characteristics, labour, consumables and more. The flow of tasks is illustrated in Figure 2.

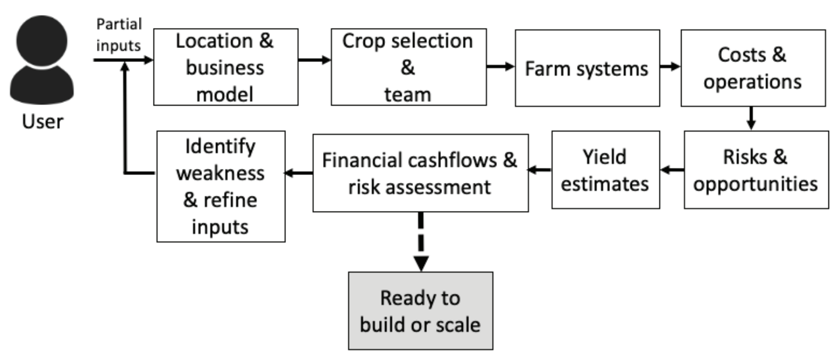

Figure 2. Flow chart of user interactions with model.

The model computes cashflow forecasts and ROI based on either farm inputs or default values. Default values are estimated by decisions on location, system selection, crop type, farm size and other inputs based on the literature [12]. Once the inputs have been gathered, risk analysis is conducted using first-hitting-time, which will evaluate whether the farm is likely to fall under certain criteria in the future when accommodating for risks as well as reported opportunities. The novel application of probability bounds analysis enables the use of both complete and partial inputs where the specified farm (in planning or operational stage) does not have complete information.

Figure 3 shows the simplified flow of computation and cost components from left to right, whilst omitting the interdependencies inherent in plant growth. The model calculates revenues and costs such as CapEx, OpEx and cost of goods sold (COGS) for resulting ROI. To illustrate how the model functions to compute risk profiling, Figure 3 is labelled with numbers 1 to 11 corresponding to equations available within the Supplementary Method Statement. This information is collected through a series of spreadsheets before being processed by a Python script to apply uncertainty quantification and produce cashflows with risk profiles for quasi-insolvency. This is applied across all the potential scenarios based on user uncertainties, risks, and opportunities, relevant to the farm type. The resulting analysis is a 15-year projection for financial metrics and resource consumption, as the typical lifetime for a vertical farm is approximately 15 years [11].

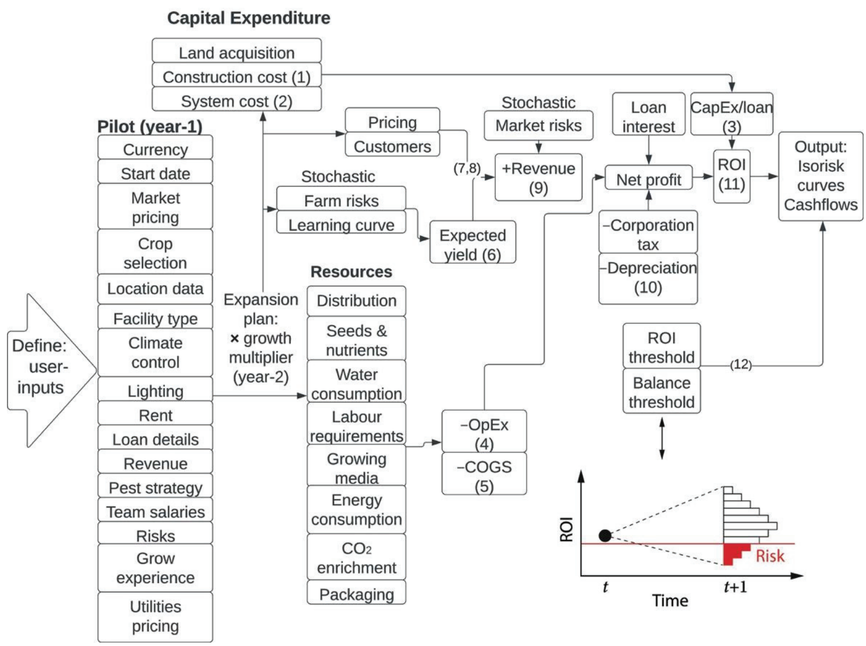

Figure 3. Financial risk model structure (flow left to right) utilising Equations (S1)–(S12).

Refer to Supplementary Method Statement for detailed breakdown of the model including its equations, assumptions and references.

3.2. Risk and Uncertainty Analysis

Stochasticity is included through random parameters such as failure rate, improved yields over time, repairs, infrastructural issues, potential pest or pathogen outbreaks and other risks. The user can also manually insert uncertainty for any parameter. How can these be accounted for if the distributions and values are unknown? Probability bounds can capture all information, even if there is only limited information available.

Probability bounds, expressed as bounds on cumulative distribution functions, are called "p-boxes" [64]. They can be used to characterise uncertain parameters, distributions, risks and opportunities without requiring overly precise assumptions [65]. There were other uncertainty techniques that could have been used instead, like Monte Carlo simulation or worst case analysis. However, this would require untenable assumptions, such as the uncertainties being small, the distribution shapes are known and the relevant science is modelled [66].

This is not the case, and p-boxes can overcome these limitations through using all the information available (even if partial) without making over-simplified assumptions. Figure 4 shows how imperfect information may be presented in a p-box form on a cumulative distribution function (CDF) whereby A's distribution is known, but not its parameters, B's parameters are known, but not its shape, C has a small empirical dataset, and D is known to be a precise distribution.

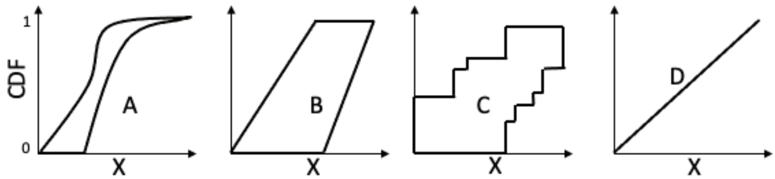

Figure 4. Probability boxes representing different types of uncertainty (cf. [66]).

The integration of probably bounds analysis enables model inputs with partial information such as an input interval of 30–50 h of direct labour per week (expressed as an min-max interval '30,50'). Moreover, the probability of a pest outbreak occurrence in a given year might be between 35–70% with a single best estimate of 50% (min-max-mean '30,70,50'), with the associated impact being 0–25% of annual yield conveyed as a beta distribution. A breakdown of the risks and their weighting according to model parameters is included within the method statement and found within 'risk_pba.py' within the Model Library in Supplementary Materials. The central limit theorem may be incorporated to give a yield estimate using a normal distribution rather than a precise value [25]. This approach accounts for risks and opportunities that would be nonsensical to provide a precise probability or impact without any historical or peer-reviewed data. In this analysis, the 'pba' package on Python [67,68] was extended to execute the probability bounds analysis necessary.

Once p-boxes are integrated within the model and a simulation has been executed, the resulting finances are analysed. The probability of the cashflows and projected ROI falling below a 'bankruptcy' threshold can be used to predict the event of insolvency defined as the first-hitting-time. First-hitting-time is a method used commonly to predict 'survival' in economics [69,70] and other disciplines [71–73]. This hybrid approach of p-boxes with first-passage time has only been applied in one instance for calculating ecological extinction risk [72], and would allow the assessment of financial risk despite deep uncertainty. As historical data and refined inputs are added, the p-box would shrink in size to compute more precise risk-profiling and financial projections.

The quasi-insolvency thresholds are defined as cashflow becoming negative (T_B) and an ROI under a threshold specified by the user (T_{ROI}). Based on a review of bankruptcy models that evaluated whether the most important and frequently used financial ratios are within the profitability group [74], this analysis focuses on the profitability metrics to assess insolvency. The company under analysis is at risk of insolvency when they have no capital runway, which means they will collapse if they do not raise additional capital whilst their revenues and expenses remain unchanged. For ROI, a venture capitalist would typically look for a return of 10–20%+ [46]. The threshold for ROI may vary with time according to investor demands. The probability of insolvency for a given year (INS) is therefore defined in Equation (1).

$$P(INS) = P[\,(B < T_B)\ \&\ (ROI < T_{ROI})] \quad (1)$$

The p-box represents all the possible scenarios modelled and the probabilities of insolvency. The resulting risk analysis can be made useful by introducing categories defined by probability of insolvency over some defined time scale:

- *Critical:* 50% probability of insolvency within 3 years
- *Substantial risk:* 25% probability of insolvency within 5 years
- *Moderate risk:* 10% probability of insolvency within 10 years
- *Safe:* Less than 10% probability of insolvency within 10 years

These categories are mapped onto the analysis to communicate the level of uncertainty and risk profile of the farm. Figure 5 shows an example of the risk assessment. The p-box (shaded in grey) primarily falls within the moderate risk category with some creep into safe and critical due to a large degree of uncertainty. This highlights a lack of either precise inputs or information about impacts and the frequency of risks. The future is unknown, but with risk mitigation and corrective action the risk profile could be improved.

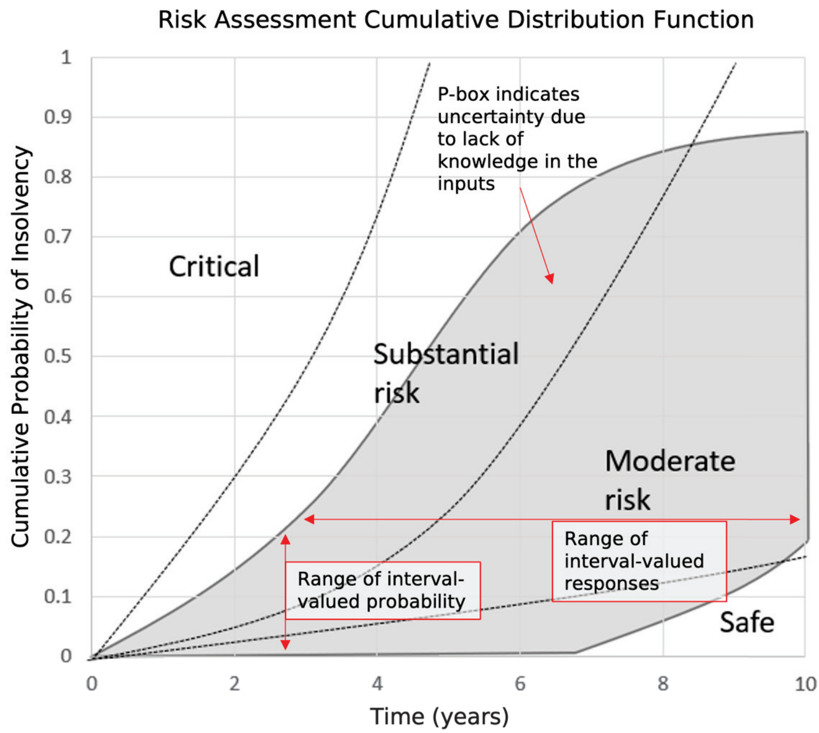

Figure 5. A risk curve using probability bounds (shaded in grey) and first-hitting time to evaluate the risk profile of a VF insolvency.

3.3. Farm Case Study Inputs and Assumptions

Two vertical farm case studies are used for this analysis: a real commercial vertical farm based in the UK and a hypothetical vertical farm in Japan informed from the literature [35]. The data for the UK case study is for a small-scale commercial VF and has been collected on-site. The information for the Japanese farm is a complete business plan example available within the literature based on the real-world experience of twenty scientists and business managers in the sector [22]. Both examples have been selected because their crop choice of leafy greens is the dominant cultivar in this sector [75]. The methodology described will be applied to both case studies in order to evaluate their profitability and risk profiles. The assumptions about the farm are listed in Table 3.

Table 3. Assumptions for UK and Japanese case studies (cf. [22]).

UK Vertical Farm	Japanese Vertical Farm
1. The farm has been retro-fitted and installed into a basement rented from a school. The school subsidises rent, electricity and water costs.	1. The farm has been constructed within a leased purpose-built facility.
2. The facility is a pilot with plans to double production capacity in the next year. Therefore, the analysis considers both the pilot and full-scale plan.	2. The facility is at full production capacity with no plan to expand.
3. Vertical towers were modelled as a growing area. The farm's imprecise yield data are used to form upper and lower bounds to compensate for the lack of robust data collection.	3. Nutrient Film Technique (NFT) racks were modelled with the annual yield provided in the example.
4. Lettuce cultivars are grown with twelve plants per tower and a growth cycle of 21 days (after 25 days in the propagation system).	4. Lettuce heads are cultivated in four phases at different spacing: 1st seedling (8 days), 2nd seedling (10 days), transplanting 1st (8 days), transplanting 2nd (8 days).
5. Alternative revenue streams (such as education) are omitted to assess the farm in isolation.	5. No alternative revenue streams are included.
6. Water consumption data are tracked on the farm for 15 months and have been characterised per month: min = 1325 L, max = 8325 L, mean = 3730 L, Standard deviation = 2039 L. Multiplied by 2 for the scaled-up plan.	6. Water costs have been grouped with electricity costs.
7. The facility has a pre-existing HVAC system that has no associated capital costs.	7. A bespoke HVAC system was installed.
8. The indirect team consists of three staff (head grower, marketer, manager).	8. Indirect staff costs were not considered by [22]. This analysis assumes five staff members (CEO, head grower, marketer, engineer and admin).
9. The farm is partly grant-funded for two years.	9. The project is funded with zero interest rates, according to [22].
10. The farm is partially insulated within a thick-brick walled basement but is not sealed, which reduces the climate control capacity.	10. The facility is insulated and benefits from a strictly controlled environment.

A summary of characteristics for the scaled-up UK farm and the hypothetical Japanese are given in Table 4. Then, a capital cost breakdown (Table 5) is followed by an operational cost breakdown (Table 6).All inputs can be found in the Supplementary Data, Tables S10 and S15. All values are converted to GBP with a conversion rate of 1 USD = 0.72 GBP.

Table 4. Farm characteristics summary for UK and Japanese farms (adapted with permission from [22]).

Characteristic	UK Farm	Japanese Farm	Unit
Real Estate			
Facility size	220	1000	m^2
Facility height	3	3.5	m
Space utilisation	45	36.4	%
Growing space	100	364	m^2
Systems			
Grow levels	30 towers per rack	6 shelves	
Number. of racks	16	241	
Stacked growing area	392	2184	m^2
Number of lights	256	5784	
Light wattage	100	32	W
Energy price	0.073–0.108	0.090–0.100	£/kWh
Annual electrical consumption	224,255	1,676,052	kWh

Table 4. *Cont.*

Characteristic	UK Farm	Japanese Farm	Unit
Labour			
Number of direct labourers	3	9	people
Number of indirect staff	3	5	people
Direct labour hours per week	20	42	hours per person
Direct hourly cost	9.50	7.34	£/hour
Crop: Lettuce			
Annual yield	8800–10,800	116,640	kg/year
Harvest weight	0.1	0.09	kg
Photoperiod	16	16	hours
Product weight	0.3	1	kg
Customer segmentation	85 (customer 1) 15 (customer 2)	100	% to customers
Unit prices	7.50 (customer 1) 3 (customer 2)	8.64	£/unit
Packaging cost	0.85	0.05	£/unit
Attributes [1]			
Business model	Hybrid	Wholesale	
Grower experience	Medium	High	
Automation level	None	Medium	
Climate control level	Medium	High	
Lighting control level	Medium	High	
Nutrient control level	Medium	High	
CO_2 enrichment	No	Yes	
Biosecurity level	Medium	High	

[1] Definition of input is detailed in method statement in the Supplementary Materials.

Table 5. Capital cost breakdown for full-scale UK and Japanese farms (adapted with permission from [22]).

Capital Costs	UK Farm	Japanese Farm	Unit
Construction			
Finishing	3850	114,775	£
Appliance	4250	108,000	£
Management costs	9029	0	£
Electrical infrastructure	8020	25,200	£
Real estate	0	0	£
Total construction costs	25,149	247,975	£
Systems			
Growing system cost	55,071	747,072	£
Lighting system cost	87,165	538,804	£
HVAC system cost	2700	56,160	£
Miscellaneous cost	9548	0	£
Total equipment cost	154,484	1,342,037	£
Total capital costs	179,633	1,590,012	£

Table 6. Operational costs breakdown for the full scale UK and Japanese farms (adapted with permission from [22]).

Production Costs	UK Farm	Japanese Farm	Unit
Operational expenditure			
Rent	0	69,120	£/year
Staff costs (non-direct labour)	70,236	171,888 [1]	£/year
Distribution	31,172	106,691	£/year
Other costs [1]	1404–6039	8594 [1]	£/year
Total OpEx	108,998	356,293	£/year
Cost of goods sold			
Direct labour costs	29,640	142,689	£/year
Growing media	5735	14,818	£/year
Packaging	22,977–32,078	2905	£/year
Total electricity cost	15,929–23,416	150,844	£/year
Water cost	97.59	N/A	£/year
Total COGS	104,000	375,192	£/year
Other costs			
Depreciation	20,417	162,454 [1]	£/year
Working capital	251,504	2,160,000	£
Loan amount	158,000	0	£
Loan tenure	7	0	years
Loan interest	5	0	% per year

[1] Inputs have been modelled based on assumptions in absence of data.

4. Results

The case study business scenarios (in Section 3.3) are simulated over a 15-year period, the typical lifetime of a vertical farm [11], for cash flows and financial risk analysis. They enable the evaluation of economic viability. The graphical results depict the lower bound on the 2.5th percentile (labelled as 'Min'), the upper bound on the 97.5th percentile ('Max'), the lower and upper bounds on the median (labelled as 'Lower Median' and 'Upper Median') of each variable of interest. The median provides insight into the value at which 50% of all the possible scenarios are above or below.

Each case study will include financial balance, annual yield, return on investment and risk assessment. Two of these metrics, financial balance and return on investment, are used to compute the risk of insolvency and therefore include a threshold. In this analysis, the risk is defined as the combination of negative cash flow and underperforming ROI, which is characterised by probability. The cumulative probability of both of these metrics falling under their respective thresholds simultaneously dictates the risk visualised. The model can easily be generalised for other financial metrics or definitions of risk. Other financial metrics and their respective max–min cases considering with and without risks and opportunities are presented in the Supplementary Data in Section 1.5 (UK farm), 1.7 (UK farm post-intervention), and 2.5 (Japanese PFAL). The full results can also be found as 'results_UK.py', 'results_UK_post.xlsx' and 'results_JPFA.xlsx' for the UK farm, UK farm post-interventions and Japanese farm respectively within the Model Library in Supplementary Materials.

4.1. UK Vertical Farm

The UK small-scale farm begins its operations with a financial balance of £180,000, which is projected over the 15-year period (see Figure 6) with increasing uncertainty. 50% of the scenarios represented by the median are split above and below the risk threshold.

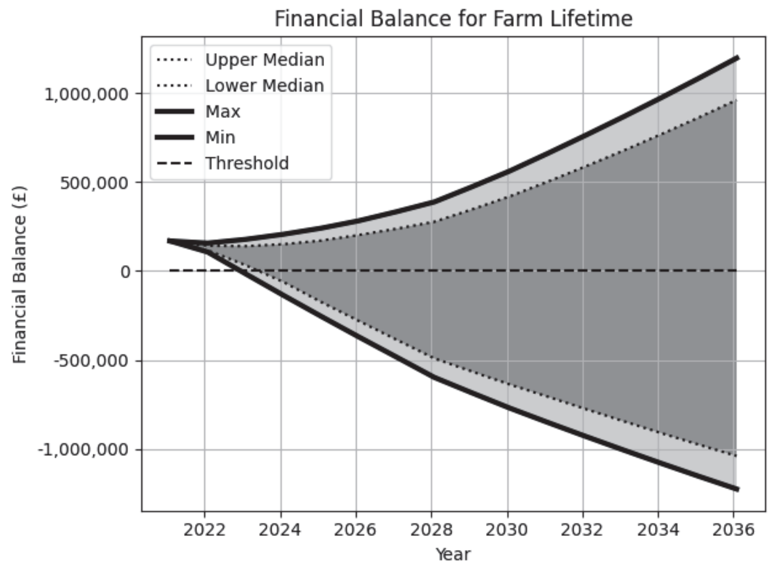

Figure 6. Uncertainty about financial balance for the UK farm over the 15-year simulation.

The annual yield for the UK farm for lettuce production is shown in Figure 7. There is a sudden increase in yield as the farm scales to full production (doubling the amount of growing systems in the facility) in 2023. There is also a high degree of uncertainty due to the lack of accurate yield tracking on the farm and the possible effects of pathogens and pests. The median is large due to input uncertainty without statistical data such as light efficiency improvements and electricity price. The effect of reducing waste and improving yield as the farm staff gain experience is reflected in the positively increasing gradient of both the max and min scenarios.

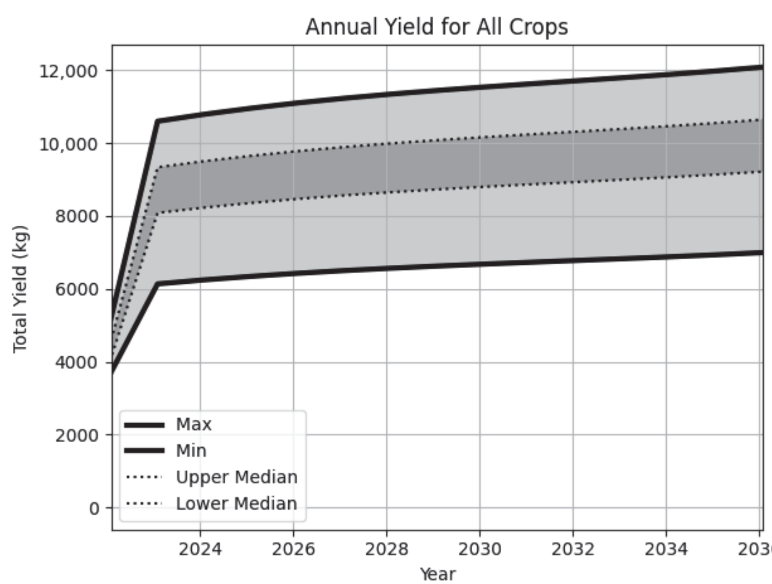

Figure 7. The annual yield for the UK farm has a range between 6000 kg and 11,000 kg after scaling up in 2023. The median annual yield would be around 8000 kg, and this will increase with experience.

Figure 8 shows the ROI over the farm lifetime. The UK farm has a predicted 15-year cumulative net profit between −£1.50 million and £1.02 million, with an ending ROI of −42% to 61%. The increases are representative of three aspects in chronological order: (i) scaling in production in 2023; (ii) repaying the full loan amount in 2029; and (iii) upgrading to more efficient LED lighting in 2031. Despite these improvements, 50% of the scenarios fall below the required ROI threshold.

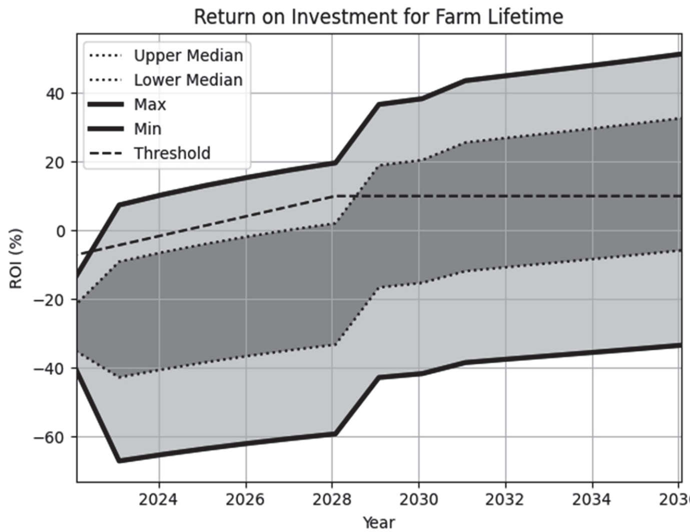

Figure 8. ROI potential for UK farm.

The resulting risk assessment for both the financial balance and ROI falling under their respective thresholds is shown in Figure 9. It paints an unfavourable picture of the farm, with all considered scenarios between critical and safe after a 2-year timespan indicating large levels of uncertainty and therefore no conclusion can be drawn. This prompts urgent corrective action to fix the business model, improve data collection practices and improve risk mitigation measures to reduce uncertainty. Interventions are discussed in Section 5.3.

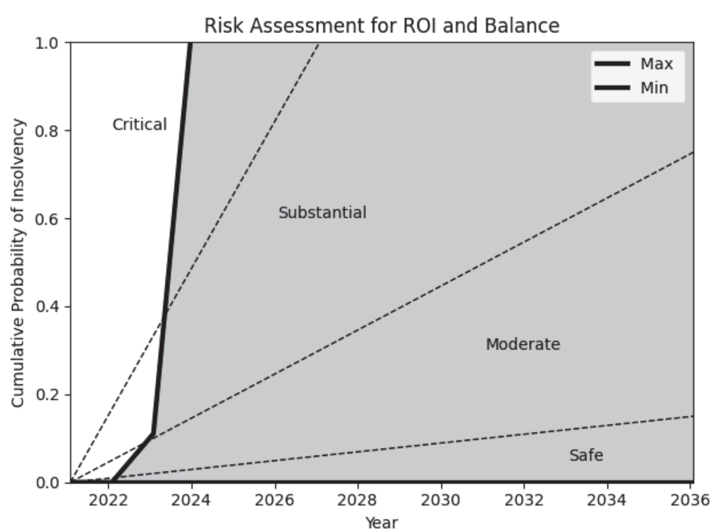

Figure 9. Risk profile for financial assessment for the UK farm.

4.2. Japanese Vertical Farm

The Japanese farm begins its operations with a financial balance of almost £570,000 and is projected over a 15-year period (see Figure 10). The graph has a narrower median compared to Figure 6 because the data provided are more precise. Over 50% of the scenarios, indicated by the dark grey area, are above the financial balance threshold, indicating a profitable business case.

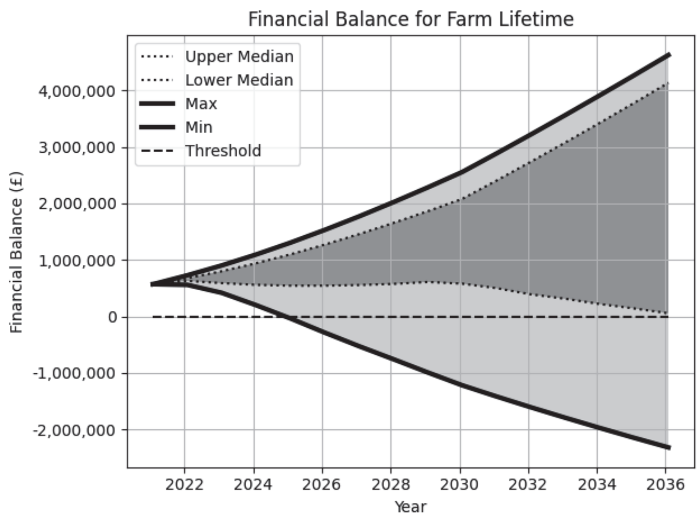

Figure 10. Uncertainty about financial balance for the Japanese farm over the 15-year simulation.

The annual yield for the Japanese farm for lettuce is shown in Figure 11. There is less uncertainty as the yield tracking is precise compared to the farm in Figure 7. The uncertainty remains due to improvements in crop varietals, labour efficiency and growing environment, whilst also having a risk (albeit lower than the UK farm) of pests, pathogens or customer withdrawls.

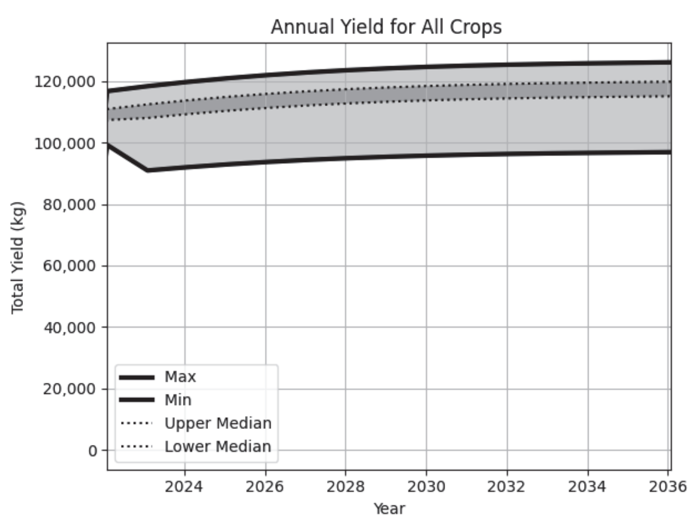

Figure 11. Annual yield for Japanese farm has a range between 90,000 kg and 120,000 kg. The median annual yield is 110,000 kg.

The Japanese farm has a predicted 15-year cumulative net profit between −£2.6 million and £4.6 million, with an ending ROI of 0% to 23%. Figure 12 shows the ROI over the farm lifetime. Most of the scenarios are profitable and have a positive ROI and after the light efficiency improvement in 2031, over 50% of the scenarios are above the ROI threshold.

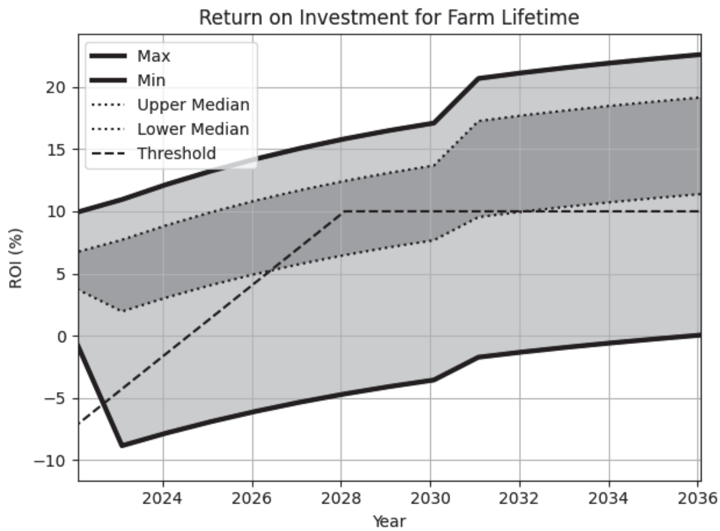

Figure 12. ROI potential for Japanese farm.

The resulting risk assessment for the combination of financial balance and ROI falling under their respective thresholds is shown in Figure 13. If no risks occur, the farm has 0% probability of insolvency and is in the safe region (best case). If risks such as power outages, equipment failures or crop failure (due to pests or pathogens) occur then the risk of insolvency reaches a 75% cumulative probability by 2029 (substantial risk). The future of the farm therefore lies between substantial and safe risk.

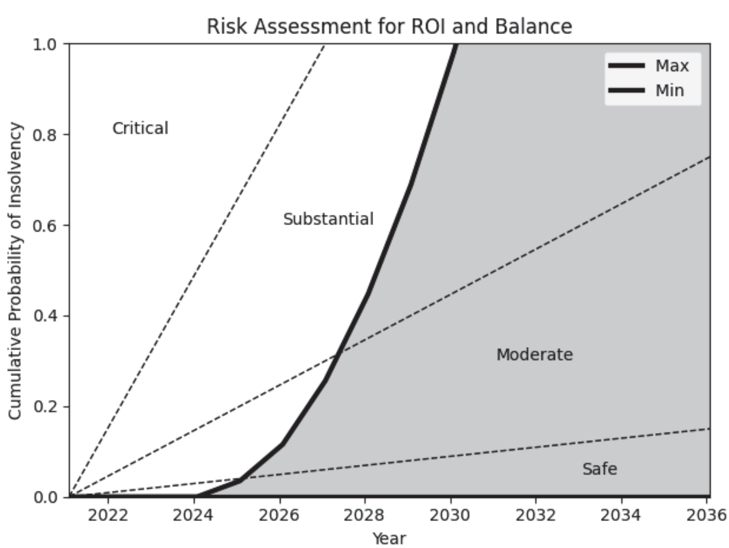

Figure 13. The risk profile for the cumulative probability of insolvency over 15 years shows that the Japanese farm has a safe to substantial risk profile.

5. Discussion

The model has simplified financial risk assessment by allowing businesses to calculate with both aleatory and epistemic uncertainty without overly precise assumptions using probability bounds. As the VF sector is still in its early stage, entrepreneurs struggle to estimate specific inputs and risks, and this method allows users to sidestep these issues. In this study, a real-life farm (UK) and a hypothetical farm (Japanese) are analysed to evaluate their risk profile in Figures 9 and 13 according to Equation (1). Default risks considered in this analysis are included in Table 2 of the method statement and analysts can create or customise their own risks using 'risk_pba.py' in the Model Library in Supplementary Materials. Users can determine whether the farm is operating at an appropriate scale and with adequate design to make a viable business model. Existing deterministic tools are not sophisticated enough to simultaneously offer best- and worst-case analysis with probability. Applying probability bounds analysis within the context of financial forecasting has never been conducted before within the academic literature. The complexity of indoor VF demands new approaches like this, as many farms have been unable to estimate economics before construction, likely resulting in either unsuccessful fundraising or wasted investments. This section discusses the two case studies, followed by proposed interventions and their effects on the UK case study. The broader implications of using this method are then described, followed by the method's limitations.

5.1. UK Farm

Prior expectations for the farm were made based on vertical tower vendor spreadsheets estimating 19,800 kg per year of 'leafy greens' yield extrapolated from the thesis of the vertical farming tower inventor [40,76]. Based on farm data collected for this analysis, an estimated 10,800 kg per year of lettuce will be achieved without intervention, which is 45% less than expected, resulting in drastically reduced profitability prospects. The dilemma for the UK farm is that it is currently operating at a loss and projections for both financial balance and ROI intersect below the thresholds for the majority of the lifetime of the farm. Drastic changes in the business model are required to mitigate this risk. Despite a rent-free location, low-cost labour, and subsidised energy expenditure (up to 50% off the UK average), the potential costs could still outweigh the company's revenues despite the hefty prices that they charge for produce. This indicates that subsidised bills are likely necessary components that should be sought out when developing a viable VF business model. It is worth noting that this analysis has been conducted during the coronavirus pandemic, in which many hospitality businesses are struggling. Customer focus has shifted from a business-to-business model to a business-to-consumer model, and delivering directly to homes has resulted in higher marketing, packaging and delivery costs. This may have led to a costly product and a critical risk profile. The case study was also isolated without considering other revenue streams, such as education-related income, to glean insights into the unit economics of the farm. The lack of hard data, especially for yield, has made evaluating the economics difficult for current farm activities up until now. This analysis enables computation despite unknowns and provides a quantitative evaluation to correct the course towards a financially safer risk profile.

There is a noticeable increase in positive ROI potential due to loan repayments ending and improved lighting efficiency starting in 2028 (Figure 8). However, the likelihood of ROI falling below the threshold is substantial, with over 50% of scenarios (shaded in grey) earning insufficient ROI. Further investment is required to be able to keep the farm financially afloat and make necessary changes towards economic sustainability. The model allows experimentation of potential interventions to form a roadmap to profitability. It has achieved this already during validation, as the analysis informed real business changes for the case study farm owners, such as more accurate data collection and adjustment of packaging and distribution methods.

5.2. Japanese Farm

Compared to the PFAL referenced [22], this analysis accounts for additional fixed costs like depreciation, staff salaries, and other costs to make it more realistic (see Table 6). Therefore, it is expected that the analysis would reveal a reduced ROI (calculated as net profit divided by capital costs) compared to the literature example. In the literature, the PFAL has a 20.5% ROI after five years, whilst this analysis predicts a −5 to 15% ROI after 5 years (50% of the farm scenarios have an ROI between 6–12.5%). The annual yield is the same as the example and is comparably higher per square-metre (117 kg per m^2 per year) than the UK farm (49.1 kg per m^2 per year). This is because the PFAL has been improved for crop varietal, crop growth recipes and labour efficiency.

The Japanese farm has a positive outlook with a risk profile between substantial (worst case) and safe (best case) in Figure 13. The unit economics are profitable, and the farm is more resilient to the risks affecting the smaller UK farm (small repairs, pest outbreaks and electrical outages). On the other hand, the Japanese farm may be more prone to labour challenges (due to a larger team size and low-cost workers), costly equipment failures and customer withdrawal (market shocks) from a supermarket for example. The average financial balance and ROI is over the threshold for the most part. However, the size of the P-box is still covering multiple zones indicating uncertainty, primarily driven by the lack of empirical data for the risks and opportunities. The risk profile is more favourable than that for the UK farm and represents an ideal farm in a more mature market. There is still a significant probability of insolvency from 2025 onwards. Changes could be made to the business model such as seeking alternative revenue streams; however, a substantial risk profile is to be expected in an innovative sector. Because the case study is hypothetical, it is not possible to say whether the risk assessment is wholly grounded in reality. Certain aspects, such as the high yield, should be probed further. If desired, the model could be used to trial other decisions and risk mitigation strategies to see how this may reduce financial risk to a safe investment.

5.3. Interventions to the UK Case Study

The model allows for consideration of alternative decisions to visualise how they alter the farm's business model and risk profile. The UK farm is in a situation of critical risk, and therefore interventions will be focused on this case study. The proposed adjustments could course-correct the farm (defined in Table 3) towards more favourable unit economics and a reduction in pathogen and pest risks. Moreover, diversifying revenue streams would reduce reliance on an optimised growing environment that may be difficult to achieve in a retro-fitted structure. Interventions are suggested in Table 7 based on learnings from the results in Section 4.1 and through experimentation with model inputs.

Table 7. Suggested interventions for UK case study.

Intervention	Input Change	Result
Tailor nutrient solution composition to specific lettuce varietal	Nutrient control: medium to high	Improved yield and produce quality by ~10% [1]
Provide carbon dioxide enrichment	CO_2 enrichment: no to yes	Improved yield and produce quality by ~10% [1]
Improve climate control through HVAC system	Climate control: low to medium. Additional 5–20% energy costs	Improved yield by ~5% [1] and reduced likelihood of pathogens and pests [2]
Alter packaging solution with digital information rather than printed leaflets	Reduce cost from £1.00 to £0.70 per unit	Reduced unit costs
Adopt robust biosecurity protocol requiring more regular cleaning of the systems	Biosecurity control: medium to high	Reduced likelihood of pathogen outbreaks [2]

Table 7. *Cont.*

Intervention	Input Change	Result
Use efficient distribution channels by focusing on bulk customers	Distribution unit costs are reduced by 50%	Reduced unit costs
Acquire further capital funding for proposed improvements	£100,000 grant in year 2	£20,000–30,000 additional capex
Utilise load shifting to optimise electricity prices (see [63])	From £0.073–0.108 to £0.073–0.085	Reduced unit costs
Introduce tours of the farm with a dedicated tour guide	£2000 revenue per month (10% increase/year) and tour guide salary budgeted	Increased revenue and mitigate risk of crop failure severely affecting income
Account for higher expenses associated with CO_2, nutrient solution, biosecurity and tour marketing	From 2% to 5% of salaries	Increased costs

[1] See Equation (S6) in method statement, [2] see Tables S2 and S3 of method statement.

The input changes for the model in Table 7 are changed within 'main_pba_UK_Farm _interventions.py' which affect the results according to the method statement. The crop limiting factor is still not entirely understood, and crop growth factors like CO_2 factor and nutrient factor effects are estimated according to [28]. The effects of these adjustments can be seen in financial balance and ROI projections (Figures 14 and 15, respectively). The combination of these two metrics results in financial risk assessment shown in Figure 16.

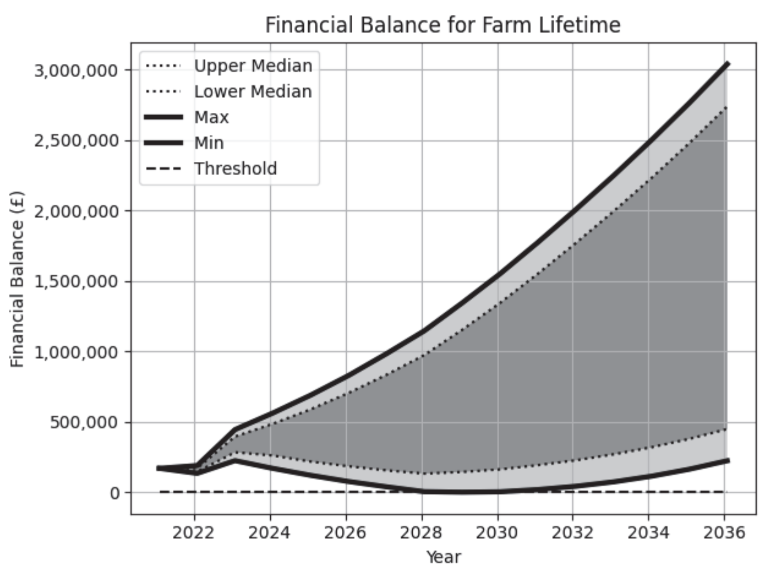

Figure 14. Financial balance projections for UK case study after suggested interventions.

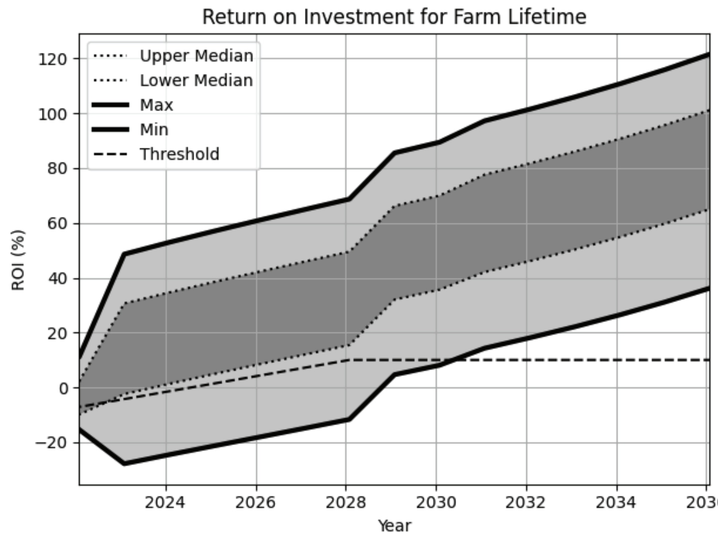

Figure 15. ROI projections for UK case study after suggested interventions.

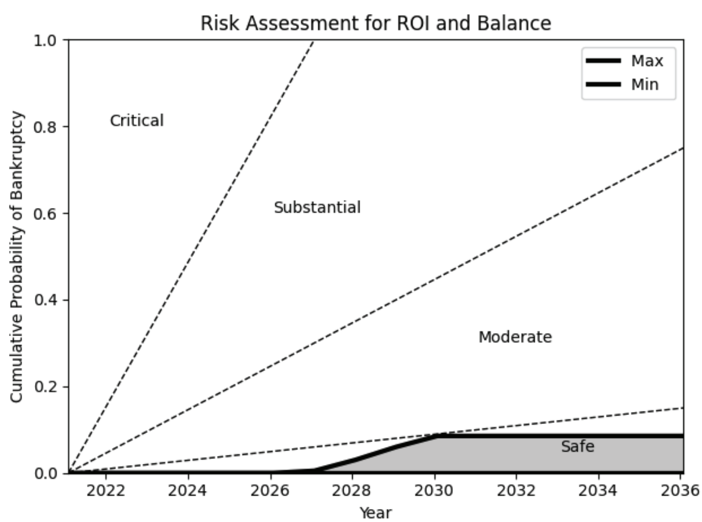

Figure 16. Risk profile for the probability of insolvency over 15 years shows that the UK farm is 'safe' after proposed interventions.

The post-intervention risk assessment of Figure 16 is now within the safe boundaries for both the worst- and best-case scenarios, providing a vastly more positive and certain outlook than Figure 9. There remains epistemic uncertainty that could be reduced through better tracking of yield, direct labour and consumables. This analysis is advantageous for highlighting the urgency in changing trajectory, whilst the company aims to scale up their operations. Further changes could be made, such as selecting higher-value products like speciality herbs; however, market research is required and the scenarios considered show that this is not necessary.

Another consideration is a decentralised model of distribution, whereby systems are placed at distribution points with value-added benefits for a service fee. For example, systems might be placed within a supermarket or within a restaurant and may be replenished from the main farm facility. This is an increasingly popular farm model [77–79] and reduces distribution costs. This has been omitted from this analysis and should be integrated in future works. Other revenue streams, such as education, have been riddled with uncertainty and unpredictability due to the coronavirus pandemic but could be included. With the suggested changes in Table 7 and without considering risks, the risk profile would improve to a 0% chance of insolvency, indicating a safe investment and a highly profitable model.

5.4. Implications

There is a lack of hard financial data publicly available from the VF sector [18], which has led to a debate as to whether or not VF is a profitable endeavour. This model was proposed to directly address this, informing both entrepreneurs and investors to determine the viability of their plans or existing farms. The economic model is the first to enable entrepreneurs within the VF sector to evaluate their business plans whilst considering deep uncertainty. 73% of CEA founders say they would choose their equipment and crop selection differently [45] and through adequate planning this can be reduced. The iterative process of tweaking a business model becomes simplified by allowing users to assess the feasibility of their business decisions without requiring precise assumptions. It helps users understand the components necessary to construct and operate a facility, planning virtually to converge towards a viable business model. Estimating the best and worst cases with an associated probability of survival provides a transparent depiction of companies' futures. Not perfectly knowing the parameters does not preclude a quantitative analysis. Furthermore, the analysis highlights where the uncertainty lies which can help prioritise where more robust data are needed. When partial information about risks and opportunities are known, they can be accounted for selectively to plan for resilience through mitigation strategies. Using risk survey protocols, as utilised in other industries [80], could contribute to further datasets required to enhance analysis. Existing analyses described in Section 2 are unable to achieve this. For example, Monte Carlo simulations require more precise assumptions around distributions and therefore can suffer from poor accuracy.

Financial and environmental, social, and governance metrics are also provided as outputs from the model as they become increasingly sought after. Further work is required to examine other case studies across various crop types and configurations to reach conclusions on the most viable business models. This study can have global impacts by enabling entrepreneurs, investors and analysts to assess the production and economics of VF or CEA more widely without overly precise assumptions. Moreover, as probability bounds analysis captures all available information, it is possible to aggregate data of varying quality and across farm types if the uncertainty is correctly accounted for.

5.5. Limitations

There are a few caveats:

- The model evaluates risk assuming the condition of perfect markets (competitive prices exist for all goods in all possible contingencies). Although there exists methods to model imperfect markets [57], these have been omitted from the analysis to avoid excessive uncertainty that reduces the ability to draw any concrete conclusions.
- The model is able to compute yield without the precise user input based on Equation (S6) within the method statement. The relationship between environmental controls and yield is nuanced and this equation adapted from existing research [28] is a simplification of a crop's limiting factor [81]. As this relationship is further understood in the academic literature, this can be expanded to incorporate the limiting factor and provide a more accurate yield estimation.
- Risks and opportunities have been modelled based on anecdotal reports [14]. Meaningful distributions would require longitudinal data of adequate risk reporting (frequency and impacts). A lack of track records means that such data do not currently exist [22]. This is a primary reason for choosing probability bounds analysis, which does not require overly precise estimations. For the time being, risks and opportunities are

based on default settings; however, users are welcome to add or modify risks from their own experience and operational history.
- Two case studies have been analysed and juxtaposed to show different systems, markets, climates and scales. Further case studies are required to generate meaningful conclusions about the industry and typical risk profiles. A comparison to a state-of-the-art greenhouse with adjusted risks would give further insight into the risk profile of other production methods. However, this was out of the scope of this article.
- The model has been calibrated to compute realistic financials for both case studies [31,73]. The analysis would benefit from a more careful validation, requiring longitudinal financial data and operational histories.
- Evaluation of economies of scale would require a deeper analysis of variable costs and how they vary with production quantity across multiple farms.
- The model can compute estimated yields for various crops. However, the analysis presented only examines lettuce farms. Investigating other case studies for other crop types (micro-herbs, mushrooms, berries) may reveal different characteristics, risks and opportunities.
- Other financial indicators such as current ratio, liabilities/total assets ratio, equity/total assets ratio and cash ratio should be included in future iterations of this model.
- Currently the model predicts bankruptcy with the same method regardless of location; however, there is a dependence between explanatory variables and the country, which should be considered in future works [74].

6. Conclusions

Industry practitioners claim that the economic viability of vertical farms is possible with a robust business model and a focus on unit economics. However, financial viability requires demonstration and comparative financial data to have scientific validity. A significant obstacle to profitability is knowledge acquisition on how to design and run an efficient VF business. The literature calls for more robust economic analyses for vertical farms. On the other hand, there is a lack of hard data for yields, cost, risks and labour. This study handles partial information by proposing a financial risk model that incorporates the risks and uncertainty of these intricate systems to enhance accuracy.

The method described in this paper assesses economic viability and financial risk despite the lack of available production and financial data. In addition, it can be used to inform improvements in farm design towards profitable business models. The financial risk analysis and model library can be found at: https://github.com/GaiaKnowledge/VerticalFarming (accessed on 6 February 2022) as a part of a wider decision support system project [12]. It utilises probability bounds analysis combined with first-hitting-time, which has been used for other disciplines in ecology and engineering [72]. This method is applied to both real-life (UK) and hypothetical (Japanese) vertical farms.

The UK farm shows that the path to profitability requires many competing factors to be optimised. This aligns with existing research that no specific placement (urban, peri-urban, rural) with varying climate conditions results in a simple net-positive or negative result [75]. For the first time, this can be assessed with incomplete data. The results for the UK case study reveal a critical financial risk (see Figure 9) requiring drastic changes to the farm business model. Currently, the farm is operating at a loss, as the business experiments with different technologies, strategies and revenue streams. A path to profitability is being forged through trialing various interventions like further capital injection and improvements to climate control. This collectively results in a more favourable and safe risk profile. The farm operators utilised the model and the results led them to prioritise the collection of more accurate data, especially for metrics that impact profitability.

A real-life case study that shows clear profitability is required in future work to prove or disprove the claim that vertical farms can be profitable. Due to the absence of available data, a Japanese farm from the literature was also used as a hypothetical case study. The hypothetical Japanese farm offers a more resilient business model with an acceptable ROI, but longitudinal data validation is required to determine whether the hypothetical farm is a realistic long-term scenario.

The economic sustainability of vertical farms is primarily driven by high crop yields per unit area as well as electricity, labour and depreciation costs. Despite this, it has become clear from this analysis that using an off-the-shelf system combined with benefits of free rent, low-cost electricity, low-cost labour and a premium price point, does not guarantee positive unit economics and low financial risk. The value that VF delivers to a location is significant and the aforementioned benefits should always be sought out to improve a project's profitability prospects. However, the economics should be carefully evaluated prior to construction. In reality, almost all vertical farms struggle to compare the economic feasibility of different systems and solutions but this can now be achieved more accurately with this economic risk model through allowing analysts to avoid making precise assumptions and more likely to capture true production and financial values.

This analytical research is exploratory and has been conducted on two case studies. It is challenging to draw generalised conclusions on this new industry due to the vast array of business models and proprietary systems being developed. There is no clear formula to profitability and every farm is operating within entirely different constraints (technology, market, climate, building and crop selection). This means that there is no one-size-fits-all approach to VF and each situation should be considered unique. From the model combined with available literature [18,22], it can be deduced that keys to higher profit margins can be found in: (i) scaling operations (whilst fixed costs remain the same); (ii) reducing capital costs due to maturing technology; (iii) improving labour efficiency; (iv) increasing produce quality and yield through crop genetics and growing environment optimization; (v) commanding a premium price; and (vi) reductions in costs such as subsidised rent or electrical efficiency improvement. In future works, more real-life case studies with comprehensive data of various crop types, business models and VF configurations are required to make concrete conclusions about the sector. Longitudinal data of operational histories and financial reporting would enable further validation of the model and facilitate benchmarking that can inform investment decisions. This sector has the potential to radically alter the way we grow and distribute food across the world but only if cost performance can be improved. Risk-empowering businesses, advancing technology, and sharing of data are several aspects that will accelerate this.

As industries become increasingly complex, techniques such as probability bounds analysis already used in other disciplines will be helpful in financial modelling. There is no dispute that the financial futures of start-up businesses are uncertain. Forecasting deterministically or through Monte Carlo simulations provide a simplistic and sometimes inaccurate view. What happens when data about precise model distributions or exact parameters are not available? This is the case for vertical farming. A method such as probability bounds analysis facilitates these computations to open up a new realm of scenario analysis and financial risk management. Vertical farming is only one complex industry of many that could benefit from such a method.

This is the first academic study applying financial risk assessment to vertical farming. By building the foundation of literature on risk in vertical farming, investors can begin to understand this emerging market which will increase access to favourable types of capital. This work enables entrepreneurs, investors, and analysts to assess the production and economics of VF or CEA more widely without overly precise assumptions. Moreover, as probability bounds analysis captures all available information, it is possible to aggregate data of varying quality and across farm types if the uncertainty is correctly accounted for.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14095676/s1, Supplementary Data, Method Statement [82–88], Model Library.

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Conflicts of Interest: The authors declare one conflict of interest. Two co-authors are the co-founders of a vertical farming research company, Farm Urban. Their input enabled the inclusion of the only real financial case study within the literature. Their involvement was limited to helping to collect and validate the data required and produced by the model. They had no role in the design, analyses or interpretation of the data.

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Pull the Emotional Trigger or the Rational String? A Multi-Group Analysis of Organic Food Consumption

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Abstract: The organic food industry in China has been developing fast with the increasing consumer demand for healthier, safer, and more nutritious foods since the epidemic outbreak. It is of great significance to understand the psychological preference of consumers for organic food and adjust the marketing strategy accordingly. In this study, we adopted the multi-group structural equation model (SEM) to analyze 571 questionnaire data and explored the effects of consumers' perception on the sensory appeal of organic food, perception on promotional stimulation, positive emotion, and perceived social value on the purchase intention of organic food. Based on the Stimulus–Organism–Response (S-O-R) model, this study divides the route affecting organic consumption behavior into the rational route and emotional route. It was proved that the emotional route (positive emotion) has a greater impact on the purchase intention of organic food than the rational route (perceived social value). In addition, there are different purchase intentions among different product types. Specifically, compared with organic tea, positive emotion has a greater effect on the purchase intention for organic rice. This study provides an important reference for the organic food-marketing strategy of enterprises.

Keywords: organic food consumption; positive emotion; sensory appeal; multi-group SEM

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1. Introduction

In the context of green and sustainable consumption, China and other emerging countries have begun to heavily promote organic consumption in recent years. In 2020, the global sales of organic food and beverage exceeded 120 billion Euros, and China accounted for 10.2 billion Euros (8.5%) [1]. China is the fourth largest organic food market in the world [1]. In 2022, China Central Document No. 1 stated that governments should continue to adjust and optimize the agricultural structure; strengthen the certification and management of green food, organic agricultural products and geographical indications of agricultural products; and increase the supply of high-quality green agricultural products. Compared with traditional food, organic food follows the production standards of organic agriculture, without using chemically synthesized fertilizers, pesticides, growth regulators, and other substances [2,3]. It contains no pesticide residues and does not use growth hormone and genetic engineering (GE) in the growing process, which is more healthy, nutritious, and natural [4]. Organic food plays an important role in promoting environmental protection and agricultural efficiency, enhancing the competitiveness of agricultural products and meeting the demand for safe and high-quality agricultural products. Consumers have linked organic food with health and nutrition since the outbreak of COVID-19. In the next few years, the organic food industry in China has great potential for further expansion [5,6].

Chinese governments have carried out a lot of publicity and education on organic food consumption. With the heavy promotion from governments, consumers are no longer unfamiliar with the concept of "organic." Yang et al. (2021) [7] found that the subjective cognition level of Chinese consumers on organic food is in a high position. However, the consumption capacity of organic food in China still lags behind other countries [1]. This indicates that only improving consumers' cognition is not enough. Ignoring the emotional appeal or emotional resonance of individuals cannot effectively promote the real organic consumption behavior of consumers [8]. Food consumption is never just to satisfy the appetite, which is closely related to culture and emotion [9–11]. Emotion is the attitude experience of individuals on whether objective things meet their needs. When objective things meet their needs, individuals show a positive attitude and this usually reflects in feelings of love, joy, happiness, etc. [12]. According to the broaden-and-build theory of positive emotions proposed by Fredrickson (1988) [13], various positive emotions such as happiness, interest, satisfaction, pride, and love, are more helpful to expand the scope of attention, cognition, and behavior of individuals; on that basis, people can more effectively obtain and analyze information, make more appropriate action choices, and have the effect of continuously enhancing personal resources for a long time. Moreover, Eastern culture is more emotional compared with the rationality of Western culture [8,14]. Therefore, it is of great significance to explore the role of emotion in organic consumption in China. In addition, the positive emotions of consumers can promote their cognitive flexibility and expand their scope of attention, making consumers aware of the differences between similar products [15,16]. This is also of great significance for brand competition.

Emotion is the most important endogenous factor in individual psychology and plays a very important role in decision-making [11,17]. More and more consumers tend to choose foods that have an emotional resonance with them. Holbrook and Hirschman (1982) [18] were the first to apply emotion to the research field of consumer behavior. They proposed that consumers were not always rational and emphasized the importance of emotion in purchase behavior. For example, Hsu and Tsou (2011) [19] employed the Stimulus–Organism–Response (S-O-R) model, starting from the impact of website quality on the repurchase intention of consumers, to measure consumers' emotional state through the Mood Scale, and selected it as the intermediary variable. They found that website quality can bring about individual feedback with positive emotions, while the positive emotion is helpful for consumers to repurchase and improve their repeat purchase intention. In marketing practice, especially in advertising design, marketers are increasingly using various emotional experiences to influence consumer behavior and decision-making. Emotion involves the whole process of consumer behavior, i.e., all the behaviors from searching and processing information, to product selection, and then to post-purchase, are closely related to the emotional state of consumers [20–22]. Therefore, it is crucial to incorporate emotional factors into the cognitive process of purchase behavior of organic consumers. The analysis of Dispoto (1977) [23] showed that the correlation coefficient between ecological emotion and ecological behavior was 0.15, and many people with little environmental knowledge still show strong emotional loyalty to the environment. This reveals that environmental knowledge and environmental emotion are two independent influencing variables. Kanchanapibul et al. (2014) [24] also considered that it is reasonable to take environmental emotion and environmental knowledge as two different variables to study their impacts on environmental consciousness and behavior.

However, only a few studies are focusing on the impact of emotion on ecological products, low-carbon consumption behavior, and organic products to date. Meneses et al. (2010) [25] analyzed emotional variables and cognitive variables and found that the recycling behavior of consumers was more related to emotional factors than cognitive factors. Based on the study of low-carbon purchase behaviors, Wang and Jing (2012) [26] found that the impact of low-carbon emotion is greater than that of low-carbon knowledge, suggesting that stimulating emotion was more effective than improving cognition in the influence of consumers' attitude towards low-carbon environmental protection. Lee and Yun (2015) [27] used the S-O-R model to study the two routes of organic consumption, i.e., the emotional route and rational route, and found that consumers are more inclined to cognitive judgment than emotion in purchasing organic food. Jose and Kuriakose (2021) [28] took Indian consumers as the object and compared the effects of emotion, practice, and rationality on organic consumption intention. They found that rational factors such as environmental motivation have little influence, and emotion plays a leading role in organic consumption.

Therefore, to continuously and effectively expand the organic consumption market in China, it is necessary to understand the driving mechanism of the organic food purchase of consumers in China. Based on the S-O-R model and the broaden-and-build theory of positive emotions, this study adopts a multi-group structural equation model (SEM) to explore: (1) Is it the rational route or emotional route that can better enhance the purchase intention of Chinese consumers for organic food? (2) Are there significant differences in the impact routes of different product types (such as organic tea and organic rice)?

2. Theoretical Framework and Research Hypothesis

2.1. Theoretical Framework

A large number of studies on consumer purchase behavior took the S-O-R model as the theoretical basis since it was proposed by Russell (1974) [29]. The S-O-R model considers that the purchase behavior of consumers is mainly caused by external stimuli (products, situations, etc.), which change the psychological activity of individuals, thereby generating motivation, making purchase decisions, and implementing purchase behavior. Therefore, the S-O-R model can be regarded as a dynamic expression of the purchase behavior process of individuals. Many scholars considered that in this dynamic process, the internal change of the organism is due to the cognition and emotion of individuals to the external stimuli, which will be reflected in the subsequent behavioral response.

One of the main hypotheses of the theory of reasoned action (TRA) and the theory of planned behavior (TPB) is that people are rational in the decision-making process and action; thus, cognitive methods can be used to predict behavior [30]. However, the addition of affective variables has been recommended as a useful extension of the theory [12,28,31]. Following this suggestion and using the S-O-R model, we define the behavioral response as the purchase intention of organic food and divide the internal changes of organisms into two-dimensional dimensions, i.e., emotion and rational (positive emotion and perceived social value), which is helpful to check whether it is the emotional route or the rational route that plays a role in organic consumption behavior in China (Figure 1). Therefore, the S-O-R model is suitable for this study.

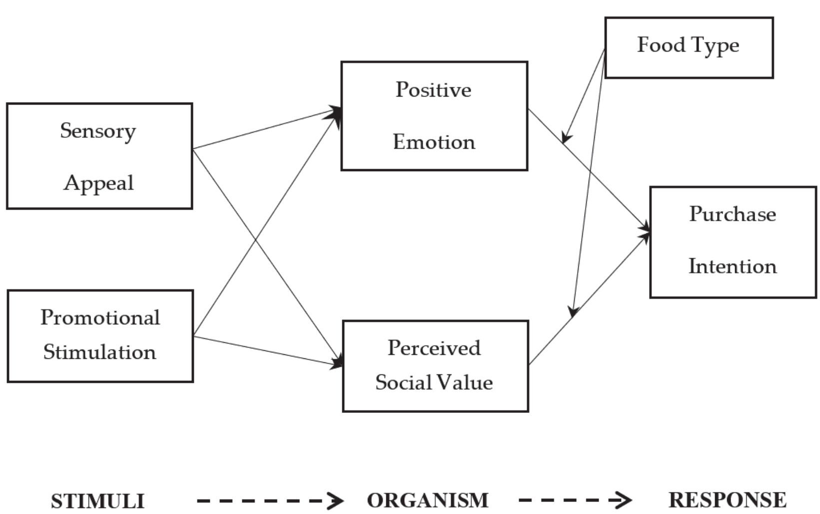

Figure 1. Conceptual model.

Lee and Yun (2015) [27] proposed that it was more suitable to focus on the stimulation of food itself to explore the purchase intention of organic food than psychosocial stimulation, because they believed that the main determinant of the purchase intention of organic food is the product attributes related to health, environmental protection, and animal welfare. However, consumers in China still have little purchasing power for organic food, and they rely more on the publicity of the government and the outside world. Therefore, it is necessary to include both food stimuli (organic food characteristics) and external stimuli (promotional stimulation) in this study.

2.2. Research Hypothesis

2.2.1. Sensory Appeal

According to the cue utilization theory [32], consumers usually evaluate products and make purchase decisions based on various internal and external information clues [33,34]. Internal information is inherent in the product itself, including taste and texture, while external information is other information related to the product, such as label, packaging, etc. [35] Acebron and Dopico (2000) [36] pointed out that both internal and external information about products can advance consumers to generate positive emotions and form judgments on product quality, which will further affect their purchase decision of consumers. These can be called sensory attributes [37]. In addition, products with different sensory attributes cause different emotional reactions in consumers [9]. Among these sensory attributes, vision is usually the first sense and overwhelms the perception of other information in attracting consumers' attention [38]. Visual cues are not only limited to the internal characteristics of the product itself but also involve external characteristics such as product packaging [39]. As the main physical characteristics of food, visual cues not only can indicate the quality of food but also link consumers to other emotional experiences [40,41]. Therefore, they are the attributes with more influence. Lee and Yun (2015) [27] found that consumers' perception of the sensory appeal of organic food can promote their purchase intention of consumers because organic food brings them positive emotions. Some studies also showed that the sensory attributes of organic food are usually related to pleasure, hedonism, and happiness [42]. Therefore, the following hypotheses are put forward:

Hypothesis 1 (H1): *Consumers' perception of the sensory appeal of organic food has a significantly positive impact on the positive emotion of consumers.*

Hypothesis 2 (H2): *Consumers' perception of the sensory appeal of organic food has a significantly positive impact on the perceived social value of consumers.*

2.2.2. Promotional Stimulation

Promotional stimulation is a form of communication used to raise consumers' awareness of the product and can distinguish them from their detractors. It can be used as a source of information to evaluate products and stores [43]. The premise of TRA is that people can completely control their behavioral intention. However, consumers are bound to be interfered with by external factors when making purchase decisions in real life [44]. When the real information about products is scarce or asymmetric, consumers will seek external help to obtain relevant purchase experience or suggestions, and then form the corresponding purchase intention [45]. Marketing promotion can be used as a source of information for evaluating products and stores [43]. The calls of environmental protection associations and governments and advertising factors can stimulate the organic purchase intention of consumers [46]. Chen and Antonelli (2020) [47] considered that external context factors can significantly improve the perceived value and purchase intention of consumers on products. Zhu et al. (2013) [48] found that situational factors of laws and policies can adjust the degree of influence of consumers' purchase intention on green purchase behavior. Miller et al. (2021) [49] found that situational effects have an impact on the perception and cognitive links of consumers, which can interact with consumers' psychological perception and then affect their purchase intention. With strong calls from governments, environmental associations, etc., consumers can demonstrate their concern and responsibility for the environment by purchasing and using organic foods, gaining more social recognition and approval [50]. Therefore, the following hypotheses are put forward:

Hypothesis 3 (H3): *Consumers' perception of the promotional stimulation of organic food has a significantly positive impact on the positive emotion of consumers.*

Hypothesis 4 (H4): *Consumers' perception of the promotional stimulation of organic food has a significantly positive impact on the perceived social value of consumers.*

2.2.3. Positive Emotion

Positive emotion refers to the emotion with a positive valence. It is associated with the satisfaction of certain needs, accompanied by pleasant subjective experience, and can improve the enthusiasm and activity ability of individuals [51]. Gutjar et al. (2015) [10] indicated that the choice of food is mainly related to positive emotions. Meneses (2010) [25] also showed that the recycling behavior of consumers is more based on positive emotion than negative emotion. Based on his research, positive emotions include joy, contentment, interest, pride, gratitude, and love. According to the expansion theory of positive emotion proposed by Fredrickson (2001) [13], positive emotions can advance individuals to break through certain restrictions and produce more thoughts under general conditions, expand the scale of attention, enhance cognitive flexibility, and update and expand the cognitive map of individuals. Isen (2001) [52] found that positive emotions can provide more information for cognitive processing. Plenty of positive experiences with a product may lead to intuitive decisions on future purchases [53]. Existing studies have demonstrated that positive emotions can predict the ecological consumption intention of individuals [54] and also have a significantly positive impact on green purchase behavior and environmental protection behavior [25]. Therefore, the following hypothesis is put forward:

Hypothesis 5 (H5): *Consumers' positive emotion has a significantly positive impact on the purchase intention of consumers for organic food.*

2.2.4. Perceived Social Value

Perceived value is the consumer's preference and evaluation of the product attributes and their utility that helps or hinders the achievement of goals in a given usage context [55]. In the era of consumerism, goods are purchased not only to satisfy individual functional needs but also to achieve the purpose of self-identity construction [56]. Sweeney and Soutar (2001) designed a scale for measuring the perceived value of durable goods, and they viewed perceived social value as the utility of a product to reinforce self-concept. They argued that when customers bought a product, they would consider the impression that the purchase would have on others [55]. Relevant studies from a social perspective have revealed that green consumption behavior stems from personal reputation and status, e.g., people are more willing to pay for environmental protection in public to gain extra points for their image [57,58]. Chinese consumers with collectivist cultural values face more than Western consumers with an individualistic culture [59]. That is, social motives influence Chinese consumers' green consumption behavior more profoundly than environmental and economic motives. Further, through organic food consumption, consumers can effectively present themselves to others [60]. This is because, compared to convention food, organic food is more expensive and pro-social, which can reflect the non-generic nature of consumers, thus helping them to gain more praise, social recognition, and good impressions [61]. Noppers et al. (2014) [62] stated that consumers brought green products because such consumption helped to project a positive image of themselves. Kohlova and Urban (2020) [63] pointed out that green consumption enhanced consumers' social status because it helped them to demonstrate wealth-related competencies. People who need to confirm their social status or self-identity will prefer organic food [57]. Therefore, out of rational thinking, consumers will choose organic foods with greater utility in order to demonstrate their social status and value preferences. Therefore, the following hypothesis is put forward:

Hypothesis 6 (H6): *Consumers' perceived social value has a significantly positive impact on the purchase intention of consumers for organic food.*

2.2.5. Product Type

Products can be classified as hedonic products and practical products according to different classification standards [64]. Hedonic products can bring emotional joy, while practical products reflect rational cognition [65,66]. In general, practical products are mainly used by consumers to meet some specific tasks and obtain more efficiency, while hedonic products are mainly used to obtain emotional demands, and the consumption is to meet the subjective feeling of consumers [67]. Although these two kinds of products reflect different consumer psychology, they are not opposed to each other. Studies have shown that hedonic attributes and practical attributes have a positive correlation [68]. Some products have both the characteristics of hedonic products and practical products; to be specific, if a product is defined as a hedonic product, it means that the hedonic attributes of this product are greater than the practical attributes, rather than only having the characteristics of hedonic products without any characteristics of practical products [68]. In the situation of different product types, the influence route of purchase intentions of consumers is different [69]. Based on the functional consistency theory, compared with positive emotion, perceived social value emphasizes the practical value of organic food and can help consumers obtain more efficiency, which is matched with the attribute characteristics of practical products and is easy for consumers to generate a positive purchase intention [70]. Based on the self-consistency theory, compared with perceived social value, positive emotion emphasizes the hedonic value, which is matched with the attribute characteristics of hedonic products and is easy for consumers to generate a positive purchase intention [71]. To easily compare the differences in purchase intention between different kinds of organic food, this study defines the tea as the hedonic product and rice as the practical product. Therefore, the following hypotheses are put forward:

Hypothesis 7 (H7): *In terms of tea, positive emotions have a greater impact on the purchase intention of organic food than perceived social value.*

Hypothesis 8 (H8): *In terms of rice, perceived social value has a greater impact on the purchase intention of organic food than positive emotion.*

3. Methods

3.1. Questionnaire Design

The questionnaire is divided into two parts. The first part is the main body of the questionnaire, including the scales of each variable, and the second part is the personal information of the respondents. Assuming that the measurement items of each variable in the model are from the maturity scale that has been widely used in the relevant literature, and have been appropriately modified based on expert opinions and the specific consumption situation of organic agricultural products. The Likert 7-point scale was used as the form of all scales.

As can be see in Table 1, the measurement of sensory appeal (SA) and positive emotion (PE) uses the scale of Lee and Yun (2015) [27]. The measurement of promotional stimulation (PS) uses a modified scale based on the design of Wang et al. (2018) [72], including the publicity of governments and academic institutions, and is suitable for the current mode of promoting organic agricultural products in China. The measurement of perceived social value (PSV) uses the scale of Wang et al. (2017) [8] and Sweeney and Soutar (2001) [55]. The measurement of the purchase intention of organic agricultural products (PI) uses a modified scale based on the design of Kim and Lee (2019) [73].

Table 1. The measures.

Variables	Items	Sources
sensory appeal (SA)	Organic tea/rice looks nice Packaging of organic tea/rice looks better Organic tea/rice has a pleasant texture	Lee and Yun (2015) [27]
promotional stimulation (PS)	Government regulation has a big impact on my purchase of organic tea/rice Government promotion has a great influence on my purchase of organic tea/rice Opinions of experts and academic institutions have a great influence on my purchase of organic tea/rice	Wang et al. (2018) [72]
positive emotion (PE)	I will feel happy if I buy organic tea/rice I will feel delightful if I buy organic tea/rice I will feel exciting if I buy organic tea/rice	Lee and Yun (2015) [27]
perceived social value (PSV)	Buying organic tea/rice is good for me Buying organic tea/rice can form a good impression for me Buy organic tea/rice to get more praise for me	Wang et al. (2017) [8]; Sweeney and Soutar (2001) [55]
purchase intention (PI)	I will learn more about organic tea/rice I will recommend organic tea/rice to my friends I will continue to choose organic tea/rice in the future	Kim and Lee (2019) [73]

3.2. Data Collection and the Sample

The questionnaire method was used in this study, and the data were collected online based on the professional questionnaire platform (Credamo). In this survey, consumers who purchased organic tea (rice) were taken as the survey object. This is because only those consumers who purchased these products can perceive the relevant organic attributes. Meanwhile, trap questions were set in the questionnaire, i.e., "100 + 100 = ?". Those who answered wrong were regarded as not seriously filling in the questionnaire.

Before the survey, we conducted a small-scale pilot survey, and a total of 30 pilot survey questionnaires were distributed. Using SPSS24.0, we removed the measurement items with a Cronbach's α value of less than 0.6. According to the information and suggestions fed back by the pilot survey, the items with unclear semantics and confusion in the questionnaire were adjusted and revised, which can ensure the effectiveness of the questionnaire. In this study, two sets of questionnaires focusing on organic tea and organic rice, respectively, were designed. A total of 571 valid questionnaires were collected, including 290 questionnaires on organic rice and 281 questionnaires on organic tea.

3.3. Research Methods

The data analysis in this study was divided into three steps. First, SPSS24.0 and AMOS24.0 were used to test the reliability and validity of variables to ensure the goodness of fit of the structural model. Second, AMOS24.0 was used to conduct a hypothesis test on the structural model to verify the relationship between sensory appeal, promotional stimulation, positive emotion, perceived social value, and purchase intention. Thirdly, the multi-group SEM was used to analyze the regulation of different types of organic foods. The multi-group SEM analysis can explore whether the route model suitable for one sample is also suitable for other samples. Existing studies have mainly focused on single organic food [74], and the studies for comparing and analyzing the differences between the purchase intentions of different types of organic foods are rare.

4. Results

4.1. Descriptive Statistics Analysis

As shown in Table 2, the number of female samples (55%) is greater than male samples (45%), which is consistent with previous research results in which women are the main buyers of families in China [7,75]. The respondents aged 25~34 account for the largest proportion (62.5%), followed by those aged 35~44, accounting for 22.8%, which means that young consumers show more purchase intention for organic foods. This result is consistent with Chekima et al. (2017) [76] and Yadav and Pathak (2016) [77]. In addition, most respondents had a bachelor's degree. In terms of family population, families consisting of approximately three to four accounted for the largest proportion, followed by those consisting of approximately five to six people. The monthly income was at the level of 6501 RMB and above. Overall, the survey samples of this study are more in line with the actual situation of organic consumption in China and can be used for further analysis.

Table 2. Descriptive statistics of consumer social demographic characteristics.

Variables	Definition	Frequency (n = 571)	Percentage (n = 571)
Gender	Male	257	45%
	Female	314	55%
Marriage	Unmarried	130	22.8%
	Married	441	77.2%
Age	18–24	65	11.4%
	25–34	357	62.5%
	35–44	130	22.8%
	45–54	12	2.1%
	55–64	7	1.2%
	≥65	0	0
Education	Junior high school or below	6	1.1%
	High school (including secondary occupation)	20	3.5%
	College	58	10.2%
	Undergraduate	414	72.5%
	Master or above	73	12.8%
Family member	1–2	28	4.9%
	3–4	362	63.4%
	5–6	165	28.9%
	≥7	16	2.8%
Monthly income (RMB)	≤3500	55	9.6%
	3501–5000	60	10.5%
	5001–6500	72	12.6%
	6501–8000	122	21.4%
	≥8000	262	45.9%

Note: Chinese currency symbols, abbreviated as RenMiBi (RMB).

4.2. Reliability and Validity Test of Samples

The composite reliability (CR) value was used to test the reliability of the questionnaire. From the measurement results of the model in Table 3, the CR values are greater than 0.7, suggesting that the indexes of each dimension have sufficient reliability and internal consistency [78]. The measurement of validity is tested by convergent validity and discriminant validity, in which the convergent validity is mainly reflected by normalized factor loading, Z-value, and average variance extracted (AVE). The results show that the normalized factor loadings are greater than 0.6 and significant, and the AVEs are greater than or close to 0.5, indicating that the scale has high convergence validity [79]. Meanwhile, the correlation coefficient between any two variables is less than the square root of AVE of each variable, as shown in Table 4. Therefore, the scale has good discriminant validity, which lays a foundation for the analysis of the structural model.

Table 3. Results of measurement model analysis.

Variables	Items	Ustd.	S.E.	Z-Value	P	Std.	SMC	CR	AVE
SA	SA1	1.000				0.728	0.530	0.747	0.497
	SA2	1.004	0.086	11.612	***	0.641	0.411		
	SA3	1.012	0.086	11.707	***	0.741	0.549		
PS	PS1	1.000				0.686	0.471	0.776	0.538
	PS2	1.090	0.084	12.931	***	0.820	0.672		
	PS3	0.898	0.069	13.082	***	0.687	0.472		
PE	PE1	1.000				0.743	0.552	0.81	0.587
	PE2	1.181	0.077	15.367	***	0.810	0.656		
	PE3	1.075	0.071	15.198	***	0.744	0.554		
PSV	PSV1	1.000				0.650	0.423	0.771	0.531
	PSV2	1.200	0.095	12.572	***	0.788	0.621		
	PSV3	1.062	0.084	12.708	***	0.741	0.549		
PI	PI1	1.000				0.824	0.679	0.862	0.676
	PI2	1.036	0.052	19.986	***	0.817	0.667		
	PI3	0.983	0.049	20.106	***	0.826	0.682		

Note: *** $p < 0.001$. Composite reliability (CR), average variance extracted (AVE), sensory appeal (SA), promotional stimulation (PS), promotional emotion (PE), perceived social value (PSV), purchase intention (PI).

Table 4. Results of discriminant validity test.

Variables	AVE	PI	PSV	PE	PS	SA
PI	0.676	**0.822**				
PSV	0.531	0.609	**0.729**			
PE	0.587	0.714	0.695	**0.766**		
PS	0.538	0.491	0.542	0.611	**0.733**	
SA	0.497	0.672	0.606	0.750	0.463	**0.705**

Note: The items on the diagonal represent the square roots of the AVE; off-diagonal elements are the correlation estimates. Sensory appeal (SA), promotional stimulation (PS), promotional emotion (PE), perceived social value (PSV), purchase intention (PI).

4.3. Test of the Measurement Model

The measurement model is evaluated using the maximum likelihood method based on AMOS24.0. From Table 5, it can be seen that the overall test results of goodness of fit of the model are χ^2/df = 2.505, GFI = 0.953, AGFI = 0.932, CFI = 0.966, and RMSEA = 0.051. These indexes of the model meet the standard, indicating that the model fits well.

Table 5. Fitting results of model.

Index	Criteria	Model Fit	Result
χ^2	the smaller the better	207.948	
df	the bigger the better	83	
χ^2/df	<3	2.505	ideal
GFI	>0.9	0.953	ideal
AGFI	>0.9	0.932	ideal
RMSEA	<0.08	0.051	ideal
CFI	>0.9	0.966	ideal
TLI (NNFI)	>0.9	0.958	ideal

Note: Goodness of fit index (GFI), root mean square error of approximation (RMSEA), standardized root mean square residual (SRMR), comparative fit index (CFI), Tucker–Lewis Index (TLI).

4.4. Test of Structural Equation Model

As shown in Table 6, all hypotheses passed the significance test. As expected, consumers' perceptions of sensory appeal and promotional stimulation had a significant positive impact on the positive emotion of consumers (β = 0.647, $p < 0.001$ and β = 0.329, $p < 0.001$, respectively). The stronger the consumers' perception of the sensory appeal of organic food or the stronger the consumers' perception of external publicity, the higher the positive emotion of consumers. Then, H1 and H2 were supported. Meanwhile, consumers' perceptions of sensory appeal and promotional stimulation had a significantly positive impact on the perceived social value of consumers (β = 0.505, $p < 0.001$ and β = 0.329, $p < 0.001$, respectively). Then, H3 and H4 were supported. Further, consumers' positive emotions and perceived social value had a significantly positive impact on the organic purchase intention of consumers (β = 0.579, $p < 0.001$ and β = 0.242, $p < 0.001$, respectively). Then, H5 and H6 were supported.

Table 6. Results of the hypothesis test.

	Ustd.	S.E.	C.R.	P	Std.	Results
H1: SA → PE	0.67	0.063	10.661	***	0.647	Support
H2: PS → PE	0.286	0.044	6.518	***	0.329	Support
H3: SA → PSV	0.424	0.054	7.828	***	0.505	Support
H4: PS → PSV	0.232	0.041	5.601	***	0.329	Support
H5: PE → PI	0.78	0.085	9.133	***	0.579	Support
H6: PSV → PI	0.402	0.102	3.953	***	0.242	Support

Note: *** $p < 0.001$. Sensory appeal (SA), promotional stimulation (PS), promotional emotion (PE), perceived social value (PSV), purchase intention (PI).

The Bootstrapping method is used to test the mediating effect. Hayes et al. (2009) suggested that the Bootstrapping method should be repeated at least 5000 times during the mediating effect test. In SPSS 24.0, we adopted the plug-in unit process 4.0 to set the sampling times to 5000 times and the confidence was 95% [80]. The results are shown in Table 7.

Table 7. Results of mediating effect test.

Paths	Total Effect		Direct Effect		Indirect Effect		
	β	T-Value	β	T-Value	β	LLCI	ULCL
SA → PE → PI	0.6296	14.2338	0.323	6.6329	0.3065	0.2171	0.4059
SA → PSV → PI	0.6296	14.2338	0.4497	9.891	0.1799	0.1065	0.264
PS → PE → PI	0.459	10.5131	0.1741	3.9992	0.2849	0.2172	0.3585
PS → PSV → PI	0.459	10.5131	0.2643	5.9661	0.1948	0.1349	0.2594

Note: Sensory appeal (SA), promotional stimulation (PS), promotional emotion (PE), perceived social value (PSV), purchase intention (PI).

The confidence interval (CI) of the indirect effect was used to judge whether the mediating effect exists. If the CI did not include 0, we rejected the original hypothesis, which means that the indirect effect was not 0 and the mediating effect existed [81]. As shown in Table 6, the indirect effect existed and was significant, indicating the existence of the mediating effect; the direct effect was less than the total effect and significant, indicating that there are partial mediating effects.

4.5. Multi-Group Analysis

To check whether the route model suitable for the whole sample was also suitable for the specific sample group, and further to check whether different product types have the same influence route [82], this study selected different product types (organic tea and organic rice) as adjustment variables to conduct the multi-group SEM test on the S-O-R model of organic foods. The operation in this part follows the measurement invariance procedure of the composite model proposed by Byrne (2004) [83]. The results are shown in Table 8.

Table 8. Fit indices for multi-group invariance tests.

Model	χ^2	DF	P	χ^2/DF	GFI	AGFI	CFI	RMSEA
Unconstrained	342.943	166	0.000	2.066	0.926	0.893	0.954	0.043
Measurement weights	358.377	176	0.000	2.036	0.923	0.894	0.952	0.043
Structural weights	369.238	182	0.000	2.029	0.920	0.894	0.951	0.043
Structural covariances	371.349	185	0.000	2.007	0.919	0.895	0.951	0.042
Structural residuals	379.028	188	0.000	2.016	0.918	0.895	0.95	0.042
Measurement residuals	431.676	203	0.000	2.126	0.908	0.891	0.94	0.044

Note: Goodness of fit index (GFI), adjusted goodness of fit index (AGFI), comparative fit index (CFI), root mean square error of approximation (RMSEA).

From Table 8, the *p*-value of all competition models is less than 0.05, and the ΔCFI between any two models is less than 0.01, indicating that the multi-group measurement invariance is valid [83]. The research conclusion is applicable to all consumers. Then, the difference in route coefficient between organic tea and organic rice was in-depth investigated, and the results are shown in Table 9.

Table 9. MGA test results.

Paths	Path Coefficients of Food Type	
	Organic Tea	Organic Rice
H1: SA → PE	0.613 ***	0.678 ***
H2: SA → PSV	0.405 ***	0.535 ***
H3: PS → PE	0.358 ***	0.291 ***
H4: PS → PSV	0.421 ***	0.296 ***
H5: PE → PI	0.382 ***	0.714 ***
H6: PSV → PI	0.373 ***	0.168 *

Note: *** $p < 0.001$; * $p < 0.1$. Sensory appeal (SA), promotional stimulation (PS), promotional emotion (PE), perceived social value (PSV), purchase Intention (PI).

As can be seen in Table 9, in the four routes of H1–H4, the groups that purchase organic tea and organic rice are both significant at the level of 0.001, and there is no significant difference in route coefficient value and direction. In the route of H5, positive emotion has a significantly positive impact on purchase intention, i.e., $\beta_T = 0.382$, $p < 0.001$ and $\beta_R = 0.714$, $p < 0.001$, respectively. In the route of H6, perceived social value has a significantly positive impact on purchase intention, i.e., $\beta_T = 0.373$, $p < 0.001$ and $\beta_R = 0.168$, $p < 0.05$, respectively. This shows that the positive emotion of organic rice consumers has a greater impact than that of organic tea consumers on purchase intention; the positive emotion of organic rice consumers has a greater impact than perceived social value. In terms of organic tea, both the positive emotion and perceived social value have a positive impact on purchase intention, and there is no significant difference.

5. Discussion

Previous studies have shown that ignoring individual emotions cannot effectively promote the real organic consumption behavior of consumers [12]. The current research mainly focuses on the influencing factors of organic consumption behavior based on the theory of reasoned action (TRA), theory of planned behavior (TPB), motivation-ability-opportunity (MAO) theory, and value-belief-norm (VBN) theory [84]. It is necessary to add emotional variables to enhance the explanatory power of the existing research [12,28,31]. In this study, we adopt the S-O-R model and incorporate rational cognitive factors and emotional cognitive factors for research. By referring to the study of Fredrickson (1998) [13] and Arvola et al. (2008) [85], this study adopts positive emotion rather than negative emotion as the emotional factor. The reason is that food purchase is more based on positive emotions [10]. Our results also confirm this point, that is, in the situation of organic food consumption, positive emotion is a useful influencing factor.

Firstly, compared with the rational route (perceived social value), the emotional route (positive emotion) has a greater effect on the purchase intention of consumers for organic food. Moreover, the positive emotion plays a partial mediating role between the perception of the sensory appeal of organic food and purchase intention, and between the perception of promotional stimulation of organic food and purchase intention. Different from the research of Lee and Yun (2015) [27], this study supports the conclusion of Wang (2015) [12] and Jose (2021) [28]. Specifically, cognition usually features with transience, shallowness, situationally, and low involvement, while emotion is profound and highly involved [12]; if only cognitive education is conducted for consumers without arousing their emotional resonance, it is difficult to turn their cognition into practical behavior. This study believes that external stimuli (sensory appeal and promotional stimulation) can advance consumers to generate a sense of pleasure and satisfaction with their appropriate behavior. They will consciously purchase organic food to maintain and increase this happy emotional experience. The research of Rana and Paul (2017) [86] also showed that the demand of consumers for organic food in developed countries is mainly due to the requirement for meeting their high-level emotional needs, such as respect and self-realization.

Secondly, this study proved that consumers' perceptions of the sensory appeal of organic food can positively affect the positive emotion and perceived social value of consumers. The increase in the sensory appeal of organic food by one unit increases the positive emotion and perceived social value of consumers by 64.7% and 50.5% respectively. Meanwhile, consumers' perceptions of promotional stimulation of organic food can positively affect the positive emotion and perceived social value of consumers. The addition to the promotional stimulation of organic food by one unit increases the positive emotion and perceived social value of consumers by 32.9% and 32.9%, respectively. These are consistent with the previous research conclusions [27,28,87], that is, consumers' choice of organic food is based on complex judgment from perceived external information (such as packaging, price, publicity, etc.) [35]. Based on various internal and external clue information, consumers can form the value judgment or sensory expectation for organic food [36]. In addition, the promotional stimulation of organic food is useful since it can provide consumers with more organic knowledge to help consumers distinguish the positive attributes of organic food from traditional food. Compared with promotional stimulation, consumers' perception of the sensory appeal of organic food has a greater impact on the positive emotion and perceived social value of consumers [88]. According to the study of Lee and Yun (2015) [27], sensory appeal is usually linked to hedonic attitude and good experience, and the stronger the sensory appeal of organic food, the more pleasant experience it can bring to consumers.

Thirdly, unlike previous studies that focused more on product function and economic value to analyze consumer purchase behavior, this study also reveals the underlying mechanisms that influence organic food consumption from the perspective of perceived social value, further confirming the existence of social motives in organic consumption. In a collectivist culture, where people care more about the connection with people around them, Chinese consumers driven by a sense of face perceive organic food as having higher perceived value. This is consistent with the findings of [14,59]. Therefore, in terms of corporate marketing, the benefits of organic food consumption for others can be promoted so that consumers feel how others around them want them to behave, rather than simply emphasizing the functional or environmental value that organic products bring to consumers.

Finally, based on the multi-group analysis results, there are differences in the relationship between the organic product type and positive emotion and purchase intention. The existing studies are mainly the multi-group analysis of the impact of demographic characteristics or regional differences on consumer behavior [85,89], and studies on the regulation of product types are rare. In this study, we used the multi-group SEM to conduct the test. Although the overall model difference remains unchanged, from the specific impact path, the positive emotion has a greater impact than the perceived social value on purchase intention in terms of organic rice, which is a surprising discovery. This is due to the fact that according to the previous research conclusions, compared with practical products, hedonic products have emotional and symbolic attributes, which match with positive emotions and can form a positive consumer response. Compared with rice, tea has more hedonic properties. One possible explanation for this is that for Chinese consumers, organic tea and organic rice are both hedonic products due to the high price of organic foods [5,6]. Moreover, the price of organic tea is much higher than the price of organic rice. From the perspective of availability, it is easier for consumers to convert their emotions on organic rice to purchase intention. This suggests that organic retailers should reduce the cost of organic food through various channels to reduce the price on one hand and improve the awareness of organic food of consumers to break the price barrier on the other hand.

This study still has the following deficiencies: First, this study only measures the purchase intention of consumers, and there is a big gap between intention and behavior. Future research can perform the measurement of actual purchase behavior. Second, although we choose the positive emotion as the intermediary according to the expansion theory of positive emotion and the characteristics of organic food, there have been some studies to explore the relationship between negative emotion and the purchase intention of consumers [90]. Therefore, negative emotion variables can be added for more systematic comparison in future studies. Third, based on the consumption and price of rice and tea in China, we treat tea as hedonic and rice as utilitarian. This is an empirical judgement that should be confirmed by adding pre-testing in future studies.

6. Conclusions

The coronavirus pandemic has intensified consumer demand for healthier, safer, and more nutritious food. Organic food is considered healthier and safer than traditional food, with a self-owned "health halo" [91]. The health needs of consumers will further advance the development of the organic food industry. To successfully satisfy the growing market demand for organic food, marketers and decision-makers should understand the psychological preference of consumers for organic food and adjust marketing strategies accordingly to change their consumption decisions for organic food. This study classifies the routes affecting organic consumption behavior as a rational route and emotional route, and proves the influence of the emotional route (positive emotion) on organic food consumption behavior. Two different kinds of products, i.e., organic tea and organic rice, are taken to conduct the multi-group SEM analysis, and it is found that the product type has a certain impact. In addition, this study also figures out the antecedents of organic food consumption behavior, namely sensory appeal, promotional stimulation, positive emotion, and perceived social value. On that basis, the following suggestions are put forward:

(1) The purchase intention of consumers for organic food is determined by positive emotion, and sensory appeal and promotional stimulation can affect the positive emotion of consumers. Therefore, in the packaging and promotion of organic food, the stimulation and guidance on the positive emotion of consumers should be paid more attention to. Enterprises should provide visual clues for organic food to enhance consumers' sensory evaluation. The appearance design and product description information design of organic food should also be more concerned.

(2) Try our best to improve the awareness of consumers on organic food. Enterprises can emphasize the positive consequences of sustainable consumption andprovide consumers with systematic information about organic food or organic agriculture. Based on the status-seeking motivation, enterprises can also highlight the prosocial aspect of organic food consumption and show the benefits of organic food to personal social value and environmental protection, thereby continuously improving the organic food consumption.

(3) Perfect the organic consumption market. The organic food consumption market in China still has the problem of generally high prices. The cost of organic food should be reduced through multi-channel strategies. Moreover, organic food manufacturers

should strengthen technological innovation, increase production, and reduce production costs, so that consumers can afford healthy and safe organic food.

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Freshwater Aquaculture Development in EU and Latin-America: Insight on Production Trends and Resource Endowments

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Abstract: This paper provides a comparative overview of decadal changes in aquaculture production in the European Union (EU-27) and Latin America and the Caribbean (LAC). Contrary to other regions of the world, freshwater fish farming in these two territories is a marginal sub-segment of the aquaculture sector. Using an indicator-based approach, we track development tendencies in freshwater aquaculture, focusing on the main established and emerging species, diversification, and shifts in the mean trophic level of farmed animals. Geographical patterns in production trends are revealed in both regions. The study attempts to explain between-region and between-country differences in aquaculture growth by analyzing freshwater resource endowments at region-level and country-level, using total renewable water resources (TRWR) as an indicator of water-abundancy. Thermal optimum of main produced species is matched against climate conditions prevailing in main producer countries to provide further understanding of spatial heterogeneity in growth rates of aquaculture sector.

Keywords: aquaculture; renewable water resources; climate; trophic level

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1. Introduction

Since the mid-1990s, nearly all growth in seafood supply has originated from aquaculture. At the global level, the contribution of freshwater fish production to total aquaculture output increased from 55.6% to 61.2% between 1995 and 2019 [1], indicating that the growth rate of freshwater aquaculture outpaces that of mariculture. In the European Union (EU-27) and Latin America and the Caribbean (LAC), the profile of the aquaculture industry is different from the other regions, since coastal (marine or brackish water) aquaculture dominates the sector in both regions. In 2019, freshwater aquaculture only contributed 25.0% and 27.4% to total fish production in LAC and EU-27, respectively [1], and the rate of its growth was lower than that of marine aquaculture in both regions.

Nevertheless, freshwater aquaculture production experienced considerable growth in the latest decades in LAC [2]. In contrast, freshwater production in the EU has stagnated for decades, however, there is large heterogeneity between growth rates of member states. Opportunities for aquaculture growth are not the same in the two regions, as they differ from each other in terms of markets, regulation environment, and resource availability. Per capita fish consumption in the EU-27 is relatively high with a value of 24 kg/year, corresponding to a yearly consumed quantity of 12.3 million tons. With only a 41% self-sufficiency rate, the EU is the most important seafood importer in the world [3]. Moreover, in the category of freshwater fish, the self-sufficiency rate of the EU-27 is only 37% [4]. Conversely, LAC has the lowest per capita seafood consumption in the world with only 10.5 kg/year which is equivalent to a demand of 6.7 million tons, largely met by marine fisheries [5]. Latin American aquaculture is a net aquatic food exporter, and even though the majority of exports originated from the marine environment, tilapia, farmed in freshwater, is also marketed in large quantities to the USA [6]. However, domestic demand for aquatic food is increasing, as among all regions of the world the highest growth rate (+18% between 2016 and 2030) in per capita seafood consumption is projected for Latin America [5].

All in all, freshwater aquaculture has a marginal role in total fish production and aquatic food supply both in the EU and LAC, but domestic markets exist and are being developed for freshwater aquatic products, and for the latter, region export markets would also offer growth potential if competitiveness was further improved. This paper attempts to review the trends of freshwater aquaculture production under these circumstances. Although there are a variety of socio-economic and regulatory conditions in which the two regions differ from each other, it was not the intention of this study to explore these. Rather, using aggregate statistics we tracked the internal tendencies of the sector. As such, the paper presents, both at a regional and country-level, how the production volume changed over the last decade and investigates which species contributed to the growth. By using an index for diversification, we conclude whether freshwater aquaculture tends towards diversification or concentration. Between-country differences in production tendencies are revealed in both regions, and we attempt to explain these with differences in freshwater resource endowments and climatic conditions.

2. Data Sources for the Analysis

Data on aquaculture production (both quantity and value) was obtained from FAO FishstatJ [1]. The unit value of production was calculated by dividing production value by production quantity. Population information, which was used for calculating production growth per capita, was derived from the World Bank database [7]. Trophic levels (TL) in aquaculture were considered in our study. TL for each species was extracted from FishBase [8]. The TL of interspecific hybrids was assigned based on the TL of parental lines. Renewable freshwater estimates were obtained from the FAO Aquastat program website [9]. At the country-level, we used the indicator 'Total annual renewable water resources (TRWR) per inhabitant' to represent the water endowment of major aquaculture producer countries. In order to calculate the region-level (EU-27 and LAC) values for the availability of renewable water, first, we summed country-level data on 'Total internal annual renewable water resources (TIRWR)' (i.e., not counting external water resources) in order to avoid the problem of multiple accounting of resources shared by more than one country [10]. Second, the sum of the country-level TIRWR values was divided by the population of the region [7] to calculate the per-capita availability of renewable water resources in the EU-27 and LAC. We presented climate information for the analysis, which was extracted from the Climate Change Portal of the World Bank Group [11]. For our study, we utilized monthly mean temperature data recorded in the 1990–2020 reference period. The thermal optimum of cultured species was copied from the META (Maritime and Environmental Thresholds for Aquaculture) database [12].

To measure the diversification degree of the aquaculture sector, we implemented an index from Hofherr et al. (2012) [13]. This index was calculated both at the country-level and region-level. This diversification index (DIV) considers the Herfindahl-Hirschman Index (HHI), which is a calculation of variety that takes into account both richness (i.e., the number of farmed items) and evenness (i.e., how evenly the quantity produced is distributed among these items). The range of DIV is set from 0 to 1, where a score close to 1 indicates a highly diversified industry in terms of the families produced, and a score close to 0 indicates a sector that is highly concentrated on one family [14]. The calculation formula of DIV is as follows:

$$\text{DIV} = 1 - \sum_{i=1}^{N} s_i^2$$

where S_i: share of production of species belonging to a family in total aquaculture production, and N is the number of fish families farmed in the aquaculture sector.

3. Aquaculture Production Trends in the Two Regions

Although at the global level, freshwater aquaculture is expanding rapidly, there is spatial heterogeneity in development patterns both between regions and within each region. Figure 1 provides an overview of those countries in the two regions considered in this study, where freshwater aquaculture output fell over the last ten years.

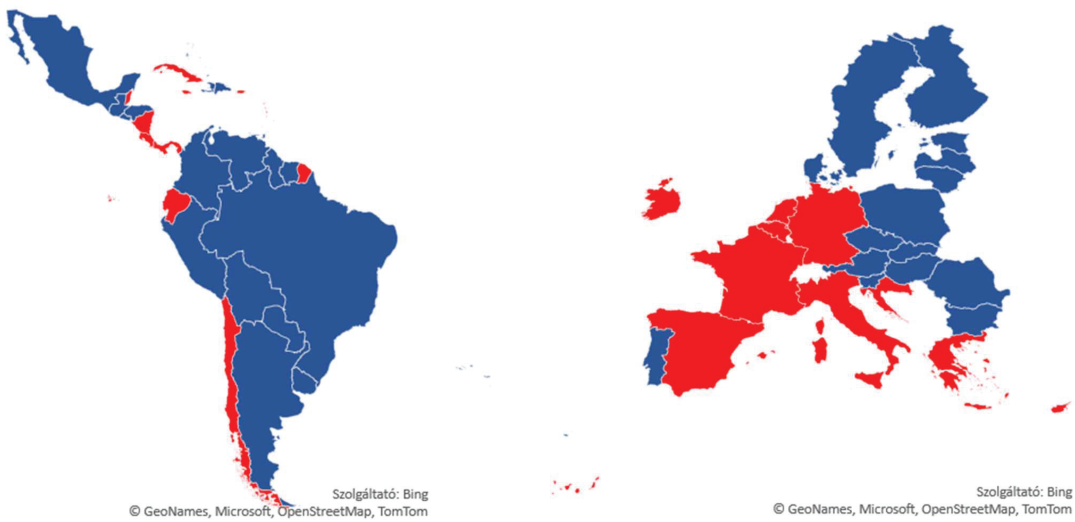

Figure 1. Geographical scope of the study. Blue- and red-colored countries represent increasing and falling freshwater aquaculture production between 2007–2009 and 2017–2019, respectively.

3.1. Production in LAC

Figure 2 presents the decadal changes in Latin American freshwater aquaculture production. During this period the output grew by 95% (from 476 to 927 kT), which is considerably higher than the growth rate of the global freshwater aquaculture level (60%) [1,5]. Brazil is by far the largest producer of LAC; it is the only non-Asian country in the top 10 of the global list of freshwater aquaculture producers (ranking 7th in 2019), and the 2.1-fold growth in Brazilian production over a decade is considerably higher than in other large global producers. However, in other major producers of LAC (Peru, Mexico, and Colombia) the sector grew at a rate even higher than in Brazil. Altogether the top-4 producers (Brazil, Colombia, Mexico, and Peru) account for 85% of total freshwater aquaculture output in the region, and contributed to 98% of the increment in production volume over a decade. Annual production in these four countries increased from 338 to 783 kT. On the contrary, there was a drop in output in some countries, including Ecuador and Chile in South America, and many of the Central American and Caribbean states (Cuba, Costa Rica, Jamaica, Panama).

Regional aquaculture development was centered around the growth of tilapia (mainly Nile tilapia) production, a non-native tropical fish with standardized rearing protocols which has robust domestic and export (USA and European) markets [15,16]. With a yearly output of 543 kT, tilapia contributes to 59% of regional production. Farming of characins, a family of tropical species native to LAC (mainly cachama, pirapatinga, pacu, and their interspecific hybrids), is produced entirely for domestic markets, and cold-water salmonids (almost exclusively represented by non-native rainbow trout) is also a rapidly growing segment in the region. Carp farming, a traditional and formerly important sub-sector in LAC aquaculture, has gradually lost its weight over the last decade (Figure 1).

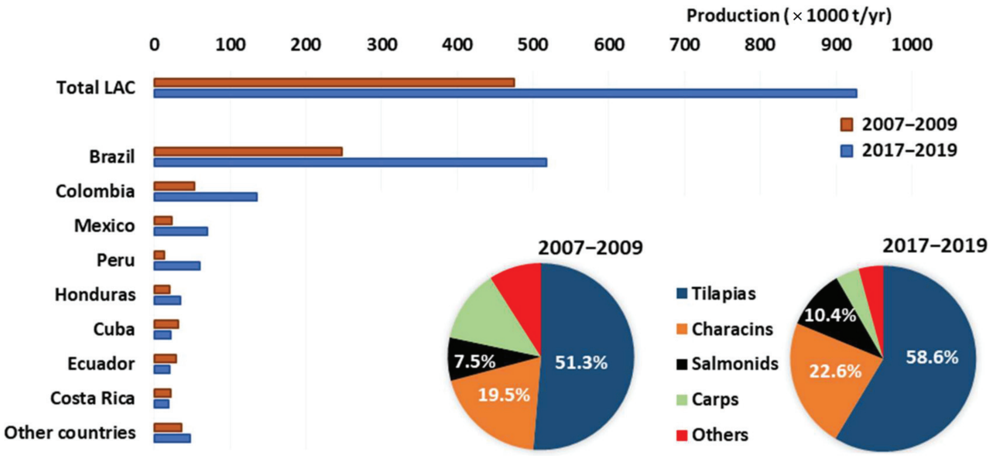

Figure 2. Freshwater aquaculture production in LAC. Data source: [1].

3.2. Production in EU

Contrary to significant development in Latin American and global freshwater aquaculture, output in the EU has not grown for decades. Production has slightly decreased from 284 to 280 kT over the last decade (Figure 3). Similar to Latin America, big differences exist between the development patterns of individual countries. There are marked west-east and south-north gradients in industry growth rates: aquaculture output in most of the Western and Mediterranean countries fell, on the contrary, Eastern and Northern EU states increased their fish production (Figure 1).

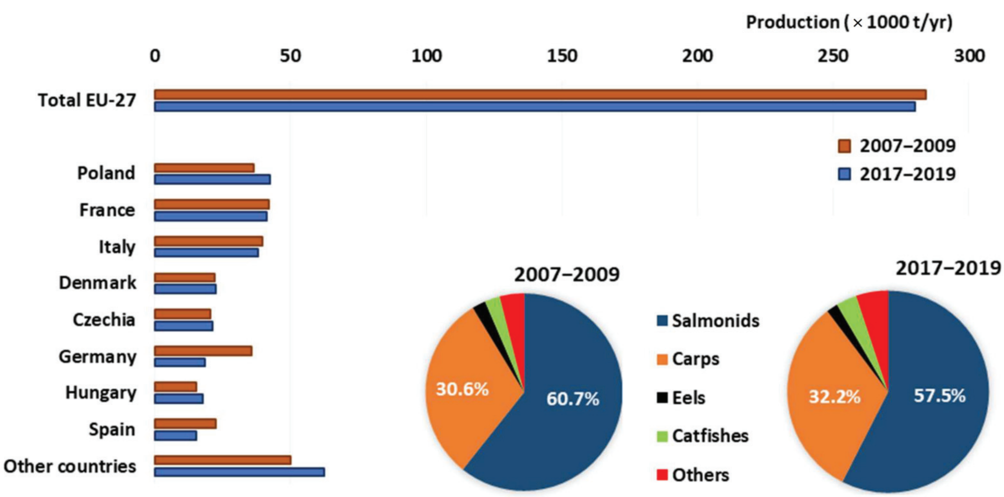

Figure 3. Freshwater aquaculture production in the EU-27 and in the top 8 producer countries (bar charts). Pie charts represent share of major groups in total production of EU-27. Data source: [1].

EU aquaculture is heavily concentrated on two species, which altogether account for 83% of production. Rainbow trout, a predatory species predominant in the aquaculture of Northern, Western, and Mediterranean countries, are farmed in cold-water systems. The production of this species fell in the period investigated, from 167 to 152 kT. The second most important farmed organism is the common carp (70 kT in 2007–2009 and 73 kT in 2017–2019), which is cultured at lower trophic levels in warm-water aquaculture, mainly in Eastern European EU states. Production statistics suggest that geographical patterns in aquaculture development are more important than general differences in growth pathways of different species, since carp production shrank significantly in France and Germany, despite the general growth of the carp industry in Eastern Europe.

In addition to rainbow trout and common carp, several other *Salmonidae* and *Cyprinidae* species are farmed as well, but in lower volumes. Next to salmonids and cyprinids, higher TL value species (*catfishes*, *sturgeons*, *perciform* sp., eel, pike) are cultured in the EU, which have a higher market value than cyprinids.

3.3. Trophic Level and Unit Value of Species Produced

At a global level, capture fisheries supply markets with carnivorous species, whereas aquaculture focuses on species that are lower in the food chain, and carnivorous species make up less than 10% of farmed output [17]. In line with global trends, the majority of species farmed in freshwater aquaculture in LAC are omnivorous and herbivorous fish, and carnivorous species (TL > 3.5) account for less than 12% of total production. Unlike global and Latin American aquaculture, EU-27 fish farming is focused on carnivorous fish, which contribute to 66% of production, while herbivorous and omnivorous species at TL < 3.5 account for only 34% of the production.

At a global level, carnivorous species are traded with higher value and have larger production costs due to protein-rich feeds applied in farming [17]. For the LAC and EU, Figures 4 and 5 match the trophic level (TL) against the unit value of cultured species (including interspecific hybrids). Unlike general patterns in global markets of cultured species, in Latin America there is no (statistically) significant correlation between trophic level and market value; most of the carnivorous species are traded with values (<3 USD/kg) similar to those at lower trophic levels, with the exception of rainbow trout and arapaima that command a higher price on the markets. On the other hand, blue tilapia has a relatively high market value in spite of its herbivorous nature.

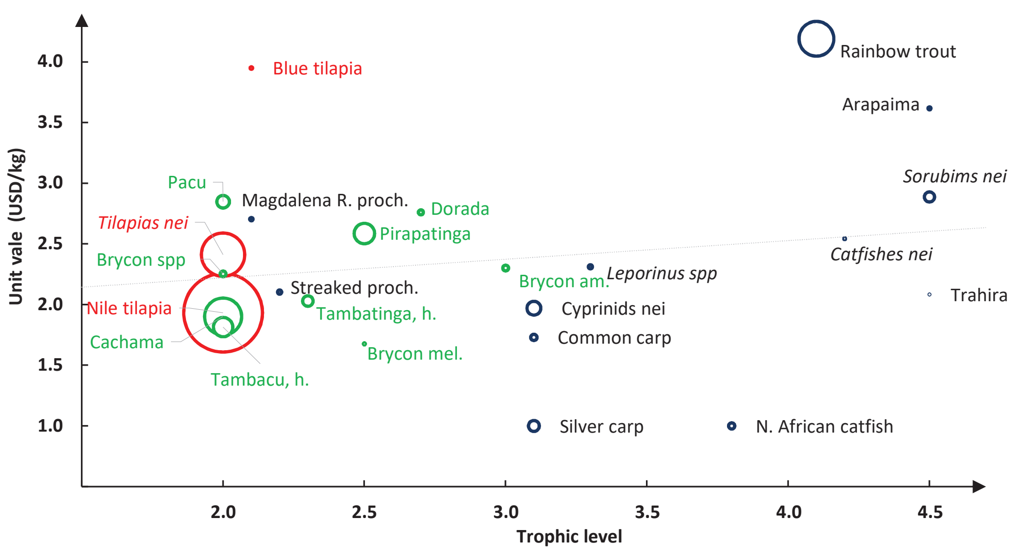

Figure 4. Bubble plot of the trophic level versus the unit value for the top-25 species in LAC aquaculture (calculated for 2019). The size of the bubbles relates to the production volume of a particular species. Cichlidae and Characidae species are marked in red and green, respectively. Items in italics are not species but higher-level aggregates. Data sources: [1,8].

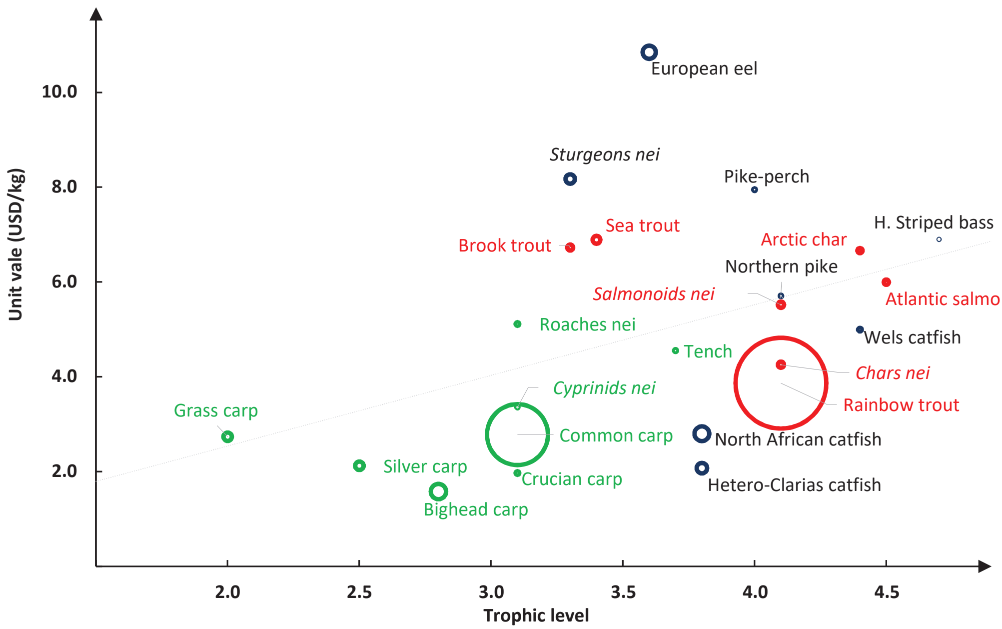

Figure 5. Bubble plot of the trophic level versus the unit value for the top-25 species in EU-27 aquaculture (calculated for 2019). The size of the bubble relates to the production volume of a particular species. Salmonidae and Cyprinidae species are marked in red and green, respectively. Items in italics are not species but higher-level aggregates. Data sources: [1,8].

Unit values of fish in the EU are found in a wider range, from 1.6 (bighead carp) to 10.9 (eel) USD/kg, with a positive gradient along the trophic chain. There is a statistically significant correlation ($r = 0.48$, $p = 0.02$) between TL and the unit value of species, implying that European consumers have a willingness to pay higher prices for carnivorous species.

Diverting culture practices toward low trophic level species is identified as a strategy for sustainable aquaculture, to reduce nutrient loading and the demand for high-protein terrestrial or marine feed sources [18]. Each level up the trophic chain decreases the efficiency of utilizing energy produced by photosynthetic organisms. For this reason, metrics calculated with the trophic level are often used as indicators for sustainability [19,20]. Though the original meaning of TL has been blurred recently with the increasing share of vegetable-based ingredients in diets of farmed carnivorous species [21], the protein content (either it is sourced from vegetable or animal ingredients) and cost of aquafeed recipes are still higher for carnivorous species than for herbivores. Therefore, we continue to consider TL as a proxy indicator of the level of requirement for costly nutrients during the culture of fish species. Figure A1 illustrates the change in mean trophic level of freshwater aquaculture production (both at the region-level and country-level) between 2007–2009 and 2017–2019. In Latin America, there was only a slight increase in the mean trophic level of the regional aquaculture, from 2.30 to 2.32, which indicates the unchanged dominance of herbivore and omnivore species. On the contrary, the mean trophic level of EU aquaculture is relatively high (3.64 calculated for 2017–2019), but slightly decreasing with a rising share of carp in total production.

3.4. Diversification and Emerging Species

Species diversification increases the resilience of industry by reducing its vulnerability to market shocks and species-specific disease outbreaks [22–24]. To analyze the diversity of the aquaculture sector, we used metrics reflecting the degree to which fish production is evenly distributed among more species. Figure A2 presents the calculated diversification index (DIV) and its change between 2007–2009 and 2017–2019, for the two regions considered. Higher values indicate higher diversity. The DIV calculated for the Latin American freshwater aquaculture was reduced from 0.68 to 0.59 in the last decade, which suggests that concentration of the industry has taken place, and the sector became less diversified at the regional level. The reduction in the DIV is mainly attributed to the increasing dominance of Nile tilapia in Latin American aquaculture (Table A1). In Brazil, Mexico, and Peru the diversification of fish production was reduced significantly, corresponding to a development pattern where an already dominant species becomes even more dominant in production (tilapia for Mexico and Brazil, trout for Peru). This reflects that the aquaculture industry sees the opportunity in concentrating efforts, investments, and infrastructure on the production of these species. However, rainbow trout and tilapia are non-native species, and most recent aquaculture plans (Peru, Colombia, Brazil) identify the culture of native species as a priority and promote this as a path to sustainability [I]. Figure 6 provides an overview of the aquaculture development of native emerging species.

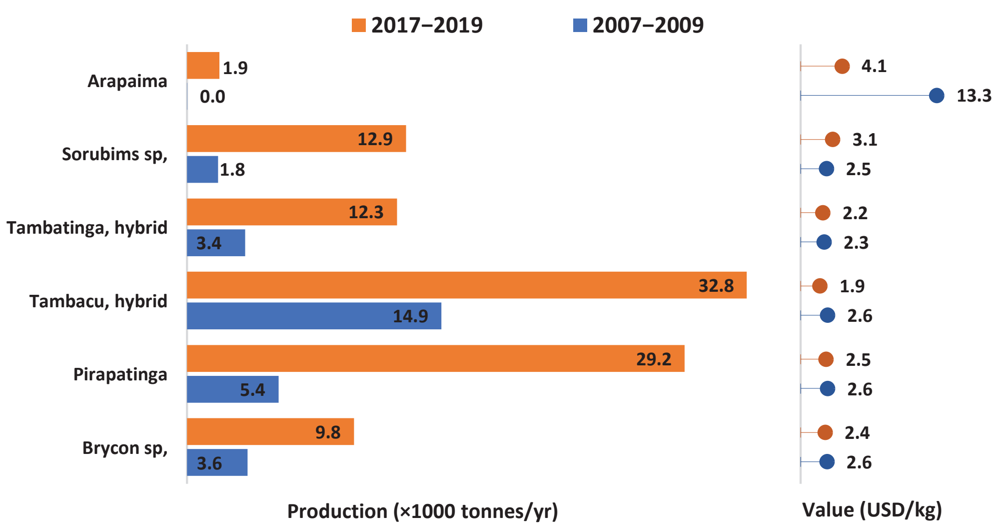

Figure 6. Emerging species in freshwater aquaculture of EU-27: production quantities and unit values in 2007–2009 and 2017–2019.

In contrast with the Latin American freshwater aquaculture, the species diversity slightly increased in the EU-27 in the last years from 0.54 to 0.56. This is mainly attributed to the shrinking contribution of trout to total production, but the increasing output of emerging species (Figure 6) also contributes to increased diversity in European aquaculture. Most of these novel species are carnivorous species with high but falling market value. African catfish (and its hybrid, the Hetero-clarias catfish) is exceptional in that it is marketed at low prices. Being an air-breathing organism and its wide tolerance for water quality, the African catfish is cultured in high densities [25] with low per-unit fixed costs, allowing farmers to position it as a low-value species. Thanks to its low price, it has a stable domestic market, and its calculated market value increased over the last decade. However, being a non-native invasive species, there are ecological concerns over escapees from culture units [26]. EU countries are important contributors to global sturgeon meat and caviar output, originating from aquaculture, but in recent years demand for these products was lower than the offer [27]. This is reflected in the decreasing unit prices (Figure 7), which has a negative impact on the growth prospects of this industry. Production of perciform species (pikeperch, perch, and hybrid striped bass) increased double-fold over the period investigated. Pikeperch is the most important native percid fish in Europe, with a very solid market price. Yet, various technological problems hamper the growth of pikeperch farming, such as unpredictability in reproductive performance and juvenile production [28]. Char farming is also an important emerging segment in EU aquaculture, especially in the Northern states, with the potential to diversify salmonid production [29]. Land-based Atlantic salmon farming is in its infancy, production is being upscaled in large RAS systems. Total RAS production of Atlantic salmon is larger than what is indicated in Figure 7, since there are land-based systems that produce salmon in salt water, and their production is reported under marine aquaculture production [29].

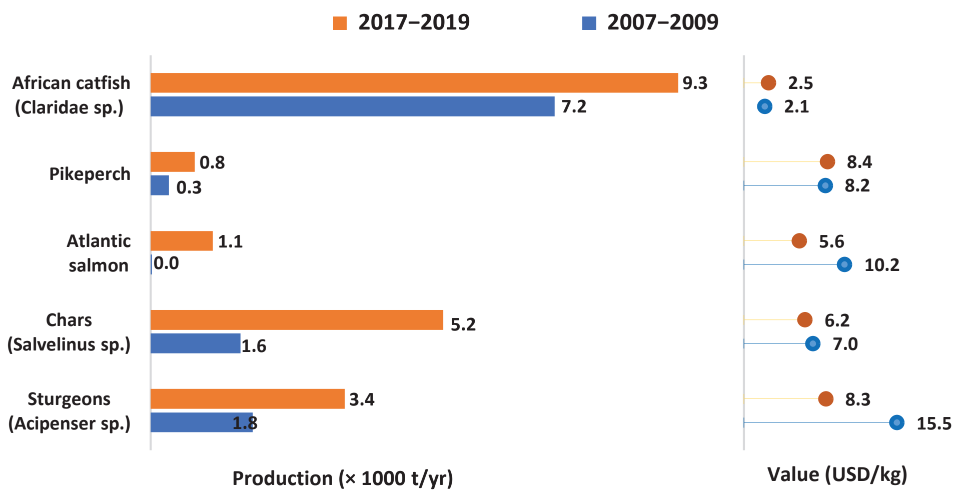

Figure 7. Emerging species in freshwater aquaculture of EU-27: production quantities and unit values in 2007–2009 and 2017–2019.

European aquaculture producers face import competition mainly from mid-value salmon and low-value pangasius originating from countries (Norway and Vietnam, respectively) where climatic and geographic conditions are ideal for these species, and the EU market penetration of these species is supported by a well-developed value chain. Conventional species (trout, carp) farmed in the EU do not have the perspective to increase domestic market share, therefore, European fish farmers try to find breakthrough points by diversifying production with species that are destined for supplying niche markets where international competition is lower.

4. Water Use and Resources in LAC and EU Aquaculture

4.1. Water Resource Intensity of LAC and EU Aquaculture Production

The intensity of resource use varies widely between culture systems. Therefore, first, we review major types of rearing systems used in aquaculture in LAC and EU before discussing the relationship between growth and freshwater resources. Although statistical reports do not break down production data by different farming systems for the Latin American region, based on literature sources it is obvious that earthen pond culture is dominant, especially in tilapia and characid sectors [2,16,30,31]. Pond farming technologies vary from low to high intensity, which differs in stocking densities, nutrient input, water quality, flow management, etc. A smaller part of the production takes place in static-water ponds under extensive (non-fed) conditions, where supplementary water is only withdrawn to replace what is lost through evaporation [16]. The largest portion of the output is farmed under semi-intensive conditions in fed and fertilized earthen ponds, where water management is either similar to that of extensive systems [31] or a moderate flow rate is provided [30]. Intensive technologies in earthen ponds are operated with high flow rates (proportional to biomass density) to provide constant water refreshment [30]. In addition to pond farming, the use of reservoirs for aquaculture is also common in LAC, either as a place for extensive management or intensive culture in floating cages [32–34]. Although recirculating aquaculture systems (RAS) are more and more widely used in culture of marine species using saltwater, they do not represent a significant share in Latin American freshwater aquaculture [16].

The main factors affecting specific (per kg) direct water use in production systems are yields (kg produced per m^3 or ha) and flow regime (frequency of water intake, intensity of water exchange). Feed-associated (indirect) water use is also significant in fed-systems, in the range of 1–2.5 m^3/kg production [35,36] System-associated water use takes place on the production site, but, by contrast, feed-associated water consumption is often incorporated into imported crop ingredients (e.g., soybean), with implications on water resources found in regions/countries far away from the fish production site. Therefore, with the consequent aim of investigating how the development of the aquaculture sector in LAC and the EU depends on the spatial availability of water resources, we focus on the system-associated water requirements of different systems below.

At a global level, RAS and cage systems are considered to use blue water resources most efficiently, with a minimal (<0.5 m^3/kg) water footprint [37–39]. However, accounting freshwater use to cage culture when multiple uses occur in water bodies is not consistent [14]. On the other end, flow-through systems are considered to be the least efficient systems in terms of using blue waters, usually with a footprint >50 m^3/kg [38–40]. Pond systems, which are the dominant environment for freshwater fish production both globally and in LAC, are in between RAS/cage and flow-through systems in terms of water use, with footprint values between 3 and 40 m^3/kg, depending on yields, evaporation and seepage conditions at the production site, and water refreshment regime applied [37]. Generally, it is considered that specific water use has an asymptotic relationship with aquaculture production intensity, since more intensive production systems were found to use water resources more efficiently (per kg of fish produced) than extensive production systems [35,37,39,41,42]. Results of studies assessing water use in LAC and EU are summarized in Table 1.

Table 1. Per kg water use in typical fish production systems in LAC and EU as per literature sources.

Species, Production System	Direct Water Use [1]	Source and Further Information on Indirect Water Use for Upstream and Downstream Segments
Rainbow trout, pond culture (Colombia)	16.9 m^3/kg	Source: [43] The study calculated blue, grey, and green water footprint (WF) for the hatching and on-growing phases: feed and electricity (input) production. Calculated WFs were 19.8, 5.5, and 6.1 m^3/kg for trout, tilapia, and chachama, respectively.
Tilapia, pond culture (Colombia)	2.7 m^3/kg	
Cachama, pond culture (Colombia)	3.9 m^3/kg	
Nile tilapia, extensive reservoir culture [2] (Mexico)	2.8 m^3/kg	Source: [30]. The study calculated blue, grey, and green WFs for the following stages: broodstock keeping, on-growing, fish processing, transport, feed, and fertilizer (input) production. Calculated WFs were 4.0, 37.8, and 68.2 m^3/kg for extensive, semi-intensive, and intensive culture, respectively (on a live weight basis).
Nile tilapia, semi-intensive pond culture [3] (Mexico)	8.7 m^3/kg	
Nile tilapia, intensive pond culture [4] (Mexico)	39.1 m^3/kg	
Nile tilapia, semi-intensive pond culture [5] (Brazil)	17–34 m^3/kg	Source: [31] Water dependency analysis focused only on blue water use during on-growing stage.
Nile tilapia, Intensive cage culture in reservoir [6] (Brazil)	<0.01 m^3/kg	Water dependency analysis focused only on blue water use during on-growing stage. Source: [33]
African catfish, intensive RAS culture [7] (Netherland)	0.1 m^3/kg	Analysis scoped system-associated (blue) water use during on-growing. If feed-associated (green) water use was added, water use would amount to 0.5 m^3/kg. Source: [37]

Table 1. *Cont.*

Species, Production System	Direct Water Use [1]	Source and Further Information on Indirect Water Use for Upstream and Downstream Segments
Carp, semi-intensive pond culture [8] (Hungary)	21.1 m^3/kg	Calculated system-associated (blue) water use based on data from country-level statistical report for 2019 [44]. If feed-associated water use was added, water use would amount to 24.8 m^3/kg.
Trout farmed in flow-through raceway tanks [9] (France)	54.2 m^3/kg	Water dependency analysis focused only on blue water use during on-growing stage. Source: [38]

[1] Definitions of direct (system-associated) water use vary across studies. Most studies calculate the total amount of water withdrawn for production, which is larger than consumptive water use. [2] Non-fed, fertilized system with 1.5 kg/m^3 max. biomass density. [3] Fed and fertilized system with a daily 30% water exchange. Max biomass density is 25 kg/m^3. [4] Fed system with a daily 100–400% water exchange. Max biomass density is 40 kg/m^3. [5] Fed, fertilized and aerated system, with supplementary water intake (offset evaporation loss) 9–14 t/ha. [6] Fed system in static water body. Max density is 37–43 kg/m^3. [7] Water exchange is 0.1 m^3/kg feed. Culture density is >300 kg/m^3. [8] Fertilized and fed system with supplementary water intake (offset evaporation loss). Yield is 710 kg/ha. [9] Constant water flow diverted from a river; oxygen supply is provided.

Calculated per kg water demands of species farmed in Latin American systems (Table 1) fall in line with finding for other regions of the world discussed above. Although results are not supposed to be directly compared since different studies use different methodologies with different system boundaries, it is important to note that a recent study found that intensive tilapia culture was associated with a higher blue water footprint than extensive farming due to high flow rates of refreshing water in the former technology [30]. This is contradictory to common findings for other regions, as discussed above, and it may challenge the view that intensification in LAC comes with water resource efficiency.

For EU-27, the statistical office of the European Union reports aquaculture production data by production method (farming system) [45]. Based on data available it is estimated that 48% of freshwater production originates from flow-through pond/tank/raceway systems, 38% is produced in static-water earthen ponds, while RAS systems and cage/pen aquaculture account for 10% and 4% of production, respectively. Under flow-through conditions mainly trout [46], and to a lesser extent, African catfish, are cultured. Cold-water trout are often reared in surface water diverted from smaller water courses, while warm-water catfish are farmed in subterranean geothermal water. In the pond farming segment, typically a semi-intensive carp-dominant polyculture is practiced with low (<1 t/ha) yields [47–49]. Contrary to Latin America, European RAS systems are constructed primarily to farm freshwater species, mainly trout, catfishes, and sturgeons [50]. There are farms also that rear Atlantic salmon and eel in a freshwater RAS environment [29]. Unlike many regions of the world, where cage farming is an important segment of both freshwater and marine aquaculture, in the EU cage systems are not typical in freshwater environments [51], only some facilities exist to farm carp and sturgeon in reservoirs and on cooling water of thermal power plants. To minimize the discharge of trout farms and comply with strict environmental regulations, partial recirculation of water was a tendency in Denmark, one of the largest producers in the EU. The main advantage of these systems is reduced nutrient emission, but there are some disadvantages that limit the development of RAS culture, such as high capital cost and worse energy efficiency due to automation [29,50,52,53].

The water demand of the flow-through trout farming segment is high (50–100 m^3/kg), and this can be reduced by up to two orders of magnitude (to 0.1–2 m^3/kg) if systems are converted to RAS [36,38,54]. Carp produced in semi-intensive pond production in an Eastern European climate have a water demand of around 20 m^3/kg ([55] and calculations in Table 1).

4.2. Role of Water Resources in Aquaculture Development

In the previous section, it was highlighted that aquaculture production growth requires some 5–50 m^3 of water per kg of additional capacity, depending on the species and production system. Tilapia and carp aquacultures in most typical semi-intensive systems demand 10–30 m^3/kg, while trout produced in conventional flow-through require more than 50 m^3/kg. Here, we match between-region and between-country differences in growth rates with differences in freshwater resource endowments. In our study, we examined two regions: LAC, which are abundant in water resources with a TRWR value of 21,476 m^3/capita/year, and the EU-27, which have a TRWR less by an order of magnitude (3041 m^3/capita/year). Growth in annual freshwater aquaculture production over the last ten years was −0.01 kg/cap (the EU) and 0.70 kg/cap (LAC).

Figure 8 plots the per-capita availability of annually renewed freshwater resources against per-capita growth in the aquaculture sector in the last decade for the top 12 producing countries in each region. Per-capita growth if aquaculture was calculated as the difference between per-capita production in 2017–2019 and in 2007–2009. Therefore, countries with increasing populations and slightly increasing production may have negative values for per-capita change in fish production (e.g., Denmark). The calculated Pearson-r correlation between the two variables is 0.53 ($p = 0.08$) for Latin American countries, while for European countries it is 0.75 ($p < 0.01$) if outlier data for Bulgaria was excluded. These values suggest a positive relationship between per capita freshwater aquaculture development and per capita freshwater availability. In Latin America, Peru, Colombia, and Brazil are the most water-abundant countries, and these countries are ranked 2nd, 1st, and 4th in terms of per capita aquaculture growth, respectively. On the other hand, Cuba is characterized by the lowest water resource availability in LAC, and this corresponds to the biggest reduction in aquaculture production.

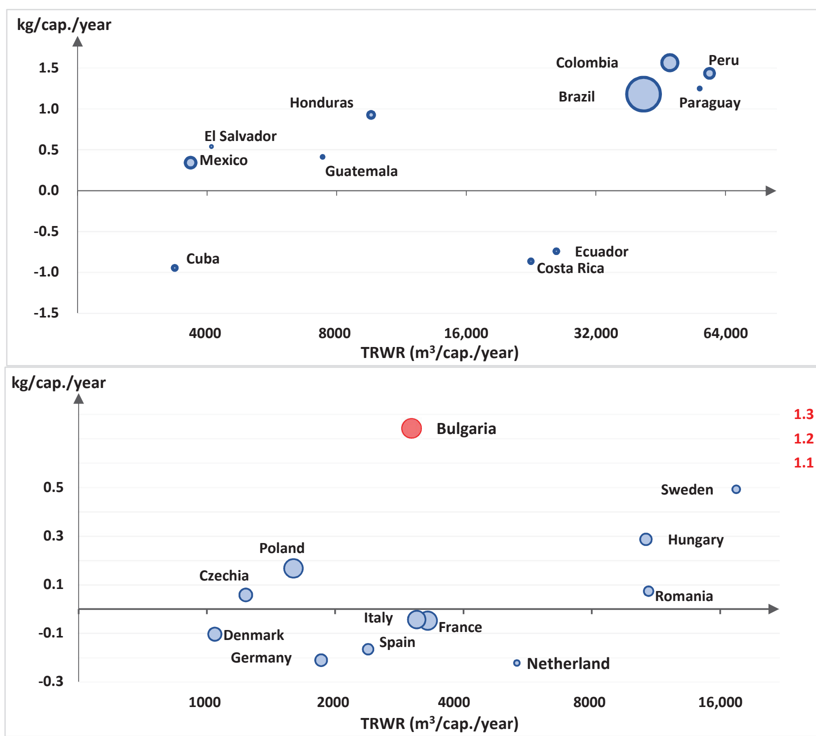

Figure 8. Bubble plot of the Total Renewable Water Resources (TRWR, 2018–2022) versus per capita growth of annual freshwater aquaculture production over a 10-year period (from 2007–2009 to 2017–2019) for top-12 freshwater aquaculture producers in LAC (**upper**) and EU (**lower**) graph. The size of the bubble relates to the freshwater aquaculture production (t/year) of the corresponding country (avg. for 2017–2019). Note that the x-axis is log-scaled, and scales differ between the two graphs. Data sources: [1,9].

Among the major freshwater fish producer countries in the EU, Sweden, Hungary, and Romania have the largest volume of water resources, corresponding to positive growth rates of aquaculture on a per-capita basis in these countries. Sweden has the highest water abundance among the major producers in the EU and this enables the high growth rate of trout production in flow-through systems, which have the highest water demand among European systems. Recirculation aquaculture is relatively undeveloped in Sweden [HH]. Among countries that have a TRWR value of less than 4000 m^3/capita/year, it can be seen that countries where carp-based pond aquaculture is dominant (Czechia, Poland, Bulgaria) increased their production, while per-capita aquaculture output fell in countries, where aquaculture sector is based on flow-through through systems (France, Germany, Italy, and Spain). Considering that flow-through systems (with a footprint of >50 m^3/kg) are more sensitive to water stress than carp-based pond farming (~20 m^3/kg), aquaculture development patterns can be partly explained by the difference in the degree of vulnerability of different systems to temporal water shortages, which are more frequent with climate change [25,56–59].

In water-poor regions, one strategy to maximize production value per m^3 of water used is to farm high-value species in recirculation aquaculture systems (RAS), which minimize water footprint. RAS aquaculture (farming sturgeons, eel, catfish, trout) has developed rapidly, especially in the European countries where per capita water renewable resources are below 4000 m^3. Denmark, France, Germany, Poland, and Spain altogether account for 75% of RAS production in the EU [50].

In addition to freshwater resource availability, the potential growth of freshwater aquaculture is also determined by climatic conditions since water temperature in most culture systems is under the control of the climate. The species for culture must be selected so that the range in temperature preference and tolerance of the species chosen is in harmony with the local climate [60]. Figure 9 provides an overview of the climatic conditions of the top 10 producers in both regions matched with the thermal preferences of the main target species. Although the graph represents data for air temperatures, it is often assumed that there is a linear relationship between air and water temperatures [57,61].

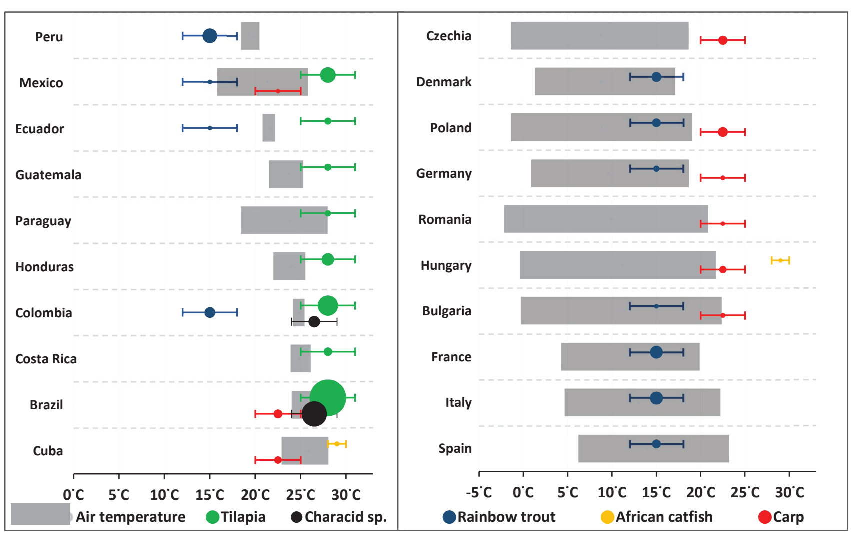

Figure 9. Climatic conditions (range of mean monthly air temperatures) versus thermal optimum of major cultured species in the top 10 fish producing countries of LAC (**left**) and EU (**right**). The size of the bubbles relate to the production volume of species. The whiskers encompass the optimal water temperature range for each species. Source of data: [11,12,62].

Most of the Latin American countries have a tropical climate with little variation in monthly temperatures, which favors aquaculture production by enabling them to plan production cycles without seasonality. Even in sub-tropical countries (Mexico), the range is narrower than in European countries, and warm-water species can be fattened in the colder season. Cold-water trout farmers at higher altitudes can also benefit from near-to-constant temperatures, as is shown in rainbow trout aquaculture development in Peru, the country with the coldest annual mean temperature among the major producer countries of the region.

Most of the EU territories are under a temperate climate, with large variations in monthly temperatures, therefore there is a strong seasonality in fish production cycles in open systems. The graphical tool helps the understanding of the difference in growth between trout and carp production over the last decade. Carp is a robust species with wide temperature tolerance and low biological sensitivity to environmental changes [63]. Temperature increase, which is an ongoing tendency, is forecasted to favor the metabolic activity and growth rate of carp under Eastern European conditions, since prevalent temperatures are far away from its upper limit of thermal preference [57,61]. On the one hand, trout is a species with a relatively low upper thermal limit, and consequently, warming may significantly enhance trout mortality and affect productivity, especially in Mediterranean countries [58]. In light of this, climate change contributes to the explanation of the difference in aquaculture production changes between Mediterranean and Northern European trout farming countries.

5. Emission of Aquaculture Production

Aquaculture generates emissions either to the air or to the aquatic space. The most pronounced environmental concerns are over (i) the release of nitrogenous or phosphorus, which may stimulate eutrophication processes in the receiving water body, and (ii) greenhouse gas (GHG) emission [64]. Unlike water footprint, which is mainly generated during on-farm activities, the majority of aquaculture-related GHGs are emitted during feed production, thus carbon footprint is largely determined by the feed conversion rates and the ingredients used in aquafeeds [65,66]. This implies that the nutritional habit of the cultured species and the regional availability of ingredients matching these nutritional requirements have a major influence on climate change mitigation. A recent study using relatively narrow system boundaries and standardized methodology across different systems and species found that tilapia farming in LAC has a significantly lower carbon footprint (2 $kgCO_{2eq}$/kg fish, in live weight) than the global average tilapia production (3.7 $kgCO_{2eq}$/kg fish), and this emission efficiency is mainly attributed to regional feeds with lower footprints and lower use of fossil energy during on-farm processes [66]. In the same study, the GHG emission of European carp production is calculated to be lower (1.6 $kgCO_{2eq}$/kg fish) than the global average carp carbon footprint (3.2 $kgCO_{2eq}$/kg fish). However, if the system boundaries of the analysis are expanded, the carbon footprint of carp production is found to be significantly higher (6 $kgCO_{2eq}$/kg fish), as infrastructure maintenance (pond dredging) and post-harvest operations (packaging and transport) are responsible for a large amount of greenhouse gas emission [67]. While most systematic review studies conclude that per-unit GHG emissions of tilapia and carp production are in a similar range, there is disagreement on whether the carbon footprint of salmonids (including trout) is higher or lower than that of carp and tilapia [65,66,68]. Similarly, there is a lack of consensus in answering the question of whether RAS produced trout have a higher carbon footprint than one from a flow-through system, as the GHG emission during RAS production is largely dependent on the source (renewable or fossil) of the electricity used for operating the system [69]. Nevertheless, on-farm energy use in RAS technology is higher than in other systems, but in the post-harvest stage the fuel demand is often lower with shorter transportation routes because RAS facilities are built in the proximity of markets [70].

Nutrient emissions of aquaculture segments are determined by the utilization (retention) efficiency of input nutrients in farmed organisms, and treatment/recovery of the non-utilized part of nutrients. While the former factor is more species-specific, the latter one is system-specific. In flow-through and cage systems the non-retained part of nutrients is generally discharged with water exchange [53,71]. In RAS systems effluents are treated and solid wastes are collected [72], while in static-water pond culture part of the non-retained nutrient input is recycled through the food web and recovered in the plankton biomass [57]. For this reason, feed nitrogen and phosphorous conversion efficiency are relatively high (>40%) in European and Latin American pond cultures [47,73,74]. If the total (feed and fertilizer) nutrient inputs are considered, then pond farming has low conversion efficiency (<20%) in comparison to other systems, because nutrients present in fertilizers are not directly utilized by target fish species and transition losses arise with nutrients transferred through three levels of the trophic web (fertilizer-phytoplankton-zooplankton-tilapia/carp) [57,75]. However, we argue that the nutrient efficiency of fertilized systems cannot be directly compared with fed systems, as for the latter one fertilizer input during the production of crops used as aquafeed ingredients should also be accounted for.

6. Conclusions and Perspectives

There are several factors that play a significant role in aquaculture development, including market demand, environmental concerns, licensing regulations, and institutional capacity [76]. This study was not written with the objective to discuss socio-economic influences that may limit the exploitation of resources, rather it concentrated on production trends and underlying factors endowments as available from aggregate statistics. We investigated the climate and availability of freshwater resources, which are crucial factors in aquaculture development [77], and shed light on their influence on the growth prospects of the aquaculture sector. The LAC, accounting for one-third of the world's total runoff [78], is well-endowed with currently underutilized renewable water resources [10] and still has a huge scope for expansion. In the European context, it is often cited that bureaucracy and restricting environmental regulations are barriers to growth [73,79], but it needs to be further understood whether regions poor in natural resources tend to have more strict environmental rules to ensure the conservation of biodiversity and ecosystem functioning and whether socio-economic and institutional influences are themselves consequences of resource scarcity. In fact, many of the European producers see the future potential of the industry rely on subsidies, rather than expansion of physical output [80,81].

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Appendix A

Table A1. Aquaculture production of top 25 species in LAC and EU-27. Items in red are not species, but larger aggregates as per given by Aquatic Sciences and Fisheries Information System (ASFIS). Source: [1].

	LAC Production (t/year)			EU 27 Production (t/year)		
	ASFIS Species	**2007–2009**	**2017–2019**	**ASFIS Species**	**2007–2009**	**2017–2019**
1	Nile tilapia (*Oreochromis niloticus*)	200,785	416,322	Rainbow trout (*Oncorhynchus mykiss*)	167,173	151,721
2	Tilapias nei (*Oreochromis spp.*)	40,740	125,177	Common carp (*Cyprinus carpio*)	70,448	73,355
3	Cachama (*Colossoma macropomum*)	49,361	107,513	Bighead carp (*Hypophthalmichthys nobilis*)	3617	6255
4	Rainbow trout (*Oncorhynchus mykiss*)	31,021	95,987	North African catfish (*Clarias gariepinus*)	5296	5966
5	Pirapatinga (*Piaractus brachypomus*)	5381	29,174	Freshwater fishes nei (*Actinopterygii*)	5587	5620
6	Tambacu, hybrid (*P. mesopotamicus x C. macropomum*)	14,935	32,844	European eel (*Anguilla Anguilla*)	6280	5139
7	Cyprinids nei (*Cyprinidae*)	21,490	18,348	Hetero-Clarias catfish, hybrid (*H.longifilis x C.gariepinus*)	1822	3372
8	Pacu (*Piaractus mesopotamicus*)	15,921	16,283	Sturgeons nei (*Acipenseridae*)	1345	3008
9	Silver carp (*Hypophthalmichthys molitrix*)	19,189	13,447	Silver carp (*Hypophthalmichthys molitrix*)	4917	3086
10	Tambatinga, hybrid (*C. macropomum x P. brachypomus*)	3422	11,894	Grass carp (*Ctenopharyngodon idellus*)	1696	2479
11	Sorubims nei (*Pseudoplatystoma spp.*)	0	12,404	Sea trout (*Salmo trutta*)	2860	2720
12	Common carp (*Cyprinus carpio*)	19,275	6145	Salmonoids nei (*Salmonidae*)	263	1628
13	North African catfish (*Clarias gariepinus*)	3838	6042	Chars nei (*Salvelinus spp*)	492	1913
14	*Brycon amazonicus*	0	4346	Brook trout (*Salvelinus fontinalis*)	693	1596
15	*Brycon spp*	0	4772	Atlantic salmon (*Salmo salar*)	26	1100
16	Freshwater fishes nei (*Actinopterygii*)	15,826	3472	Arctic char (*Salvelinus alpinus*)	404	1549
17	Dorada (*Brycon moorei*)	0	1346	Crucian carp (*Carassius carassius*)	33	337
18	Streaked prochilod (*Prochilodus lineatus*)	0	3167	Roaches nei (*Rutilus spp*)	13	710
19	*Leporinus spp*	0	3739	Wels(=Som) catfish (*Silurus glanis*)	1369	1051
20	Magdalena River prochil (*Prochilodus magdalenae*)	0	1634	Silver, bighead carps nei (*Hypophthalmichthys spp*)	0	771
21	Arapaima (*Arapaima gigas*)	8	1898	Tench (*Tinca tinca*)	1299	985
22	Blue tilapia (*Oreochromis aureus*)	2583	1862	Pike-perch (*Sander lucioperca*)	327	780
23	*Brycon melanopterus*	0	516	Northern pike (*Esox Lucius*)	286	585
24	Catfishes nei (*Ictalurus spp.*)	0	1347	Cyprinids nei (*Cyprinidae*)	1245	591
25	Trahira (*Hoplias malabaricus*)	186	746	Striped bass, hybrid (*Morone chrysops x M.saxatilis*)	197	344

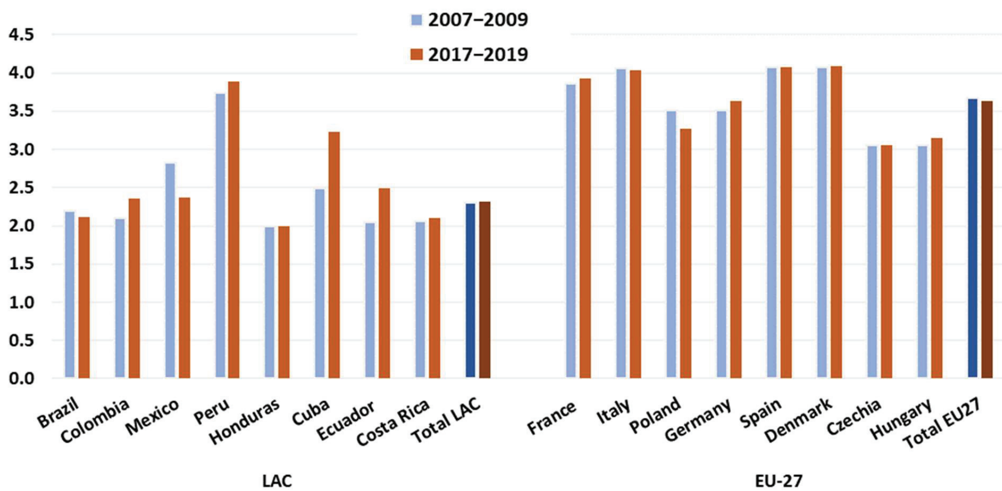

Figure A1. Average trophic level of freshwater aquaculture production at the region-level and country-level (calculated for 8–8 largest producers) in 2007–2009 and 2017–2019. Data sources: [1,8].

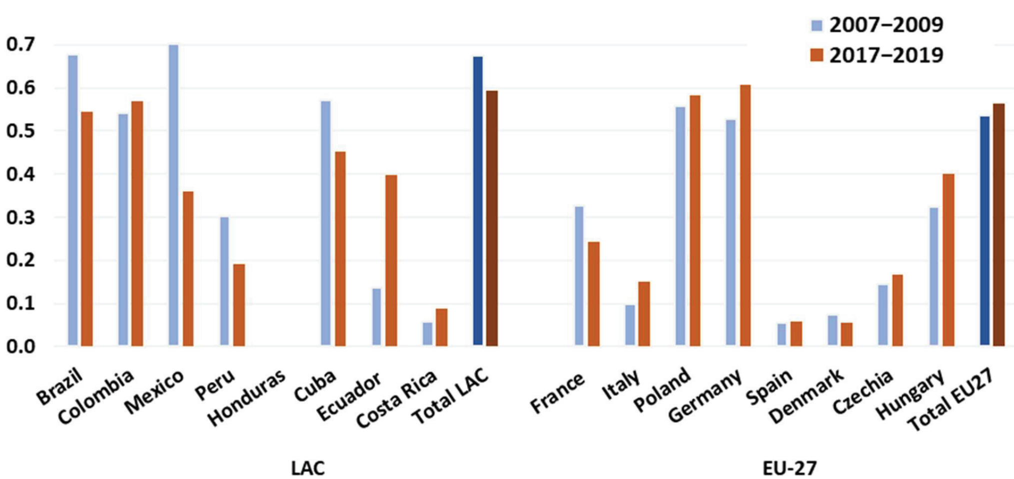

Figure A2. Calculated diversification index (DIV, between 0 and 1) in freshwater aquaculture production at the region-level and country-level in 2007–2009 and 2017–2019. Note that DIV is 0 for Honduras because one family accounts for 100% of production. Data source: [1].

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The Potential of Blockchain Technology in the Transition towards Sustainable Food Systems

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Abstract: Food systems are both contributing to and affected by environmental degradation and climate change. The transition towards resilient and sustainable food systems is essential to ensure food security and minimise negative environmental impacts. Innovative technologies can accelerate this transition. Blockchain technology (BCT) is attracting attention as it can deliver transparency to complex global food supply chains and has the potential to guide current food production towards better sustainability and efficiency. This case study investigated the opportunities that BCT can offer to food supply chains. Qualitative interviews with eight main BCT providers were conducted to evaluate the current state of BCT and put it into perspective by mapping out advantages, disadvantages, incentives, motives, and expectations connected to its implementation in global food systems. A thematic analysis showed that, while BCT was considered beneficial by all interviewees, uptake is slow due to high implementation costs and the lack of incentives for companies throughout the food chain from farms to food industry and retail. Results further revealed that the advantages of BCT go beyond communication of trustworthy information and development of closer producer–consumer relationships. In fact, it can provide the opportunity to decrease food waste, enhance working conditions throughout the supply chain, and promote sustainable consumption habits. As BCT may be increasingly used in the food supply chain, the results give a basis for future research that may leverage both qualitative and quantitative methods to examine actors' behaviours. Also, the importance of improving user experiences through functional applications and software to facilitate the adoption of the technology is stressed.

Keywords: blockchain; sustainability; food systems; food supply chains; transparency; agri-food; traceability

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1. Introduction

With rapid population growth and damaging anthropogenic influences on nature, the likelihood of overshooting the Earth's capacity to regenerate is high, and ambitious goals for reductions in negative environmental impacts have been set at a global scale [1–3]. The agri-food sector is a considerable contributor to climate change and one of the sectors most affected by its consequences [4]—for example, through greenhouse gas emissions—while being severely influenced by climate change [5]. The agri-food sector is also affected by the fact that it induces losses in biodiversity on which future agriculture may depend [6]. Other challenges to a sustainable food future are issues related to, for example, healthier eating; soil and water management; climate change effects such as drought, heat stress, and flooding; diminishing yields; and compromised food security [1,7–10]. The issue of food waste is also a concern, for about one third of all food produced is lost or wasted annually on a global scale, which comes at a cost for society (e.g., wasted resources), and has financial implications for businesses in the food chain (e.g., inefficiencies or loss of reputation due to damaged or spoiled products) [11]. In parallel, there is increasing consumer interest in ethical and sustainable consumption as environmental awareness in society increases [12]. New concepts for future food systems aim at circularity, with improved food waste management and closed nutrient cycles, and at minimising food waste by careful transportation and storage and by maintaining the cold chain in distribution [13]. Developments within the modern food system have resulted in the concentration of production within a few large transnational corporations, which dominate the agricultural inputs, distribution, and retail sectors [14,15]. These corporations impose a strong influence on food system governance [16,17], for example through their role in "shaping the dominant agricultural model adopted around the world" [15] (p. 28), disconnecting global causes from local impacts, and by dominating "agricultural policy agenda at both national and international levels" [16] (p. 532).

Food supply chains are commonly long, scattered, and opaque, with a substantial distance between food producers and consumers, which leaves the latter with limited insight into the consequences of their purchasing behaviour [15,18]. Hence, traceability in the food supply chains is a central concern. In addition, parts of the food supply chains suffer from lack of digitalisation [15], which can be a consequence of insufficient or unequal digital resources, skills, and motivation [19]. Annosi et al. [20] also pointed this out, showing that barriers for digitalisation in the food chain included difficulties to coordinate with partners that were different in size, had incompatible 'digital mindsets', or made different strategic choices on digitalisation. Hence, these differences, and the generally low level of digitalisation, may result in inefficient processes and increased susceptibility to human error, a lack of trust and a high risk of food fraud [15]. Food-fraud incidents in particular have become a global food-system challenge, and 'food scandals' occasionally emerge, e.g., the horse meat scandal in Europe in 2013 where horse meat in processed food products was labelled as beef, or when conventional produce is fraudulently labelled as organic [21]. Lack of transparency and trust in current food chains also leads to major concerns about food quality and safety, loss of reputation and financial damage [12]. Opacity also poses a financial risk [22]. Due diligence challenges in modern food supply chains mainly arise due to missing or fraudulent data, incompatibility of data systems used by the different actors and time-consuming paper-based processes [23]. Meanwhile, there is a higher environmental awareness of consumers and pressure from policy-makers and investors, that have increased the need for more trustworthy and accurate data in food supply chains [4,23]. Arguably, food supply chains are increasingly shaped by consumer interests and rising demand for transparency [24].

The Food and Agriculture Organization (FAO) of the United Nations (UN) recognises that sustainable food value chains require access to information for all parties involved and stresses the critical importance of a functioning governance structure [8,25]. The European Commission has identified increasing transparency as an important feature for all actors involved in the food supply chain, so that each actor can easily access the necessary information on the sustainability of a product [26]. A transition to sustainable and more resource-efficient food systems is a necessity. A "Great Food Transformation" entailing structural change on multiple levels has been called for [9]. Technology-led innovations can substantially mitigate environmental deterioration and also dominate research and policy agendas [27].

One of the means identified to increase sustainability and transparency in food systems is blockchain technology (BCT), which could offer advantages to food supply chain management such as transparency, traceability [28], and data security [29]. Implementation of BCT is still in its infancy and the extent to which food system sustainability can be improved by BCT has yet to be determined, but as pointed out by Antonucci et al. [30] and Ratta et al. [31], the technology is promising and has potential for applications in several sectors.

The aims of this study were to identify the potential of BCT for aiding a transition towards sustainable food systems and to shed light on its practical implementation and potential in food supply chains. As BCT is expected to improve sustainable supply-chain management, this work sought to provide insights into its practical use, thereby supporting the overall sustainability of the food system, by assessing the following two research questions: (1) What are the opportunities and challenges to implementing BCT in current food systems? (2) How can BCT facilitate transition towards more sustainable food systems? These questions were addressed by applying a qualitative research approach involving interviews with experts working with BCT providers for food system actors.

2. Theoretical Considerations

2.1. Sustainable Food Systems

A common definition of food systems encompasses the entire range of actors and their activities and relates them to the broader economic, societal, and natural environments in which they are embedded, while a sustainable food system is defined as delivering food security and quality that does not compromise future generations' access to a sustainable food supply [32]. However, food-system analyses to date have mainly assessed issues relating to food security [33,34] and environmental impacts, e.g., in life cycle analysis [18,34]. The Food System Framework proposed by the Institute of Food Science and Technology (IFST) [35] embeds the food supply chain in the three dimensions of sustainability and integrates it in a broader scope of sustainability. The framework points out key areas aiming to develop knowledge, policies, initiatives, and guidance in favour of transition towards more sustainable food systems. The framework is divided into six thematic areas: (1) Resource risks and pressures; (2) Healthy sustainable diets; (3) Circular economy and sustainable manufacturing; (4) Novel production systems and ingredients; (5) Decent work and equitable trade; and (6) Transparency, traceability, and trust.

2.2. BCT and Sustainable Food Systems

Since the publication of the white paper by Nakamoto [36] about Bitcoin and secure financial transactions between two parties without the need for an intermediary, there have been intense discussions on cryptocurrencies [37]. The underlying technology is widely recognised as a potential game-changer for certain sectors and disruptive for many other sectors. Known as distributed ledger technology or blockchain technology (BCT), it is defined as a decentralised immutable ledger able to store, process, validate, and authorise transactions (*ibid.*). Metaphorically, each transaction entered in the blockchain at a specific time is stored in a single unit, known as block. Each block contains a digital fingerprint of the user that inserts the data, which is called hash. Additionally, a cryptographical identification marker of the preceding block is added. In that way, a blockchain is a linear, chronological continuity of stored information, visible for any (authorised) user in real-time. Once a block is added to the chain, it is securely stored as an immutable, transparent, and permanent feature of the blockchain [38]. The immutability and decentralisation of data differentiate BCT from conventional data-handling systems. Consequently, trust and transparency between parties are increased [27], while anonymity and data security are ensured [38]. BCT is proving to be a valuable technology in different sectors and increasingly so in the food sector [39]. However, there is still limited knowledge of BCT in the agri-food context. Most studies of BCT in the agri-food sector have focused mainly on software aspects [30]. The first wave of blockchain applications in the food sector addressed issues of trust, transparency, and information sharing among stakeholders in the food chain [40], which will likely play an important role in traceability management for agri-food [41,42].

2.3. Conceptualising a Sustainable Food System Framework in the Context of BCT

An adapted version of the IFST model was used as the analytical framework in this study (Figure 1). This model, the Sustainable Food System Framework, outlines the BCT-based food supply chain in the centre of key areas of sustainable food systems. The food supply chain is circularly embedded in the three dimensions of sustainability—the environment, society and the economy—and their overlapping areas. In the modified framework, the original six themes in the Food System Framework are revised to: (1) Resilience and resource efficiency; (2) Sustainable and healthy diets; (3) Circular economy; (4) Profitability and efficiency; (5) Sustainable supply chains and fair trade; and (6) Transparency, traceability, and trust. Examples of the food system's impact and dependence on each sustainability area are shown in Figure 1 and described below.

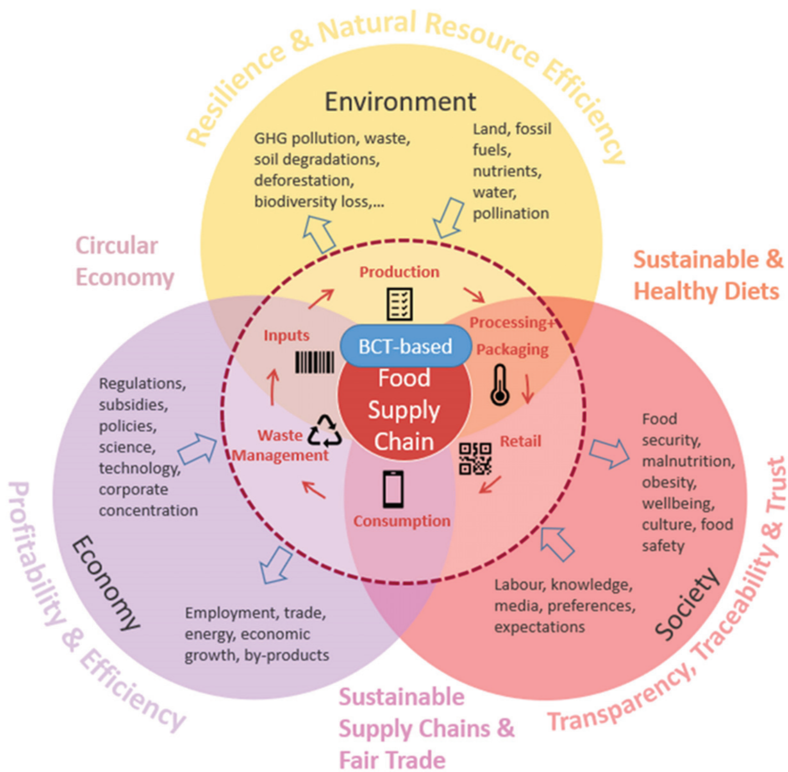

Figure 1. The Sustainable Food System Framework and potential influences from blockchain technology (BCT). Own conceptualisation based on IFST [35].

2.3.1. Resilience and Resource Efficiency

Using BCT, data on environmental conditions can be captured along the whole food value chain to facilitate the identification of risks and pressures. BCT can store and share data, e.g., on humidity and temperature during transportation and storage, which can help prevent foodborne disease outbreaks and recalls [12]. Individualised perishability dates (adapted to the conditions under which the food has been produced, transported, and stored) on food products provided by BCT can prevent household food waste [43]. More efficient resource planning and transportation, enabled by increased visibility and transparency, can reduce environmental impacts on food systems [44].

2.3.2. Sustainable and Healthy Diets

BCT can convey information about specific attributes of food products to the consumer, enabling informed decision making and aligning with demands to purchase healthy, ethical, and sustainable products. Hence, consumers can make well-informed and careful decisions that are less influenced by the media [45]. BCT could perhaps also be used to avoid food fraud and ensure food safety, thereby protecting public health [46–48].

2.3.3. Circular Economy

BCT promotes better planning and can improve circular flows in production [27]. Responding to the increased amount of food packaging, consumers, it has been shown, can be motivated to recycle food containers if receiving crypto-tokens is an incentive [27]. The European Union action plan for a circular economy acknowledges the importance of BCT in accelerating circularity, de-materialising the European economy, and promoting an entrepreneurial culture [26]. Food waste mitigation by preventing recalls is another way to improve circularity in food systems. As pointed out by Kouhizadeh, Zhu, and Sarkis [49], issues such as resource waste and biodiversity losses can be managed and resolved through BCT.

2.3.4. Profitability and Efficiency

BCT is part of a transition towards more data-driven agriculture and food production in general [10]. It is recognised that big data, Internet of Things (IoT), Artificial Intelligence (AI) and machine learning, together with physical innovations (e.g., sensors, machines), are transformative for food systems [43], facilitating decision-making by actors along the food chain [50]. Economic sustainability can be improved by reducing costs and enhancing efficiency as direct consequences of disintermediation, while reducing market uncertainty and inefficiency [51,52]. As BCT is able to record different dimensions of a food product, it eliminates the need for a third party to manage the data centrally [27]. Smart contracts can facilitate certification management and help process improvement by automated verification of the data [53].

2.3.5. Sustainable Supply Chains and Fair Trade

The most important advantage of BCT lies in the increased transparency, traceability, and trust it provides [54]. If data on specific attributes of a food product can be transparently passed on to the consumer, this can enable informed decision-making and, by verification of certificates, satisfy consumer demand to purchase ethical and sustainable products [45,54]. It has been shown that ethical working conditions as part of social sustainability can be verified by consumers directly, once supply chains become transparent [44]. Shorter supply chains, a possible outcome of BCT, may also increase farmers' status and foster the development of their community [50].

2.3.6. Transparency, Traceability and Trust

BCT is expected to restore consumer trust, improve sustainability and detect and prevent corruption and fraudulent activities by supply-chain members [27]. It reduces the current information asymmetry in centralised supply chains and supports increased equality in bargaining power among parties [52]. Through the greater transparency, regulators can easily and regularly monitor markets to prevent collusion [52]. As suggested by Köhler and Pizzol [55], a direct impact of BCT is to increase trust within the supply chain. A fast reaction to the increased consumer and government demand for greater transparency in food supply chains will likely benefit those companies which adopt BCT [51]. However, there has been no standardisation on the kind of data that need to be made available [56,57]. Governance is seen as pivotal for successful and sustainable implementation of the technology, but requires structural and organisational changes [56].

3. Research Approach

A single case study approach [58] was applied. This is seen as an appropriate method when exploring complex topics, as it builds on previous research by providing additional data and insights [59]. Technology providers of BCT in food supply chains were set as the unit of analysis. This was motivated by the aim of this study to identify the potential of BCT for aiding transition towards sustainable food systems, whilst there are yet few examples on implementation of BCT throughout food-supply chains [56]. Hence, frontline technology providers targeting the food sector were deemed to be the actors with the most holistic insights on the implementation of BCT in the food system. This study did not focus on a specific geographical area, nor on a specific food commodity. This is because of the lack of broad use of BCT in the food sector, but the study's broad parameters allowed it to identify challenges and possibilities across the whole sector and from different locations.

3.1. Data Collection and Analysis

Data were obtained in eight interviews with experts working in firms providing BCT-based platforms intended for the food sector (Table 1). Interviewees were purposively selected for their extensive knowledge and experience of practical use of BCT. All those selected work closely with various players in food supply chains and have insights into the requirements and challenges connected with implementation of BCT in food supply chains. The sampling procedure followed three consecutive steps: (1) Firms offering BCT for supply chain management were identified in the background research phase; (2) the websites of potential firms were checked and firms that fulfilled the criteria of offering a BCT solution for food supply chains were listed; and (3) 14 potential interviewees were contacted, resulting in five positive responses. During the interviews, new potential participants were recommended (snowball sampling), resulting in three additional participants.

Table 1. Details of the interviewees.

Code	Function	Firm/Code	Details	Country
R1	Project and Marketing Manager	C1	C1 is a tech start-up offering customisable blockchain-based technology that can be implemented in existing (food) supply chains to improve transparency and traceability, food safety and efficiency	Germany
R2	Former Manager, now self-employed	C2	C2 is a BCT solution for all food supply chain players, enhancing transparency via real-time shared data. R2 is now developing a start-up around ecosystem services certificates, helping farmers who provide ecosystem services with an additional income from trading certificates.	Netherlands
R3	Co-Founder, CEO	C3	This start-up is a technology provider creating a more agile, efficient and certain supply chain for food. It captures data using IoT sensors, secures the data with BCT and uses AI to create real-time supply chain visibility, apprising all supply chain partners of issues as they arise and predicting issues before they occur.	USA
R4	Functional Expert	C4	C4 is a company by and for the commodities trading and shipping industry. It was established by some of the largest corporations worldwide in agricultural commodities trading, e.g., in grain and soy. The platform aims at modernising and increasing efficiency in agri-food supply chains based on BCT.	Switzerland
R5	Head of Projects and Impact	C5	C5 is a social enterprise and a merger of two start-ups. It is providing smallholder farmers with mobile technologies to access information, financing and the global market, thus strengthening their position in the food chain. It uses cloud, AI and BCT.	India
R6	Chief Marketing Officer	C6	C6 is a start-up that digitises fresh food produce. It works with digital IDs to track products along the supply chain and to share the information with the actors in the supply chain and consumers via QR codes. It is based on AI and BCT and aims at collaborative commerce and increased visibility of supply chain actions.	Singapore
R7	International Business Developer	C7	C7 is a fast-growing start-up that uses BCT as end-to-end tracking solution to increase internal supply chain traceability and to provide transparency for consumers via QR codes on products.	France
R8	Co-Founder	C8	C8 is a young tech company working with a combination of technologies in order to increase visibility in agri-food (especially seafood) supply chains.	USA

The interviews followed a semi-structured interview guide comprised of seven thematic areas: (1) the interviewee's expertise and area of work; (2) the current use of BCT in food supply chains; (3) the effect of BCT on actors in the food supply chain; (4) the potential of BCT in transforming food systems; (5) the role of BCT in power distribution in food supply chains; (6) the role of governance and regulations; and (7) consumer aspects of BCT. The interviews were conducted through different digital communications platforms (Zoom, Webex, and Skype), lasted for around 30–60 min, and were recorded upon the interviewee's agreement. The recorded interviews were transcribed and coded, and thematic analysis was applied for systematic identification and organisation of the empirical findings [60]. In the coding process, passages of the transcripts were transferred into a table (with ordinary word processing software) according to the six identified areas outlined in the conceptual analytical framework based on the IFST [35] (Figure 1); this process enabled the consistent interpretation of data, a variety of research questions, and the interviewees' experiences [61]. For competitive reasons and data protection, the names of the firms are anonymised.

3.2. Quality of Collected Data

To ensure the quality of the study, construct validity, internal and external validity, and reliability were assessed [58]. The explorative nature of the study did not allow for the assessment of causal relationships, and therefore internal validity was not accounted for. Construct validity was ensured by the semi-structured interview guide, which was subsequently coded and thematically analysed to minimise the influence of the researchers on the findings. External validity ensures transferability of results, which in this study was accounted for by interviewing firms operating in the same sector in similar functions across three continents. Respecting boundary conditions, the results reflect transferable findings in an emerging field of study. Data triangulation and the use of multiple sources of information (such as interviews in combination with an extensive literature review) increased the reliability of the analysis [62]. Finally, validity was increased by meticulous documentation of data collection and processing. Personal reflections during the research process were recorded and member checking (sending back interview summaries to the participants; [62]) was done to give the interviewees an opportunity to clarify statements.

4. Results and Discussion

4.1. BCT and Its Applications in Food Systems

The results obtained are presented and discussed thematically below. Analysis of the findings followed the conceptual framework in Figure 1.

4.1.1. Resilience and Natural Resource Efficiency

The interviewees emphasised that collection of sustainability-relevant data is increasing, and a number of start-ups are entering the field of measuring production-specific parameters for improving yields and sustainability (e.g., availability of soil enzymes, fertiliser, pesticide and water use). A problem pointed out is that the data are not fully utilised and do not reach the consumer. Although BCT offers the possibility to include relevant data, such as antibiotic use in livestock farming, nitrate levels in food, carbon footprint, or local sourcing, the current application of BCT rarely considers this type of data. The case firms reported encouraging producers to fully disclose relevant information, but a current lack of regulation, high expenditure, and issues of competition prevent them from sharing data. The lack of specification and guidelines means that producers can decide to reveal only marketing and branding information. Since they can choose what data to share, or not to share, they only showcase positive aspects, without having to justify negative aspects. Surprisingly, the potential for recording product-related and environmental data, as pointed out by [12,44], is currently not utilised in practice. Most interviewees claimed that environmental considerations are not the driver for BCT implementation in the food sector, as indicated by the following statement: "The thing we want to solve is accuracy and efficiency. Our core idea is not about sustainability or quality parameters. That's something which will probably get added". However, there were contrasting examples of current uses of BCT with regard to environmental sustainability, including sharing production data with agronomists for optimisation, supply-chain actors, and eventually consumers, as one interviewee exemplified: “We work with the really specific farm-level information, which we are able to integrate. If producers want to say that their produce is sourced locally or that they are reducing their carbon footprint or pesticide use, we’re able to (. . .) show things like [that]”.

4.1.2. Sustainable and Healthy Diets

According to the interviewees, there is no direct connection between healthy and sustainable diets and BCT. They pointed out that transparent information on provenance and production methods can have an impact on product choices as consumer awareness of animal welfare and environmental outcomes increases. They also mentioned that BCT can help consumers adopt a healthier and more sustainable diet if information is shared with them and they have an interest in changing their diet. Sharing information with consumers to enable them to make more informed decisions is a key concern, as pointed out by [38], but some interviewees clarified that consumers do not want to know everything about a food product even if they claim to expect full transparency. One respondent described the dilemma as follows: “We should only show consumers things that will benefit them and that they are able to absorb and understand”. Supply-chain actors, on the other hand, would require access to different information like shipping dates, storage details, etc. In their business, pre-selection of information given to the consumer is performed by the firms, which decide what they want to share. A typical application would be a QR code on the packaging that delivers transparent information verified by BCT.

4.1.3. Circular Economy

The interviewees emphasised that all actors in the supply chain need to be involved to create a more circular economy. By monitoring food quality throughout the journey, food waste can be prevented, and money and resources saved, which is in line with the application of BCT in other areas (e.g., [27]). One interviewee gave a practical example of how BCT can contribute to circularity by reducing food waste through facilitating a reverse, intelligent market for soon-to-expire food that retailers can buy from wholesalers at a discounted price if they know they can sell it within a specific timeframe. Several interviewees highlighted that communicating the benefits to consumers via a QR code can create more societal awareness. Most importantly, according to one respondent, the claims made by a producer can be verified with BCT, which increases their significance. None of the interviewees could point out a comprehensive cradle-to-cradle solution integrating both the input sector and waste or recycling systems. According to [27], BCT can improve the transition to a circular economy in food systems, but this was not an expressed aim of any of the case companies. This indicates that the circular economy concept and BCT application in food systems are rather new and the connection seems to be unprioritised for now. For the future, one respondent anticipates merged platforms: “Right now, platforms have a single functionality, like one platform providing insight on where the food comes from, one platform for logistics, one platform for better information on how food is produced [. . .]. What we will be seeing in the future is what is called a system of systems. These platforms will be put together in some form and provide information across the entire food chain and on multiple functionalities.”

4.1.4. Profitability and Efficiency

The interviews revealed that current food supply chains are still largely paper-based and reliant on manual work, and thus inefficient and time-consuming. In particular, long international and trans-continental supply chains were identified to suffer from lacking intergovernmental consensus on data sharing and the required technical equipment.

However, according to the interviewees, governments are increasingly demanding a change towards more digitised commodity trading to facilitate and enhance efficiency in the food sector. This is also in line with the general development of more data-driven agriculture and food production [12]. Previous research has pointed out that BCT has strong potential to increase economic sustainability [51,52], but there is no consensus on the relative cost of BCT. Half the respondents reported that, although BCT itself is not too expensive, implementation in existing data-handling systems is rather resource-intensive for small and medium-sized companies. Such companies will only become interested when benefits clearly outweigh the costs required for adoption of BCT. Changing the system would require everyone in the chain to open up their firewalls to place a blockchain node, a step that is only feasible for larger companies and that is, according to one interviewee, "the key for why only large businesses can afford to do this [now]".

The implementation of BCT can help to save money by avoiding recalls, and it could be a risk-mitigating device that outweighs the initial costs of changing an existing system and maintaining a new data-handling system. The interviewees suggested that BCT can make the system "*safer and much quicker*", but a constraint is poor internet access in large parts of the world. There was also no consensus on whether technology will become more affordable in the future. While consumer demand for more transparency is driving the implementation of BCT, this seems to be dependent on its effect on food prices, as one interviewee noted: "Someone has to pay for implementing a new system. If the cost is passed on to the consumers, they need to see the added value". BCT can lead to lower food prices, as it can save costs by recall prevention, while the higher costs originating from more sustainable food production can be balanced out by the higher efficiency and stable prices.

4.1.5. Sustainable Supply Chains and Fair Trade

The interviewees strongly believed that the broad use of transparency-enhancing technologies like BCT will change the power distribution and increase fairness among trading partners. This is well in line with the general view on BCT [52,55]. However, how the system is designed and applied will be important, as one interviewee highlighted: "If we share product information, provenance and condition data in an egalitarian way in which everyone owns the data, and no one owns the data, it creates widespread business benefits for all supply chain players, not just the big ones. If you can make it so that it is affordable and understandable [. . .], it can really change the system." BCT has the potential to disrupt corporate concentration and power imbalances, but one respondent warned: "while blockchain has the potential to provide insights and information to each and every one, we are in real danger of it being dominated by the current large parties that are already dominating the market".

The extent to which BCT can change the dynamics in supply chains was exemplified by one interviewee working with smallholder farmers in developing countries: "[Our aim is] to increase their livelihood standards and help them to connect to direct markets, because [. . .] the farmers [today] lack affordability and accessibility of information and are often dispersed and in remote rural villages". Technologies can bridge the information gap and at the same time erase middlemen who withhold information from farmers and make profits without adding value to the food product. Another interviewee stated specifically that "one of the learnings from this entire human-digital economy is the reduction of the middle effect" and thus the potential to shorten supply chains, enabling farmers to sell their produce directly to buyers. BCT could also have the potential to devolve more power towards end-consumers. In general, the shift is seen from the dominant party to farmers and consumers, as one interviewee exemplified: "As soon as you start knowing the source, it [. . .] means the consumers know more about where [the food] came from and it gives [the producers] more power, because all of a sudden, they are being seen".

4.1.6. Transparency, Traceability, and Trust

For the most common theme, intersecting with all sustainability dimensions, there was broad consensus that delivering transparency is the main benefit of BCT in food systems. This is in line with results from other studies (e.g., [27,55]). The interviewees recognised that retailers are experiencing pressure from consumers, who are demanding more clarity on food origin and provenance. Issues of sustainability and food fraud are already driving consumers to request reliable certificates of origin. However, transparency within the supply chain and transparency for the consumer are regarded separately. According to one interviewee, there is currently a lack of transparency, created by antiquated paper systems, data silos, differing regulatory requirements between different countries, and a natural fear among supply chain companies of losing competitive advantage through transparency. This explains why digitalisation in agri-food supply chains has lagged behind that in other industries. The interviewees pointed out that much of the data captured on farm level today is not utilised to improve overall supply chain management. Several respondents explained that BCT provides the ability to trace back information, helping to identify weak points in the supply chain and thus helping the supplier and other actors in assuring that the product paid for meets expectations and requirements and that complaints can be addressed correctly.

4.2. BCT and the Transition towards a More Sustainable Food System

The current food system faces multiple sustainability challenges, as pointed out by the International Panel on Climate Change [3] and the FAO [8,25]. The findings presented in this study show how the application of BCT can facilitate change towards more sustainable food systems. An overview of the use of BCT, including how it relates to specific sustainability issues important in food-system transformation, is provided in Table 2.

The interviewees reported stronger impacts of BCT implementation on the economic and social sustainability dimensions than on the ecological/environmental dimension. This may indicate that the implementation of BCT in the food area is mainly driven by firms outside the food system with core competencies in the area of BCT and information management, rather than food production. Nevertheless, several applications relating to production, resource, and waste management were pointed out. It is clear that the technology can promote a more circular economy in the food and agriculture sector (e.g., [13]). As a tool for communicating information between actors in the food chain, BCT may be an important complement to existing certification schemes that currently delimit the amount of information. An issue is whether BCT will enhance consumer access to all information, or whether a dominant actor (e.g., the retailer or the technology provider) will restrict the information recorded. BCT is likely not the decisive technology for a more sustainable food system but may assist in the transition towards more data-driven agriculture and food production in general [24]. Rather, an ecosystem of technologies (e.g., IoT, AI, machine learning) can together enhance decision making in food systems and lead to more sustainability. The success of BCT will rely on creating an integrated and holistic system of these emerging technologies, which are substantially underrepresented in the agri-food sector compared to other sectors and which have seen a low degree of investment [43].

In accordance with the findings, food-system impacts from the implementation of BCT can be depicted using the Sustainable Food System Framework [35], shown in Figure 2. The BCT has been identified to have strong direct implications for three of the six sustainability pillars, mainly for 'Transparency, traceability, and trust', attributing it the biggest arrow in the figure. As BCT can strengthen supply-chain players, the direct impact on 'Sustainable supply chains and fair trade' is portrayed as the second strongest impact. After successful implementation, BCT has the potential to increase 'Profitability and efficiency' as the third main effect. As for the other pillars, the impact of BCT is identified to be less strong and caused indirectly by its strengths to deliver immutable, decentralised, and transparent information. By that, resources can be attributed more accurately while recalls, food waste, and food fraud can be prevented. Furthermore, communicating trustworthy information to consumers increases their knowledge and subsequently can promote more sustainable and healthy purchasing decisions.

Table 2. Current Challenges for food systems and the use of blockchain technology (BCT).

Food System Framework Category	Importance in Food System Transformation	Use of BCT
Resilience and resource efficiency	Food systems contribute substantially to climate change Highly reliant on functioning ecosystems Food insecurity as consequence of climate change	Store and share data from agricultural precision technologies Prevent waste through individualised perishability dates More efficient planning via increased transparency
Sustainable & healthy diets	Plant-based diets are more environmentally friendly Consumer education and preferences are crucial for rethinking the food system Globally higher demand for energy-intensive foods Environmental awareness in society is increasing Higher demand for sustainable products	Provide the consumer with transparent and verified data for better decision making
Circular economy	Food waste minimisation Nutrient recycling	Better planning can improve recycling Motivation via crypto tokens Traceability helps to identify flaws in the supply chain and prevent food contamination and spoilage
Profitability and efficiency	Food waste and GHG emissions are inefficiencies in food systems Lack of digitalisation Long and complex supply chains Opacity/Transparency	Reduced costs (via disintermediation) increase economic sustainability Minimisation of human error Safe data transfer reduces risk Disintermediation of supply chains
Sustainable supply chains and fair trade	Concentration of power to a few multinational corporations Absence of cooperation and policies on international level	Immutability and reliability of data can detect and prevent corruption and increase trust in the supply chain BCT reduces information asymmetry and improves equality in bargaining power Collusion can be monitored and prevented Verification of ethical working conditions and fair trade
Transparency, traceability, and trust	Distance between producers and consumers Environmental impacts of food are rarely visible to the consumer Lack of trust in brands and labels Food safety concerns	BCT increases transparency for all supply chain members Transparency increases trust, brand image and decision-making

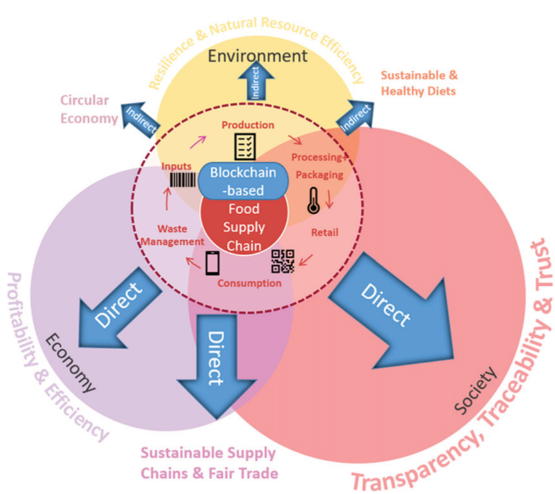

Figure 2. Impact of blockchain on food system sustainability (Own elaboration based on the results, applied on the Sustainable Food System Framework [35]).

4.3. Implications for Practice

This study revealed that tech companies find BCT beneficial, while the fact that the case companies are growing fast indicates the relevance and legitimacy of the business model. On the other hand, the respondents reported that many competitors have left the market already. This is in line with other research findings suggesting a discrepancy between technical feasibility and operational constraints, as well as false expectations [56,63]. The present study showed that BCT is only one in a set of tools that will eventually make food supply chains more sustainable. Surprisingly, this has not been addressed in previous research. Viewing BCT as a part of an integrated, real-time shared data ecosystem (rather than as an isolated technology) is crucial to attributing accurate value to the technology and preventing ambiguous expectations.

Businesses are struggling with implementation of BCT for several reasons: First, the novelty and complexity of the technology have led to misconceptions about the term BCT and the capacity of the technology. While the interviewees noted that BCT has not lived up to (unrealistic) expectations, its real potential was still seen as game-changing and it was considered to be well worth implementing in food supply chains. Hence, some of the interviewees reported that their companies actively avoid mentioning BCT to avoid misconceptions and scepticism, revealing the discrepancy between what companies and the general public see in the technology. However, all respondents reported good experiences with the technology from their own perspective and based on customer feedback. Second, while the technology itself is not necessarily expensive, implementation is still costly. This is a barrier particularly for small and medium-sized businesses, and this corroborates the finding by [20] that there are difficulties to coordinate partners that are different in size. Incorporating BCT into existing data-handling systems will require human resources and system changes for all supply chain players. Further, this points out the importance that BCT software and applications are tested using a quality software and user-experience analysis to ensure that they are user friendly and functional. This is to make it accessible for users as a way to overcome unequal digital resources, skills, and motivation among actors in the food chain [19]. Finally, the choice of BCT architecture is fundamental for the openness of supply chain members to implementing a BCT system. Since food supply chains include the international trade of commodities, as pointed out by [56], there is a need for assurances that confidential data will be handled securely and will not lead to competitive disadvantages.

4.4. Limitations and Future Research

Due to differences in their company's global distribution, respective target markets and size, and to the different posts they hold in their company, the interviewees were not directly comparable. Nevertheless, they provided similar estimates of the place of BCT in sustainable food supply chains. The interviewees' expertise in the agri-food sector also varied, and their position outside food supply chains can be perceived as both a benefit and a drawback for the quality of the findings of this study. Furthermore, their work with multiple actors without having to increase a single player's profit gave a certain diversity in responses. Incorporating the feedback of other actors across one food supply chain could provide further valuable insights into motives, expectations, and outcomes regarding the use of BCT and paint a more holistic picture of advantages and disadvantages offered by the technology. Other similar technologies can be expected to emerge, and time will tell whether they become a permanent feature of food supply chains.

This study focused on technology providers, but did not include the whole supply chain, as there are currently few examples on where BCT has been implemented in the whole chain [56]. It would be useful to continue the research, as BCT becomes more widespread in the food chain, with the design of BCT services, user experiences of software and applications, and other practical issues related to current documentation and certification systems. Future research should include qualitative assessments of firms throughout the chain, including upstream supply chain players (e.g., farmers and smaller agri-food firms), as their use of the technology must function in their daily operations. But as BCT becomes more widely used in the food chain, quantitative studies with food industry and other actors would also be needed to deepen the current understanding of the topic. There may also be a need to improve industry standards on data sharing and transparency, while accounting for the role of policies. Integrated systems using AI and IoT together with the BCT can provide further resource efficiency and lower the use of input supplies in food production, an area that needs further research. Finally, comparing the environmental sustainability (with tools like life cycle assessment) of food in conventional systems and in BCT-facilitated supply chains could facilitate quantitative reasoning on the value that BCT can add to more sustainable food systems.

5. Conclusions

The acknowledged benefits of BCT are enhanced visibility and traceability, as well as the immutability of records. This can lead to the creation of trust, efficiency, and to some extent fairness in today's long and complex food supply chains. Enabled by increased transparency, the educational effect for consumers can shift demand towards more sustainable products, strengthen the position of farmers, and disseminate good practices. In general, communicating verified and trustworthy information on food provenance, combined with extra information on, for example, recipes or perishability dates, can increase awareness and aid the transition towards a more sustainable food system. From an environmental perspective, however, the advantage of BCT itself seems to be restricted to resource savings due to recall prevention and better planning of the supply chain. In order to convince all actors along the supply chain of the benefits of BCT, despite initially high costs of implementation, more governmental or societal pressure at global level might be an inevitable requirement.

The modified Sustainable Food System Framework applied in this study proved to provide a stable basis for analysing the contributions of BCT to sustainability in the food system. BCT was found to have an impact on all sustainability areas identified as important for food systems transition. Thus, BCT has potential if added to existing supply-chain management practices, but this will require the collective engagement of all stakeholders. Given the global disparity in access to internet and data, and the lack of continuous digitalisation of food supply chains, full adoption of BCT in the food system remains a challenge.

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Article

Influences of Green Eating Behaviors Underlying the Extended Theory of Planned Behavior: A Study of Market Segmentation and Purchase Intention

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Abstract: Green food has been introduced into the market for several years. Nevertheless, most Thai consumers do not commonly purchase green food in their daily routine. This research article aims to identify the market segments and significant factors affecting green food purchase intention in Thailand based on the theory of planned behavior. It employed a sample of 458 green food consumers in five regions of Thailand. Based on the Food-Related Lifestyle model, we used cluster analysis to classify the market segments. Additionally, we employed a multi-group structural equation modeling technique to explore and compare customers' behaviors in different segments. The results demonstrated two primary market segments for green food products, including (1) non-green consumers and (2) green consumers. The findings indicate that green consumers' self-realization related to environmental issues positively affects their attitude and purchase intention, while non-green consumers reveal none of these relationships. Surprisingly, social norms related to green food consumption influence non-green consumers' attitudes toward green food more than it does toward green consumers. This research paper enlarges the understanding of Thailand's green food market regarding the market segments (non-green and green consumers). Furthermore, it points out implications on how marketing practitioners may penetrate those segments.

Keywords: green food; green labeling; green consumer; food-related lifestyle; food industry

1. Introduction

Green products have played a significant role in the global environment showing that consumers are more aware of the negative impacts on the environment caused by global warming [1]. Green products as eco-friendly goods and the green production process uses eco-friendly technologies that are not disadvantageous to nature. Furthermore, characteristics-wise, a perfect green product should be organically grown, reusable, recyclable, biodegradable, non-toxic, non-animal testing, and use eco-friendly packaging [2]. A green product covers different aspects such as product functionalities, product design, product package, and product value [3]. In the food industry, green food products are produced in an eco-friendly way that does not harm the environment. The definition of green food involves a cleaner process starting from collecting resources, consuming, and decomposing the product [4]. Accordingly, the process of producing green food helps to prevent environmental pollution and enhances ecological advantages. Green food is harmless and includes nutritious food for consumer health. Green food should also be organic and nutritious for humans [5].

Environmental issues are the primary concerns of governments and citizens. Rahman and Reynolds [6] recommended that consumption of green products is strongly influenced by consumer buying behavior. Research shows that consumers with environmental conservation awareness are rapidly increasing, and many consumers expect green products and services from producers globally [7]. Consumers' decisions to purchase the green product depend on a specific group's perception, values, behavior, and the individual's attitude [8]. Since 2017, the green consumer markets worldwide have generated approximately USD 290 billion annually. In addition, 14% of the gross world product (GWP) of a green product represents the eco-tourism market, increasing global environmental awareness [1]. This information shows that the number of green consumers has increased significantly, and the food industry should not ignore the green food market.

In Thailand, since January of 2020, there have been policies to reduce the use of plastic bags in convenience stores, supermarkets, and shopping malls. Jafarzadeh et al. [9] stated that 2020 would be the year of green, including green food, green packaging, and green organizing according to the environmentally friendly trend that has become the popular trend worldwide. Yanakittkul and Aungvaravong [10] also reported that 37% of Thais use only natural and organic products or green products daily. Nevertheless, the green market is new to Thailand, especially green foods. Therefore, a market segmentation study is a prerequisite for marketers to implement marketing strategies successfully. Segmenting customers allows marketers to understand the customers' behaviors deeply. This approach also allows marketers to tailor marketing strategies and deliver products and services in response to the segment's needs. However, few studies on green food and green consumers in Thailand are related to market segmentation and purchase intention. Thus, we considered exploring the consumers' buying behavior and categorizing consumers into segments to fulfill the knowledge gap.

In 2020, Thailand produced 25.37 million tons of waste [11]. Food packaging is one of the main contributors. Tangwanichagapong et al. [12] reported that the amount of all packaging materials has increased, and in particular plastic packaging, which has increased at a rapid rate in Thailand. Packaging waste comprised 22.5% of total municipal solid waste, and plastic was the major type of packaging found in the waste stream (15.8%), followed by glass (3.5%) and paper (3.2%). According to Sawasdee et al. [13], one of the biggest sources of solid waste from the food industry in Thailand is due to discarded non-degradable packaging; hence, green marketing focuses on creating more eco-friendly packaging. Yashasvini and Sundar [14] stated that eco-friendly packaging could reduce waste production and can minimize costs. Many resources are lost in the collection and degradation of plastic. However, eco-friendly packaging is naturally degradable, serves as a recyclable fuel, or is absent altogether. Therefore, it saves resources and investments. Thai authorities have been increasing their efforts to tackle the environmental problem, especially plastic waste and plastic packaging. They aim to reduce packaging and use bio-materials and green packaging instead. The Thailand Single-Use Plastic Reduction Roadmap aims to reduce 50% of packaging waste by 2025 and 55% by 2030. Plastic packaging reduction, increase in product recyclability, and the use of recycled material are the main environmental focuses. Green products are products that are produced in an environmentally friendly production process, while green packages are packages that are harmless to the environment [15]. In Thailand, most firms have expressed their social and environmental responsibility by offering green packaging. Hence, consumer products are becoming more available in recyclable and biodegradable packages. Fangmongkol and Gheewala [16] stated that biodegradable food containers from bagasse have a good environmental performance in Thailand.

Firms in Thailand acknowledged the need for recycling, waste reduction, and sustainable packaging. As an example, PTT Public Company Limited, the largest energy company in Thailand, strengthened its commitment to environmental friendliness by using compostable cups in coffee shops. CP ALL Public Company Limited, the largest operator of retail and wholesale businesses for consumer goods in Thailand, states that all plastic packaging of products under the company's control must be reusable, recyclable, or compostable by 2025. The company supports the use of materials from sustainably managed renewable resources, such as paper material that is certified by the Forest Stewardship Council (FSC) or by the Program for the Endorsement of Forest Certification Scheme (PEFC). It aims to increase the amount of compostable packaging material, such as the usage of polybutylene succinate coated paper and the replacement of plastic with biodegradable material. It aims for recycled material and increases reusable packaging. ThaiBev Public Company Limited, Thailand's largest beverage company, aims to increase the amount of bio-based and bio-degradable materials used in plastic bottles and plastic bags.

This paper aims to explore the significant relationships among factors such as self-efficacy, environmental concern, utilitarian eating value, perceived price, attitude, perceived behavioral control, subjective norm, and purchase intention associated with consumer buying behavior and marketing segmentation of green foods. The variables are mainly derived from the theory of planned behavior [17]. It helps to predict consumer behavior by exploring subjective norms, perceived behavioral control, attitude, and purchase intention. We added four additional variables, which are utilitarian eating value, environmental concern, perceived price level, and self-efficacy. These variables can help to predict consumers' purchase intention. The cluster analysis and structural equation modeling (SEM) methods were used to explore the market segments and examine the significant relationships of these variables. These approaches are suitable for this research because we are trying to create a multi-factor model to predict the purchase behavior of a cross-sectional sample divided into multiple groups [18,19].

This paper is organized as follows: Section 2 begins with a review of the literature on the existing theories; Section 3 outlines the research methodology involving pilot test and cluster analysis, sample and data gathering, development of measures as well as data analysis and statistical measures; Section 4 presents the analyses and findings; Section 5 discusses the research implications for theory and practice; Section 6 shows the research limitations; Section 7 summarizes this research article by discussing major conclusions drawn from this study.

2. Literature Review

Several research articles related to food marketing utilized employing the SEM approach. Most research results revealed relationships among consumer attitudes and marketing terms interpreted by consumer perceptions and behavioral intention [20–23]. Following those recent papers, we propose that the relationship of variables in this paper could be created using the SEM framework. The following sections provide details regarding theories and the related literature that helped create a structural model and hypotheses for this research.

2.1. Theory of Planned Behavior

The theory of planned behavior (TPB) consists of attitude, subjective norm, and perceived behavior control [17]. The theory of planned behavior is universally used to predict consumer behavior [24]. Dowd and Burke [25] applied the theory of planned behavior in the previous study regarding food choice. Additionally, prior research adopted TPB to examine green food intention among Asian consumers [26]. Hence, TPB has become a successful theory for predicting and forecasting consumers' buying behavior globally. According to Qi and Ploeger [27], TPB is one widely used framework to explain consumers' food choices. Considerably, in the food industry, TPB could predict approximately 60% of consumer intentions and estimate 50% of fast-food predictions. Qi and Ploeger [28] found that the TPB is useful in predicting consumers' green food purchase intention. Wang and Wang [29] studied the theory of planned behavior to predict the green food and beverage behaviors in protecting the food environment and found that commitment, perceived behavioral control, and perceived knowledge are the most influential factors of green food and beverage.

Nevertheless, the present study enhanced its conceptual framework partly from the extended TPB. This theory suggests that a person's behavioral intention influences one's behavior. The behavioral intention construct is an indicator of one's willingness to perform a given action. Instead, the behavior construct is an individual's observed response in a given situation concerning a given target [30]. This paper assumes that green consumers (behavioral intentions) are more likely to consume green food products (behavior). Additionally, it is hard to measure actual behavior. Hence, the real behavior construct is omitted in this study following Ketkaew et al. [19], Nosi et al. [21], and Watanabe et al. [22].

2.1.1. Subjective Norm

A subjective norm refers to a particular behavior influenced by social forces such as their communities, associates, or close family members' friends. It can change an individual's behavior performance [17,23]. Hence, this study suggested that the subjective norm affects intention. Furthermore, various studies found that subjective norms are significantly related to attitude, perceived behavioral control, and purchase intention [31,32]. Perceived behavioral control has been indicated as a significant component of an individual's intentions to purchase green commodities [33]. We, therefore, developed H3, H5, and H8: the subjective norm has a positive influence on the perceived behavioral control, attitude, and purchase intention.

2.1.2. Attitude

Ajzen [17,23] revealed that perceived behavior control affects intention. Previous studies recommend that customers' attitudes toward environmentally friendly commodities play a mediating role in the connection between consumption value and purchase intention [7,34]. Empirical studies suggested that attitude and purchase intention are positively correlated [35,36]. Additionally, a prior study on eco-friendly products and green purchase behavior indicated that consumers' attitude positively affects green purchase intention [24]. Furthermore, a recent study revealed that there is a positive and significant relationship between a green attitude and purchasing behavior [37]. Hence, we set up H7, i.e., attitude has a positive influence on purchase intention.

2.1.3. Perceived Behavioral Control

Ajzen [17,23] claimed that perceived behavioral control affects intention. Several studies indicated that perceived behavioral control is an essential component of intention [38,39]. Therefore, the consumer's perceived behavioral control variable directly affects purchase intention. Higher perceived behavioral control leads to a higher possibility of purchasing green food products [32], and this relationship is mediated by attitude [40]. Additionally, the previous studies recommended that perceived behavioral control is associated with individual factors such as skill, time, money, and resources [41,42]. Thus, we developed H6 and H9: perceived behavioral control has a positive impact on attitude and purchase intention.

2.1.4. Purchase Intention

Purchase intention refers to consumers' readiness to purchase sustainable products [43]. Prior research said that consumers prefer to perform a behavior to engage when they have a more accepting attitude towards purchase intention [17,23]. Purchase intention represents the possibility of engaging an individual's behavior, which can be affected by perceived behavioral control, subjective norms, and attitude. The positive attitude toward green foods, subjective norms, perceived behavioral control, and self-efficacy are used to predict the possibility of purchasing green foods [44]. Ahmed et al. [45] found that attitude, subjective norms, and perceived behavioral control have positive effects on the purchase intention of young consumers of organic food. Moreover, Liu et al. [46] discovered that attitude plays the most important role in predicting consumers' green purchase intentions.

2.2. Utilitarian Eating Value

Hoffman and Novak [47] defined utilitarian eating value as overall values judgment of functional advantages. Consumers with utilitarian motivation concentrate primarily on instrumental value. Therefore, people with the utilitarian component are generally considered goal-oriented people. Additionally, a previous study suggested that utilitarian value positively influenced subjective norms [48], whereas Ajzen [49] found that attitude and subjective norms affect the intention to execute a specific behavior. Hence, utilitarian value is related to an individual's decision-making process of consuming green food before the actual purchase [50,51]. This leads to H1: utilitarian eating value has a positive influence on the subjective norm.

2.3. Perceived Price

Zagata [52] recommended that perceived price is associated with the construct of perceived behavioral control. In contrast, Al-Swidi et al. [53] suggested that perceived price relates to the construct of attitude. Consumers' perception that organic food is expensive has a positive effect on purchase intention [54]. The higher price of products represents a higher quality and functional benefit [55]. Thus, premium prices expand organic products' attractiveness and influence one's perceived behavioral control. We established H2: The perceived price level has a positive impact on the perceived behavioral control.

2.4. Environmental Concerns

Environmental concern is a significant factor in encouraging the consumer to improve their consumption behavior to be environmentally friendly [28]. Green consumers are aware of using and consuming natural resources, which are limited resources. Hence, environmental concerns can cause green consumption behavior. Prior studies found that environmental concern positively influences the attitude towards green food consumption [56]. Environmental concern is a principal motivational element for purchasing any merchandise, including organic commodities [57]. Moon et al. [58] extended the theory of planned behavior by adding beliefs about the outcome of ecological actions and found that the perceived seriousness of environmental problems is one of the most influential determinants of green purchase intentions. Thus, H4 states that environmental concern has a positive effect on attitude.

2.5. Self-Efficacy

Self-efficacy refers to people's judgments of their competence to arrange and conduct courses of action needed to accomplish designated categories of performances [59]. In commercial terms, self-efficacy implies an individual's evaluation of products [60]. Self-efficacy is based on past behavior or experience [61]. It can identify factors of behavioral intention and can be influenced by demographics, personality traits, and attitudes toward surrounding aspects [17,23]. Theoretically, self-efficacy is a powerful factor that predicts and encourages decision-making of purchase intention [62]. Hence, self-efficacy directly influences purchase intention. Therefore, we created H10: self-efficacy has a positive impact on purchase intention.

Based on the literature review, this research established ten hypotheses and proposed the following conceptual framework. We also proposed that the market segments of green food play a moderation effect in this structural model. The model examined the relationships among factors such as utilitarian eating value, environmental concern, perceived price, subjective norm, perceived behavioral control, self-efficacy, attitude, and purchase intention linked with consumer buying behavior and marketing segmentation of green foods based on the theory of planned behavior. A solid blue line shows the effect of one factor on another factor. A dashed orange line shows the effect of market segments on a factor.

3. Research Methodology

3.1. Pilot Test and Cluster Analysis

The first purpose of the study concerns the market segmentation for green food products. Thus, we performed the pilot study by collecting data from consumers in five regions in Thailand. It was suggested to have a minimum sample size of 20–30 for the pilot study [63]. We decided to collect data from 60 respondents. More specifically, by employing the food-related lifestyle (FRL) instrument, this study shows consumer groups' existence sharing typical food lifestyles, preferences, and purchases of green food production. The FRL dimensions were established from the 69 statements containing 23 scales with three items each [64]. All items are related on a 7-point Likert-type scale. Ward's hierarchical clustering approach was performed to segment consumers into two groups. Moreover, a t-test was executed to identify whether any differences existed between the means of variables that belong to each cluster to determine the number of clusters. Each cluster was named based on the characteristics of the descriptive statistics for each cluster.

3.2. Sampling, Data Collection, and Development of Measures

Data collection in this research was based on quota sampling. The data were gathered from 500 respondents. The data were collected in front of supermarkets in five regions (north, northeast, central, east, and south), which can be used as a representation of Thailand. There were 100 respondents per region. The cities in the five regions are Chiang Mai in the north, Khon Kaen in the northeast, Bangkok in the center, Pattaya in the east, and Phuket City in the south. The selected supermarkets sell both green and non-green food. The data collection was conducted during the COVID-19 pandemic, but all required health standards were met, including distancing, mask-wearing, hand washing, body temperature screening, etc. It was suggested to have a minimum sample size of 200 for any SEM analysis [65]. In this study, data from 500 respondents were collected. After removing irrelevant data, outliers, and errors, 458 responses were usable. Hence, the rate of invalid samples was 8.4%. The data remained confidential. The data were gathered based on a structured questionnaire. Questionnaires had introductory questions, demographic questions, and questions regarding customer attitudes towards green eating behavior (see more details in Appendix A).

The demographic profiles reveal that most of the participants were female (78.2%); 48.5% of the respondents were aged below 21 years. People aged between 22 and 38 years old were 48% of the total, 2% were aged between 39 and 53 years of age, and the smallest group was those over 54, which accounts for 1.5%. With respect to income, 81.4% have an income less than THB 15,000, 13.8% make THB 15,001–20,000, 1.5% make THB 20,001–25,000, 1.1% earn THB 25,001–30,000, and 2.2% have an income more than THB 30,000. For taste experience, 85.2% have consumed green food, and 14.8% have never purchased green food before; 94.1% will consume green food products in the future, and 5.9% will not buy green food production.

In order to assess customer attitudes toward green eating behavior, the research methods used were data collection via a survey using questionnaires and data analysis using quantitative methods. Leung [66] stated that quantitative research is accomplished according to primary numerical data and statistical interpretations under a reductionist, logical, and rigidly objective paradigm. Hence, this study used a questionnaire to identify the main factors that affect green food purchase intention. Bell and Bryman [67] argued that quantitative research involves the collection of numerical data and presentation of the relationship between theory and research as deductive. In this paper, a survey was used to perform data collection of customers in Thailand.

The collected data were information from Thai customers based on a questionnaire survey that was conducted in front of supermarkets in five regions of Thailand. The survey questionnaire followed eight identified factors that affect green food purchasing, i.e., self-efficacy, environmental concern, utilitarian eating value, perceived price, attitude, perceived behavioral control, subjective norm, and purchase intention. These eight indicators were assessed by a total of 34 questions. The questionnaire was divided into three sections. The first section comprised introductory questions that identify regular and potential buyers of green food. The second section consisted of demographic profile questions in the form of multiple-choice questions, including gender, age, income, and family size. The demographic profiles were also used as a nominal variable to classify the scale. In the third section, the survey provided a linear scale of the eight indicators to allow individual participants to assess their views. The linear scale was composed of seven levels of agreement (1 = strongly disagree, 2 = disagree, 3 = somewhat disagree, 4 = neutral, 5 = somewhat agree, 6 = agree, and 7 = strongly agree). The second factor (environmental concern) targets the consumers' behavior towards green packaging and the reduction in plastics. Consumers with a large environmental concern are likely to aim for green food and green packaging.

3.3. Data Analysis and Statistical Measures

Before scrutinizing the data, we addressed common method variance (CMV) in this study. CMV occurs when variables in the same model are estimated employing the same technique or derived from the same source. The findings have systematic error variances among those variables and might have biased the assessed relationships [68]. This study gathered the data, including dependent and independent variables from the same respondents, thus exhibiting a CMV risk. We applied Harman's single factor test following Podsakoff et al. [68]. The results disclosed the cumulative variance of 49.835 percent (less than the 50% threshold), which further assured the absence of CMV.

The study's data analysis used the structural equation modeling (SEM) method. SEM encompasses such diverse statistical techniques as path analysis, confirmatory factor analysis (CFA), and causal modeling with latent variables. SEM was executed to estimate the model's estimation in two steps [69]. Step 1 validates the CFA model to measure each indicator's relationship and its variable, whether valid and reliable. This step requires appraising the goodness of fit (GOF), convergent validity, and discriminant validity. As for the GOF and convergent validity conditions, the designated thresholds included CMIN/df < 3.00, CFI > 0.90, RMSEA < 0.10, AVE > 0.50, and CR > 0.70 [17]. As for the discriminant validity condition, this paper studied issues of multicollinearity and the identity matrix of the indicator variables. The study used Pearson's moment correlations with the threshold <0.80 to check multicollinearity [70]. The Kaiser–Mayer–Olkin (KMO) and Bartlett's sphericity tests were employed to check an identity matrix [71]. These criteria were all satisfied. Step 2 evaluates the structural model to measure whether the entire structure is reliable, including the estimation of GOF. The designated fit indices thresholds were CMIN/df < 3.00, CFI > 0.90, and RMSEA < 0.10. In step 3, to examine the segment's moderating effect on the structural relationship, we conducted a multi-group moderation analysis [72]. This step performs a measurement invariance (MI) analysis utilizing the segment as a moderator dividing the sample into two groups (non-green consumer and green consumer) and then performing a z-test for the difference between the two groups' factor loadings. A z-test was used for the multi-group analysis in SEM [20,73,74]. The results of the statistical analysis are discussed in the next section.

4. Result of the Study

4.1. Pilot Study and Market Segmentation

The *t*-test result showed questions that were significant at <0.05. The target was classified into segments by analyzing segments of FRL questions and assessing the segments through *t*-tests. The findings revealed that there are two segments, including (1) non-green consumers and (2) green consumers. These names follow the characteristics of each cluster inferred from the descriptive characteristics. The test results demonstrated significant differences between the means of the FRL scores of the segment 1 and 2 consumers, with all the *p*-values below 0.01. The overall means of segment 1 ranged from 2.65 to 3.65, and segment 2 ranged from 4.14 to 5.75. Segment 1 comprised those who do not care about reading food labels. Their decision to purchase food depends on their preferences; they are pleased with inexpensive food without regard to its nutritional value or environmental friendliness. People in segment 2 are typically concerned with food label information and base their food consumption decisions on criteria such as price, food nutrition, and environmentally friendly or "green" food products.

According to Table 1, there was a sample size of 100 in segment 1. The sample consists of 41 males and 105 females. Most of the participants were age below 21 years old and were college students, and had earned less than THB 15,000 per month. In segment 2, there was a sample size of 358. The composition of sample size consists of 59 males and 253 females. Most of the participants were aged between 22 and 38 years old and were college students, earning less than THB 15,000 per month.

Table 1. Descriptive statistics for demographic profile.

Demographic Variable	Categories	Segment 1 (Non-Green Consumers)		Segment 2 (Green Consumers)		Total		Significance Chi-Square Test
		n	%	*n*	%	*n*	%	
Segment size		146	31.9	312	68.1	458	100.0	
Gender	Male	41	9.0	59	12.9	100	21.8	0.027
	Female	105	22.9	253	55.2	358	78.2	
Age	<21	75	16.4	147	32.1	222	48.5	0.364
	22–38	69	15.1	151	33.0	220	48.0	
	39–53	1	0.2	8	1.7	9	2.0	
	>54	1	0.2	6	1.3	7	1.5	
Income	<15,000	125	27.3	248	54.1	373	81.4	0.481
	15,001–20,000	16	3.5	47	10.3	63	13.8	
	20,001–25,000	1	0.2	6	1.3	7	1.5	
	25,001–30,000	2	0.4	3	0.7	5	1.1	
	>30,000	2	0.4	8	1.7	10	2.2	
Family size	1	3	0.7	4	0.9	7	1.5	0.001
	2	52	11.4	61	13.3	113	24.7	
	3	68	14.8	200	43.7	268	58.5	
	4	23	5.0	47	10.3	70	15.3	
Tasted experience	Ever	115	25.1	275	60.0	390	85.2	0.009
	Never	31	6.8	37	8.1	68	14.8	
Consume in the future	Will	136	29.7	295	64.4	431	94.1	0.553
	Will not	10	2.2	17	3.7	27	5.9	

Source. Data adapted from authors (2022).

There are two primary steps to perform a statistical test on structural equation modeling (SEM): measurement and structural models [69].

4.2. Measurement Model

The measurement model was examined using CFA. The model was determined for internal consistency, reliability, convergent validity, and discriminant validity in this context. All constructs were connected with covariances to perform CFA [17]. The indicator must involve each construct before testing. In order to enhance the goodness of fit (GOF) relationship, we allowed covariances among errors within the same construct.

4.2.1. The Goodness of Fit (GOF)

Table 2 illustrates the GOF measures and their thresholds. The results were acceptable in that all the measures passed the required threshold. CMIN/df (2.649), Tucker–Lewis index (TLI; 0.944), comparative fit index (CFI; 0.951), incremental fit index (IFI; 0.951), and root mean square error of approximation (RMSEA; 0.060) passed the designated threshold.

Table 2. The Goodness of Fit of Measurement Model.

Fit Index	Value	Threshold	Assessment
p-value	0.00		Acceptable
CMIN/df	2.649	<3.00	Passed
TLI	0.944	>0.90	Passed
CFI	0.951	>0.90	Passed
IFI	0.951	>0.90	Passed
RMSEA	0.060	<0.10	Passed

Source. Data adapted from authors (2022). Note. TLI = Tucker–Lewis index; CFI = comparative fit index; IFI = incremental fit index; RMSEA = root mean square error approximation.

4.2.2. Convergent Validity

Convergent validity was estimated by comparing the model results with the fit index threshold. The average variance extracted (AVE) [75] and composite reliability (CR) [17] were determined. The thresholds for AVE and CR are 0.50 and 0.70, respectively. Table 3 shows the suggested thresholds of the convergent validity measures, and the calculated indicators are as follows.

Table 3. Convergent validity.

Construct	Indicator	Loading	*p*-Value	AVE	CR
Self-efficacy (SE)	SE1 to 5	0.757 to 0.939	***	0.761	0.941
Environmental concern (EC)	EC1 to 5	0.791 to 0.937	***	0.772	0.944
Utilitarian eating value (UT)	UT1 to 5	0.728 to 0.873	***	0.660	0.906
Perceived price (PP)	PP1 to 4	0.783 to 0.906	***	0.730	0.915
Attitude (AT)	AT1 to 5	0.870 to 0.932	***	0.810	0.955
Perceived behavioral control (PC)	PC1 to 3	0.845 to 0.913	***	0.772	0.910
Subjective norm (SN)	SN1 to 5	0.741 to 0.884	***	0.690	0.917
Purchase intention (PI)	PI1 to 4	0.898 to 0.955	***	0.861	0.961

Source. Data adapted from authors (2022). Note. AVE = average variance extracted; CR = composite validity. *** significant at <0.001.

Table 3 shows the SE (self-efficacy), EC (environmental concern), UT (utilitarian eating value), PP (perceived price), AT (attitude), PC (perceived behavioral control), SN (subjective norms), and PI (purchase intention) constructs nicely passed the convergent validity criteria when comparing the calculated measures with their thresholds.

4.2.3. Discriminant Validity

Discriminant validity is the level to which two or more theoretically similar constructs are different. This is assessed by comparing the square root AVEs (on diagonal) with the correlations of the related matrices [74]. According to Table 4, each AVE's square root was higher than the off-diagonal correlation coefficients, recommending that all constructs could theoretically measure the different constructs, and this result was acceptable.

Table 4. Discriminant validity.

Construct	PI	SN	PC	AT	PP	UT	EC	SE
PI	0.928							
SN	0.798	0.830						
PC	0.636	0.707	0.790					
AT	0.824	0.844	0.776	0.900				
PP	0.573	0.612	0.775	0.679	0.854			
UT	0.639	0.650	0.708	0.717	0.730	0.812		
EC	0.579	0.532	0.610	0.642	0.666	0.661	0.879	
SE	0.586	0.577	0.633	0.640	0.643	0.703	0.684	0.720

Source. Data adapted from authors (2022).

4.3. Primary Structural Model

After examining the measurement model, we connected all the constructs to develop the structural model according to the purpose model in Figure 1. Furthermore, we studied the variables via the main objective structural model. The results of most of the goodness of fit (GOF) criteria show how constructs support each other. All GOF indices were satisfied with the thresholds of [76] (see Table 5).

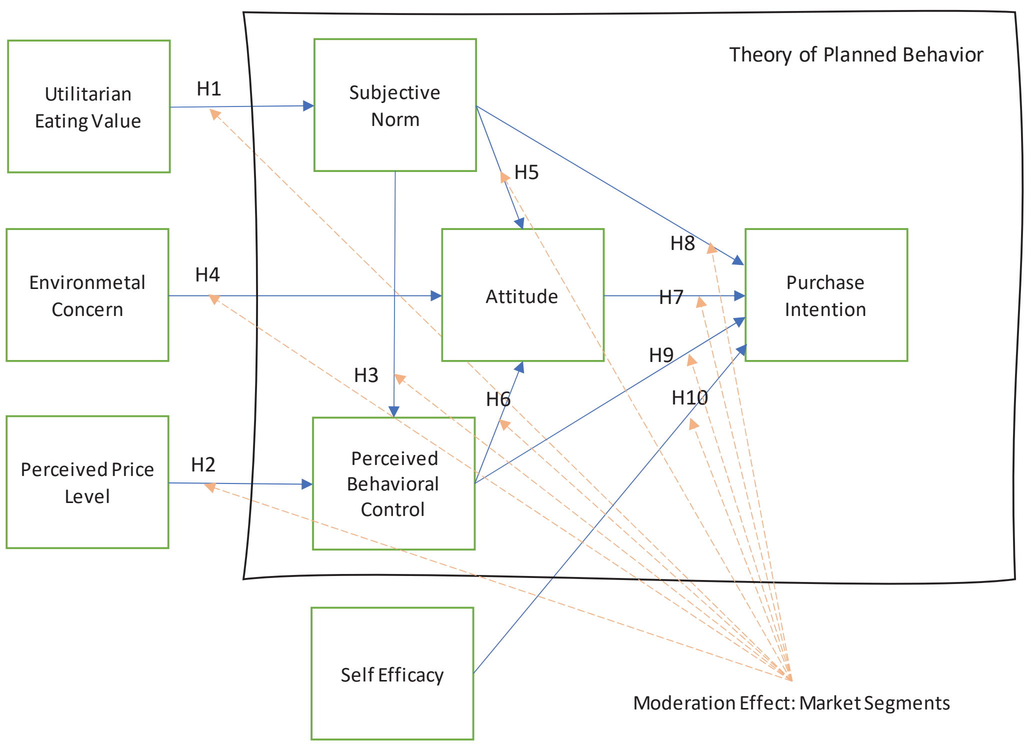

Figure 1. Proposed Model. Source: Figure created by authors (2022).

Table 5. The GOF of the Structural Model (SEM).

Fit Index	Value	Threshold	Assessment
p-value	0.00		Acceptable
CMIN/*df*	2.679	<3.00	Passed
TLI	0.943	>0.90	Passed
CFI	0.949	>0.90	Passed
IFI	0.949	>0.90	Passed
RMSEA	0.061	<0.10	Passed

Source. Data adapted from authors (2022).

According to Table 6 and Figure 2, the structural model's test results supported H1 to H8 and H10 at the significant level of 0.001 or less, whereas H9 was not supported. The relationships among the constructs were highly significant in statistics. The researchers established the analysis by considering the following constructs: utilitarian eating value, perceived price, subjective norm, environmental concern, perceived behavioral control, attitude, self-efficacy, and purchase intention adapted to the theory of planned behavior [17,23]. H1 was supported first, indicating that the utilitarian eating value had positive influences on subjective norms with a standardized factor loading of 0.695.

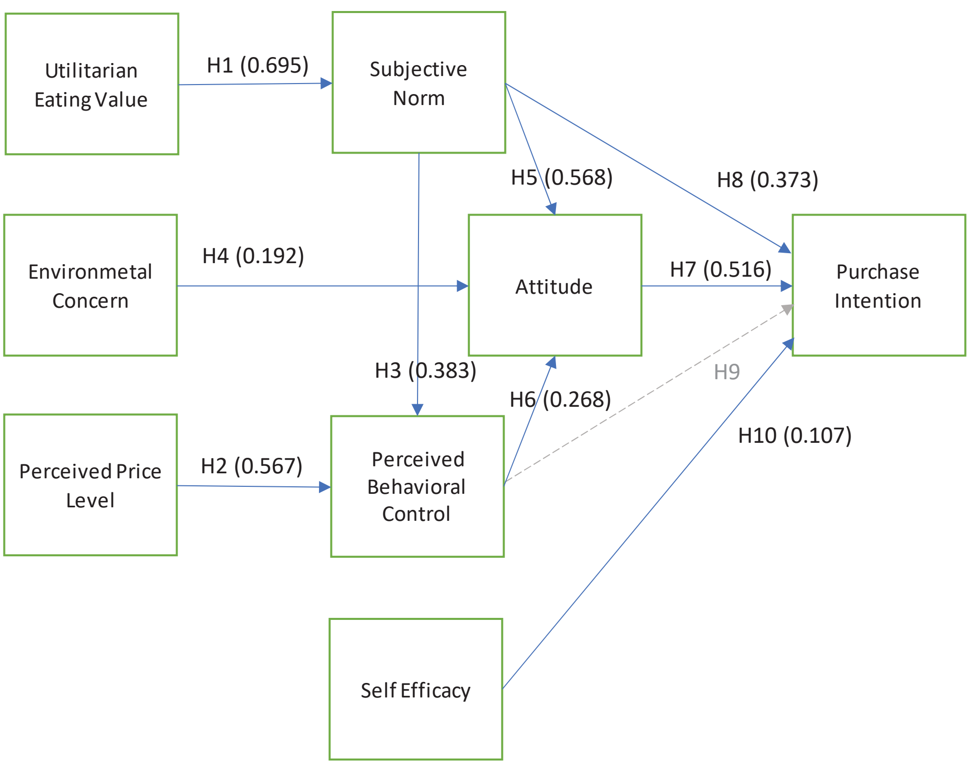

Figure 2. The structural model. Source. Figure created by authors (2022).

Table 6. Test results from the structural model.

Path	Relationships	Standardized Estimate	Result
H1	UT → SN	0.695 ***	Supported
H2	P → PC	0.567 ***	Supported
H3	SN → PC	0.383 ***	Supported
H4	EC → AT	0.192 ***	Supported
H5	SN → AT	0.568 ***	Supported
H6	PC → AT	0.268 ***	Supported
H7	AT → PI	0.516 ***	Supported
H8	SN → PI	0.373 ***	Supported
H9	PC → PI	−0.094	Rejected
H10	SE → PI	0.107 **	Supported

Source. Data from this study (2022). Note: *** Significant at <0.001, ** Significant at <0.01.

H2 was supported, which predicts that perceived prices had a significant effect on perceived behavioral control with a standardized factor loading of 0.567.

H3 was also supported, recommending that subjective norms directly affected perceived behavioral control with a standardized factor loading of 0.383. H4 predicted that environmental concern significantly influences consumers' attitudes toward green food products; it was also supported (standardized estimate = 0.192). This study's findings recommended that Thai consumers are aware of environmental defense issues and obtain their responsibilities towards environmental defense. Therefore, customers with pro-environmental behavior have a positive attitude towards green food production.

H5 was also supported, implying that the subjective norm directly affects consumers' attitudes toward green food consumption with a standardized factor loading of 0.568. Further, H6 was supported, which suggested that perceived behavioral control positively impacts consumers' attitudes toward green food products with a standardized factor loading of 0.268. H7, regarding the positive impact of consumers' attitudes on their purchase intention for green food consumption, was supported (standardized estimate = 0.516). H8 was also supported and confirmed that subjective norms significantly influenced green food purchase intention with a standardized factor loading of 0.373.

H9 was rejected, which stated that perceived behavioral control is not influenced by purchase intention in consumer buying behavior in the green food industry. Finally, H10 was supported, claiming that self-efficacy positively affects purchase intention for green food production with a standardized factor loading of 0.107.

4.4. Multigroup Moderation Analysis (MGA)

4.4.1. Measurement Invariance

Measurement variance (MI) is a method to demonstrate the difference between two groups of the measurement model, whether different or not [72]. Multigroup analysis helps us understand the constructs of questionnaires in the same way by assessing the responses between two groups (non-green consumers and green consumers). According to the measurement model (CFA), the multi-group analysis reveals the following: (1) configural invariance (unconstrained model), (2) metric invariance (equal factor loading), and (3) scalar invariance (equal intercept). If only configural invariance and metric invariance are satisfied, then partial MI is supported, allowing one to compare factor loadings between two groups. Nevertheless, if partial MI detains and scalar invariance is accepted, then full MI is formed, which lets us compare factor loadings between them. Table 7 exhibits the assessment of MI successively performed after the CFA model.

Table 7. Measurement Invariance.

Fit Index	Configural Invariance	Metric Invariance	Scalar Invariance	Threshold
p value	0.00	0.00	0.00	
CMIN/*df*	1.967	1.931	1.929	<3.00
TLI	0.934	0.936	0.936	>0.90
CFI	0.942	0.943	0.941	>0.90
IFI	0.943	0.944	0.942	>0.90
RMSEA	0.046	0.045	0.045	<0.10
Assessment	Acceptable	Acceptable	Acceptable	

Source. Data from this study (2022).

According to Table 7, the CMIN/*df* values of configural invariance, metric invariance, and scalar invariance passe the threshold of <3.00. Other fit indices such as TLI, CFI, IFI, and RMSEA of configural invariance, metric invariance, and scalar invariance are considered also pass the thresholds of >0.90, >0.90, >0.90, and <0.10, respectively. Therefore, full MI was established, allowing us to conduct further analysis in the next section.

4.4.2. Z-Test for Loading Differences

We next used critical ratio difference to gather z-test results by comparing factors loading between two segments (1. non-green consumers and 2. green consumers) from structural models [19]. In the multi-group analysis, we used the pairwise parameter comparison to estimate each parameter's critical ratios' difference to test differences in statistically significant. The factor loadings are significantly different between two segments (1. non-green consumers and 2. green consumers) when the value of the critical ratio is more than the threshold of 1.96. The paths of H1, H2, H3, H5, H6, H7, and H8 were statistically significant for non-green consumers. The paths of H1, H2, H3, H4, H5, H6, H7, and H8 were statistically significant for green consumers.

Table 8 and Figure 3 demonstrate that the paths of H1, H2, H3, H4, H5, H6, H7, and H8 for both segments are statistically significant (see the stars), which is in line with the results shown in Table 6. The paths of H9 and H10 for both segments were not statistically significant; they are also consistent with the findings in Table 6. However, only two path differences exist in H4 and H5 (see the stars under the critical ratio difference column).

Table 8. Test result from loading differences. (N = 458, Non-green Consumers = 146, Green Consumers = 312).

Path	Relationships	Standardized Loading		Critical Ratio Difference
		Non-Green Consumers	Green Consumers	
H1	UT → SN	0.682 ***	0.669 ***	∣ −0.453 ∣
H2	P → PC	0.640 ***	0.536 ***	∣ −0.715 ∣
H3	SN → PC	0.314 ***	0.418 ***	∣ 1.333 ∣
H4	EC → AT	0.046	0.272 ***	∣ 2.431 ∣ *
H5	SN → AT	0.764 ***	0.404 ***	∣ −3.643 ∣ *
H6	PC → AT	0.194 *	0.371 ***	∣ 1.399 ∣
H7	AT → PI	0.547 **	0.543 ***	∣ −0.004 ∣
H8	SN → PI	0.325 *	0.360 ***	∣ 0.132 ∣
H9	PC → PI	0.119	0.109	∣ −0.470 ∣
H10	SE → PI	−0.065	−0.127	∣ −0.172 ∣

Source. Data adapted from authors (2022). Note: *** *p* value < 0.001, ** *p* value < 0.01, * *p* value < 0.05.

The critical ratio value of H4 is slightly greater than the threshold, suggesting that segment 1 and segment 2 have different perspectives on environmental concerns and green attitudes. This result is consistent with the existing literature [28,56]. Additionally, environmental concerns do not affect (loading = 0.046 and insignificant) attitudes toward green labeling products for the non-green consumer segment because they do not think that environmental issues are caused by human consumption. Some of them are unnoticeable environmental issues. Thus, a non-green consumer who is unaware of an environmental problem will not have a good attitude toward green food. In contrast, segment two (green consumers) weigh environmental concerns as particularly important and are willing to improve their consumption actions. They attempt to find the resolution of environmental issues. Hence, a green consumer deeply concerned about the environment will have a positive attitude toward green labeling.

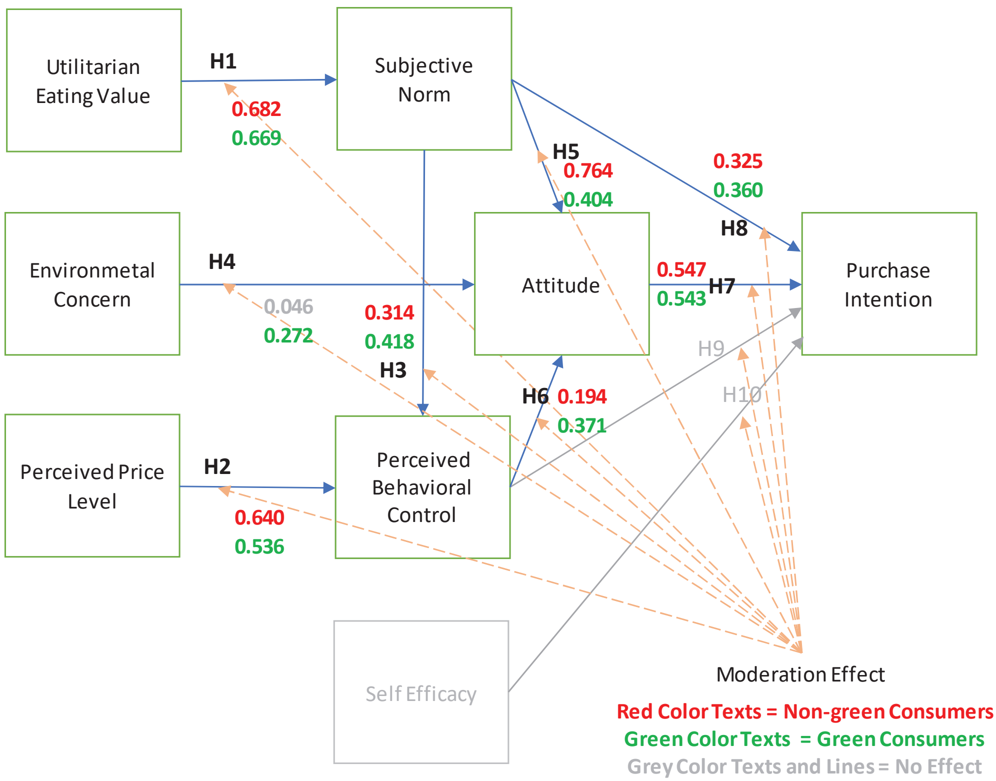

Figure 3. Moderation Effects and Structural Model. Source. Figure created by authors (2022).

H5 demonstrates a high level of critical ratio at |−3.643|, which means that the paths of segments 1 and 2 are significantly different. According to the standardized loadings, non-green consumers' subjective norms impact their attitudes more than green consumers. Non-green consumers are more likely to consume any food regardless of environmental attitude toward green food production because their consumption choice is influenced mainly by friends. However, green consumers constantly consume green labeling as usual. This is sometimes due to their environmental awareness—communities can impact dietary choices. This finding is in line with the existing literature [32].

5. Discussion

We found that the utilitarian eating value had positive influences on the subjective norm, consistent with previous studies regarding green food production [48]. The results imply consumers prefer functional attributes of green food products concerned with environmental friendliness and would like to receive social acceptance when making food decisions before purchasing. Customers feel more pressure from other peers to purchase green food products. They may become more engaged in purchasing green food products [51]. We found support that perceived prices had a significant effect on perceived behavioral control. This confirms previous research findings on the positive influence of price on perceived behavioral control [5,52]. The premium price increases the perceived behavioral control and purchase intention for green food. Consumers believe that the higher price of green products represents a higher quality and functional benefit [55]. We discovered that subjective norms directly affected perceived behavioral control. This result suggested that perceived social pressure from others can form a consumer to act an eco-friendly behavior. This behavior relates to an environmentally friendly lifestyle in their consumption pattern of green food products. We found that environmental concerns significantly influence consumers' attitudes toward green food products. The findings are consistent with previous studies by Zhu et al. [56]. We identified that the subjective norm directly affects consumers' attitudes toward green food consumption. This finding revealed that others' perceived social pressure could establish an individual's attitude toward eco-friendly food consumption. Furthermore, we found that perceived behavioral control positively impacts consumers' attitudes toward green food products. This finding implied that the perceived behavioral control in eco-friendly lifestyle increased and attitude toward green food products became more positive [40]. Additionally, we detected the positive impact of consumers' attitudes on their purchase intention for green food consumption. Thus, buyers with a positive attitude toward eco-friendly food packaging are more willing to purchase those products [24]. We found evidence that subjective norms significantly influenced green food purchase intention. The results indicated that subjective norm emerged as the strongest among the other significant factors of the purchase intention of eco-friendly packaged products. This reflects that Thai consumers received peer pressure from others about the environmental protection issue. Thus, consumers desire social acceptance and moral responsibility towards the environment, which influences their food purchasing choices. We discovered that perceived behavioral control is not influenced by purchase intention in consumer buying behavior in the green food industry. It contradicts the theory of planned behavior hypothesis proposed by Ajzen [17,23], which implied that purchase intention was not dependent on the consumer's perceived behavioral control. We identified that self-efficacy positively affects purchase intention for green food production. This result revealed that self-efficacy in green food consumption might encourage decision-making of purchase intention in green food production.

6. Research Implications

The following suggestions were presented to three main stakeholders: producers, consumers, and policymakers. Green labeling is an essential tool to disclose goods and services' environmental and social performance from a green-producer viewpoint. Thus, a producer can use green labeling as a benchmark for the enhancement and competitiveness of their products. Green food manufacturing companies and green packaging producers should create green labeling merchandise because it can influence the purchase decisions of consumers who are genuinely concerned about environmental issues. Marketers and research and development (R&D) teams would directly benefit from this research by receiving and understanding consumers' buying behavior and consumer types in the potential market for green food products and green packaging.

Moreover, this research can help consumers understand more about green food and green labeling because green labeling offers consumers information regarding the green components of the products. This information is a form of increased quality evaluation of goods and services. The green consumer can use green labeling as an essential factor in making a purchasing decision. With the help of green labeling, consumers can target to purchase green food and green packages.

Furthermore, this research can be a practical tool for estimating and improving Thailand's sustainable foods and packages production from a policymaker's perspective. Policymakers must be aware of the importance of green labeling and other green food/package production by using green labeling as a complementary tool to generate food producers' motivations to produce eco-friendly food products and green packages. Moreover, Thai policymakers should create an environmental awareness campaign to inform Thai consumers of the benefits of consuming green labeling food. These policies can encourage them to produce and purchase more green foods and packages.

In addition to the described practical implications, there are theoretical implications. This research revealed relationships among consumer attitudes and marketing terms interpreted by consumer perceptions and behavioral intention. The utilitarian eating value has a positive effect on subjective norms. Perceived prices have a significant effect on perceived behavioral control. Subjective norms have a positive impact on perceived behavioral control. Environmental concerns, the subjective norm, and the perceived behavioral control significantly affect consumers' attitudes towards green food. Consumers' attitudes, the subjective norm, and self-efficacy have a positive impact on the purchase intention for green food consumption. These research findings provide evidence for the theory of planned behavior. The subjective norm and attitude of consumers can be used to predict consumer behavior towards the purchase intention of green food.

7. Limitations of the Study

Thus, this study's information is insufficient to support the generalized market because we only focused on green food products, which are particular in the market compared with general food. Future research may apply other antecedent variables to the current structural model, such as hedonic eating value, to understand consumers' experiences. Moreover, it may change the consumer segment's moderator to a more varied segment such as age.

8. Conclusions

Environmental awareness and consumer behavior have changed dramatically in recent years. Consumers have raised their environmental awareness and adjusted their consumption behavior to reduce overall environmental impacts by using more eco-friendly products and services. Thus, we analyzed market segmentation by collecting data based on the food-related lifestyle criteria and performing cluster analysis. Consequently, we found consumers were divided into (1) non-green consumers and (2) green consumers. Moreover, this article aimed to examine the significant relationships among factors such as self-efficacy, environmental concern, utilitarian eating value, perceived price, attitude, perceived behavioral control, subjective norm, and purchase intention associated with consumer buying behavior and marketing segmentation of green foods. The hypothesized relationship was analyzed using a structural equation modeling (SEM) technique. This study formed ten hypotheses, as previously explained. We performed quantitative research based on structured questionnaires with 458 valid respondents consuming green food in Thailand. Most of the hypothesis test results supported the previously formed hypotheses except for H9, which concluded that perceived behavioral control was not related to their purchase intention of green food. Additionally, the multi-group analysis suggested that green consumers make their purchase decision of green foods based on their perception of environmental issues, whereas non-green consumers demonstrate no effects.

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Appendix A. Questionnaire

Appendix A.1. Introductory Questions

(a) Are you a regular buyer of green food?
(b) Are you a potential buyer of green food?

Appendix A.2. Demographic Data of Respondents

1. Gender
   Male, Female
2. Age (years)
   <21, 22–38, 39–53, >54
3. Income (Thai Baht)
   <15,000, 15,001–20,000, 20,001–25,000, 25,001–30,000, >30,000
4. Family size
   1, 2, 3, 4
5. Tasted experience
   Ever, Never
6. Consume in the future
   Will, Will not

Appendix A.3. Customer Attitudes

7. Customer Attitudes towards Green Eating Behavior
   - 7.1. Self—Efficacy [59,62] Do you trust farmers to grow a green plant for green food? Do you trust the procession of a producer to produce green food? Do you trust the government to manage green food policies? Do you trust the green food certificate from the certificate authority? Do you strongly trust green food?
   - 7.2. Environmental concern [28] Do environmental issues impact your purchasing decision on green food? Does your knowledge of environmental issues impact your purchasing decision on green food? Does your realization of environmental issues impact your purchasing decision on green food? Does the threat of environmental issues impact your purchasing decision on green food? Do the government policies about environmental issues affect your responsibility to the environment?
   - 7.3. Utilitarian eating value [50,51] Is the price of green food reasonable? Do you rather consume only food that you had before and you know it is tasty? Does the food portion of green food can supply your hunger (per meal)? Do you like a variety of food recipes? Do you like a variety of green food recipes?
   - 7.4. Perceived price [52,53] Is the price of green food expensive? Is the price of green food reasonable? Is green food more expensive than normal food? Is the price of green food higher than you expected?
   - 7.5. Attitude [17,23] Does buying green food benefit your purchasing decision? Do you buy green food for your safeness? Do you demand to buy green food? Do you buy green food for a better quality of life? Are you interested to buy green food?
   - 7.6. Perceived behavioral control [17,23] Does it depend on your decision whether you buy green food or not? Do you believe that you could buy green food whenever you want? Do you have enough money, time, and a chance to buy green food?

7.7. Subjective norm [17,23] Do people around you support you to consume green food? Do people around you expect you to consume green food when you are at home? Do environmental groups influence your consuming decision about green food?

7.8. Purchase intention [17,23] Will you buy green food if it is available in the shop? Do you intend to buy green food? Do you want to buy green food? How possible is it that you will buy green food?

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foods

Article

Can the Part Replace the Whole? A Choice Experiment on Organic and Pesticide-Free Labels

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Abstract: Chemical pesticides are a serious impediment to agricultural sustainability. A large-scale reduction in their use to secure food supplies requires more innovative and flexible production systems. Pesticide-free production standards bring together the strengths of all participants in the food value chain and could be the catalyst for this transition. Using a choice experiment approach and green tea as an example, this study investigated consumers' preferences for organic and pesticide-free labels. According to the findings, organic and pesticide-free labels and brands are all major factors that affect consumers' purchase decisions. Consumers are more willing to pay for organic labels than pesticide-free labels. There is a substitution effect between organic labels and pesticide-free labels. Complementary effects exist between organic labels and national brands, pesticide-free labels, and national brands. Consumer trust has an impact on consumers' choice of organic labels and pesticide-free labels. The use of pesticide-free labels is an alternate approach for small- and medium-sized businesses in a specific market to lower the cost of organic certification.

Keywords: organic labels; pesticide-free; choice experiment method; willingness to pay; green tea; consumer preference; eco-label

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1. Introduction

A critical attribute of food safety is pesticide residue [1]. Using chemical pesticides can significantly increase food production and improve agricultural efficiency, but it also causes damage to the natural ecological environment and the quality and safety of agricultural products [2]. The overuse of chemical pesticides can lead to the rapid growth of resistance in target pests, as well as serious impacts on non-target organisms, for example, endocrine disorders in rats, birds, and fish [3]. Pesticide residues can spread throughout the environment, contaminating different ecosystems and damaging food and water resources. Examples include high nitrate levels in groundwater, reduced soil fertility, and increased greenhouse gas emissions [4]. Chemical pesticides are considered to be one of the most prominent barriers to agricultural sustainability [3]. Pesticide risk reduction is at the top of many countries' policy agendas, but most have failed to meet their targets [5]. Existing policies often fail to promote widespread adoption of pesticide-free production practices due to the lack of cost-effective alternatives [6]. The vigorous development of organic agriculture is one approach to addressing the problem of agricultural products quality and safety [7]. Organic certification requires attributes such as no chemically synthesized fertilizers, pesticides, growth regulators, or other substances, and no pesticide residue, growth hormones, or genetic engineering [8].

In China, the organic food market is rapidly expanding and has reached a considerable size. Nonetheless, the share of available organic food remains small [9]. According to the Global Organic Agriculture Statistical Yearbook 2020, global sales of organic food and drinks exceeded EUR 95 billion in 2018. Of this, China's organic food sales were EUR

8.1 billion, accounting for only 8.3% [10]. Organic farming production in China necessitates a 3-year conversion period and increased labor expenditure [11]. Despite the potential premium, organic agricultural products incur higher production costs than conventional agricultural products and require significant investment, which many Chinese small- and medium-sized businesses (SMEs) cannot afford [12]. For consumers, the high cost of organic production leads to higher prices for organic agricultural products, which has hindered many consumers from buying [13].

Large-scale reductions in pesticide use in the context of unfavorable food production require more innovative and flexible systems to complement organic farming [14]. Pesticide-free production standards, which combine the strengths of all food value chain players, may be the cornerstone of this shift [15]. In Switzerland, the IP-SUISSE producer organization is introducing a nonorganic, private–public standard for pesticide-free wheat production [15]. Studies have demonstrated that the pesticide-free attribute is the most important aspect of consumer interest when purchasing organic produce [16,17]. The study by Britwum, et al. [18] on consumers' perceptions regarding the desired attributes of organic produce found that consumers place the highest importance and confidence in the "free of growth hormones" and "free of synthetic pesticides" aspects of organic labeling. For Chinese consumers, purchasing organic agricultural products is motivated more by concerns regarding food safety and personal health and less by environmental protection [19,20]. Generally, institutional pesticide-free certification is less difficult and less costly to achieve than certified organic labeling. Do consumers prefer separate pesticide-free information? If consumers are willing to pay for separate pesticide-free information, SMEs can use such certification without assuming the prohibitive expenditure of converting to organic operations. For SMEs, pesticide-free information could offer a strategic alternative to give farmers a competitive advantage. Consumers will then be able to buy healthy and safe products at a lower cost. Hence, investigating consumers' preferences and willingness to pay (WTP) for organic labels and pesticide-free information will directly affect agricultural certification decision-making.

A series of studies have been conducted on consumers' preference, WTP, and the influencing factors of organic labels [13,21–24]. Regarding how consumers perceive pesticide-free attributes, scholars believe that previous research has not been systematic and in-depth enough [18,25]. Bernard and Bernard [26] examined the WTP for two core attributes of organic labeling (pesticide-free and non-GMO), finding that consumers were willing to pay for the pesticide-free information. By contrast, Edenbrandt [25] surveyed Danish consumers and found that pesticide-free information was less important to consumers than the organic label, indicating that Danish consumers preferred to buy organic produce. These contradictory findings warrant further investigation.

Tea is one of the three most recognized drinks worldwide. China is the largest tea-producing country and a major tea-consuming and exporting country in the world [27]. Green tea production accounted for 61.70% of the total tea production in 2020. The export volume of green tea is 293,400 tons, accounting for 84.1% of China's total tea exports [28]. With consumers' increasing concerns regarding the quality of life and the rising threshold of international trade in tea, the production of organic green tea represents an important approach for enhancing the competitiveness of green tea in China, promoting green tea export, and expanding domestic demand for green tea. Existing literature focuses on the organic consumption behavior of milk [29–31], rice [32], and other crops [33,34], but there are fewer studies on the organic consumption behavior of tea [35]. Thus, green tea was chosen as the experimental subject in this study.

The choice experiment (CE) method can estimate consumers' preferences for different product attributes and assess the relationships between attributes. It avoids the limitations of the contingent valuation method that can only measure a single attribute of a product [35]. Based on the above background, taking green tea as an example, this study applies the CE method to analyze the following questions: (1) Under current conditions, do Chinese consumers have a preference and WTP for organic and pesticide-free labels? (2) Are pesticide-free labels valid in comparison with organic labels? (3) What are the factors that influence consumers' WTP for organic and pesticide-free labels? This study can provide valuable information for market expansion and marketing of organic agricultural products and also reduces the degree of information asymmetry between SMEs and consumers, providing a reference for SME producers to control production costs.

2. Materials and Methods

2.1. Attribute Selection

The CE method is widely used to measure product preferences and is an excellent approach for estimating multiple attributes. Attribute selection is the basis for determining the validity and precision of the results [36]. Previous studies have shown that food safety attributes and brands are crucial to consumers' preferences in green tea [34]. This study assumes that green tea is a collection of organic labels, pesticide-free labels, brands, and prices. Table 1 presents the attributes and levels.

Table 1. Green tea attributes and respective levels.

Attributes	Levels
Organic label	None; Organic label
Pesticide-free label	None; Pesticide-free label
Brand	None; Regional brand; National brand
Price	101 RMB/500 g; 111 RMB/500 g; 116 RMB/500 g; 121 RMB/500 g

Organic labels are widely evident in the real market. Tea companies use organic logos in product packaging to distinguish products from conventionally produced teas. There are currently no certified pesticide-free labels in tea packaging, and only some e-commerce tea companies present reports confirming pesticide-free status on product details pages. To highlight the pesticide-free characteristic and facilitate respondents' understanding, this study used a simplified logo to represent pesticide-free status, referring to Grebitus, et al. [37]. The pesticide-free label used in this study refers to the green tea are grown without chemical pesticides, herbicides, or synthetic fertilizers.

The brand is also an important factor in consumer decision-making. The brand is a "search attribute" that serves as an extrinsic factor to signal and enhance consumers' trust [38]; thus, consumers are willing to pay a higher price premium for preferred brands [34,39]. The cultivation and promotion of brand identity can motivate green tea producers to improve and optimize product quality. From the perspective of SME tea producers, branding should be vigorously established and promoted. Generally speaking, national brands are considered to have higher quality and safety than regional brands [35,40]; however, different tea drinking habits exist in different regions, and the effect of teas' origins is extremely prominent [41,42]. Hence, regional brands may be more easily accepted by local consumers [35]. Previous studies have conducted investigations regarding geographical indications or origins [42], but few studies have analyzed both national and regional brands.

Price is one of the most significant factors in consumers' purchase decisions. To set realistic price levels, this study averaged the prices of the top 50 bulk green teas sold on Taobao. Given the considerable premium for green tea in gift boxes, only green tea in bags is used. It should be noted that the green tea set up in this study does not exactly exist in the real market. Generic green tea can be considered as the lowest level of hypothetical green tea varieties [43]. Therefore, the final average price of green tea was set at 101 RMB/500 g, and the other three levels are set at 10%, 15%, and 20% higher.

2.2. Experimental Design

According to the settings in Table 1, a total of $2 \times 2 \times 3 \times 4 = 48$ dummy scenarios are generated in the full-factorial experimental design. If each choice set contains two different green tea profiles, respondents will face 2256 choices. Considering the cost and feasibility, this study applied a D-optimal design, as it can ensure validity (D-efficiency) while reducing the asymptotic standard error among attributes [44]. After D-optimal using Negene 1.0 software, a final set of 36 options was randomly generated with a D-efficiency of 93.73%, a D-error of 0.089, and an A-error of 0.103.

According to Kessels et al. [45], due to consumers' limited information load capacity, the number of consumer choices is appropriate at eight. Thus, 36 choice sets were assigned to six versions of the questionnaire, and each version of the questionnaire contained six choice sets. Following Wu, et al. [46], "neither option A nor option B" was included to simulate purchase circumstances more realistically. Hence, each choice set contained two virtual green tea product sets and one "neither option A nor option B." Figure 1 shows an example of the choice set.

Figure 1. Example of a choice set. Note: (**A**–**C**) in the figure means the alternative in the choice set.

Several studies have argued that trust would affect consumers' preferences [47]. Low trust is associated with lower ratings of the label itself, which further reduces purchase intention [48]. Two kinds of labels were set in this study. Referencing Wu [49], this study established items of consumers' trust in organic labels and pesticide-free labels. These items were scored using a five-point Likert scale from 1 for "absolutely disagree" to 5 for "absolutely agree." Table 2 presents the detailed items.

Table 2. Characteristics of consumer trust in organic label and pesticide-free label.

Variable	Items	Mean	SD
Organic Trust	I trust in the certification process of organic labels	4.153	0.646
	I trust that the organic green tea on the market is produced according to organic standards	3.965	0.844
	If I see the organic label on the front of the package, I will trust that the product is organic	4.027	0.781
Pesticide-free Trust	I trust in the certification process of pesticide-free labels	3.903	0.828
	I trust that the pesticide-free food on the market is produced according to pesticide-free standards	3.854	0.871
	If I see the pesticide-free label on the front of the package, I will trust that the product is pesticide-free	3.767	0.899

Notes: SD = standard deviation.

2.3. Sample Size Determination

The rule of thumb is usually used to calculate the required sample size. The minimum sample size is determined by a combination of three factors: the number of choice sets (t), the number of alternatives (a), and the maximum number of levels (c)of the attribute [50,51].

$$N > \frac{500 \times c}{t \times a} \tag{1}$$

Hence, the minimum sample size of this study is 500 × 4 ÷ 6 ÷ 3 = 111. Furthermore, according to Yamane (1967) [52,53], the minimum sample size in the study should be:

$$n = \frac{Z^2 p(1-p)}{e^2} = \frac{1.96^2 \times 0.5 \times (1-0.5)}{0.05^2} = 384.16 \tag{2}$$

where Z is the significance level of 95%, the value of the distribution table $Z = 1.96$, p is the estimate of the correct prediction of n for $p = 0.5$, e is the sampling error allowed with $+/-0.05$ (5%). It is noted that the sample size calculated according to the formula is the minimum sample size suggested due to the requirement for stability of the utility estimates. In the actual research situation, the required sample size is larger than the minimum value.

2.4. Data Collection

For respondent selection, actual consumers of the product should be selected as the target, as only respondents who are familiar with green tea will be concerned about the various attributes [54]. According to Determann, et al. [55], no significant difference was found between online and offline surveys for consumers' preferences in CE; hence, this study used an online survey.

We chose the Questionnaire Star platform (a professional online survey company) to conduct the online survey. The Questionnaire Star sample base is widely sourced and covers a wide range of consumer groups of different ages, occupations and income levels. It is widely used in consumer preference research [56]. As a commissioned network survey, the respondents are generally randomly selected by the commissioned company in its sample database through the network system. To ensure that the respondents identified by random selection met the requirements of this study, the following controls were also conducted in this study. (1) By setting the sample filter question before the formal questionnaire responses: "Have you purchased green tea in the last year?" (2) Screening of targets by age information in the sample pool. This ensures that the participants in the choice experiment survey are real consumers who are at least 18 years old and have had experience in purchasing green tea. Additionally, this study set a validation question [57], "Please select the 'red' option from the following options." Respondents who chose another color were direct to the end of the surveys. A total of 430 valid questionnaires were returned, and Stata 16.0 was used to calculate the final questionnaire data.

The questionnaire consisted of three parts: (a) consumers' trust; (b) comparing alternatives in CE; (c) respondents' socio-demographic characteristics. Given that CE is a hypothetical experiment, hypothetical bias may be present. Referencing Tonsor and Shupp [49], this study presented a brief introduction to respondents, using pictorial examples and textual descriptions of organic labels and pesticide-free labels. After this, two multiple-choice questions were set in this study: "Which of the following characteristics does the organic label contain?", "Which of the following characteristics does the pesticide residue-free label contain?" Only those who choose both correct questions are considered valid. This ensures that respondents understand the meaning of organic and pesticide-free labels before conducting the CE.

2.5. Models

Based on the consumer utility theory proposed by Lancaster (1966), the utility perceived by consumers from a product does not come from the product itself but from its attributes; thus, in the discrete choice model, the utility obtained by consumer n for choice i is expressed as follows:

$$U_{nit} = V_{nit}(\beta_n) + \varepsilon_{nit} = \delta(ASC) + \alpha_n(X_i) + \gamma_n(-P_i) + \varepsilon_{nit} \quad (3)$$

where U_{nit} is the utility obtained by consumer n from choice i in choice set t, V_{nit} (β_n) is the observable utility of parameter β_n, and ε_{ni} represents a random error. V_{nit} (β_n) consists of three parts. ASC is the specific choice constant. When ASC is 1, it indicates that the respondent chooses the "opt-out" option. X_i is the factor that affects the observable utility V_{nit}, which includes the product attributes and the respondent's characteristics n. P_i is the retention utility, which represents the premium paid for a change in $X_{i.}$ β_n = (δ, α_n, γ_n) is a vector of parameters reflecting respondents' ASC preferences and other attributes.

In this study, the main effect of the attributes was determined using Equation (4). Organic label (ORG), pesticide-free label (PEST), regional brand (RGB), and national brand (NAB) were the categorical variables, and the "none" label was used as the baseline. Price was the metric variable in accordance with the four price levels designated in the experiment. The utility function model is expressed by Equation (4):

$$\mathrm{U}_{nit} = ASC + \beta_1 Price_{nit} + \beta_{2n} ORG_{nit} + \beta_{3n} PEST_{nit} + \beta_{4n} RGB_{nit} + \beta_{5n} NAB_{nit} + \varepsilon_{nit} \quad (4)$$

where ASC is the "opt-out" option and the coefficients from β_1 to β_{5n} are the parameter vectors of the attributes estimated.

For the interaction effects of the attributes, organic trust (OTRU) and pesticide-free trust (PTRU) were the explanatory variables representing consumer trust in organic labels and pesticide-free labels, respectively. Indices of these two attitudinal variables were created by the mean values of the item scores. The utility function with interaction is expressed by Equation (5):

$$\begin{aligned} \mathrm{U}_{nit} = {} & ASC + \beta_1 Price_{nit} + \beta_{2n} ORG_{nit} + \beta_{3n} PEST_{nit} + \beta_{4n} RGB_{nit} + \beta_{5n} NAB_{nit} + \varepsilon_{nit} \\ & + \beta_{6n}(ORG_{nit} \times OTRU_n) + \beta_{7n}(PEST_{nit} \times OTRU_n) + \beta_{8n}(RGB_{nit} \times OTRU_n) \\ & + \beta_{9n}(NAB_{nit} \times OTRU_n) + \beta_{10n}(ORG_{nit} \times PTRU_n) + \beta_{11n}(PEST_{nit} \times PTRU_n) \\ & + \beta_{12n}(RGB_{nit} \times PTRU_n) + \beta_{13n}(NAB_{nit} \times PTRU_n) + \varepsilon_{nit} \end{aligned} \quad (5)$$

Consumer n's WTP for attribute x is estimated by Equation (6):

$$WTP_n = \beta_{nx} / \beta_{np} \quad (6)$$

3. Results

3.1. Socio-Demographics of Consumers

Table 3 presents the socio-demographics of the respondents. Among the final sample of 430, there was a slightly higher number of female respondents (54.46%) than male ones (45.54%). This is consistent with some previous studies wherein females are the primary household buyers [58]. Respondents aged 25–34 years hold the largest share (59.90%), followed by those aged 35–44 years (16.34%). Although middle-aged consumers are the main buyers of green tea, the rise of younger consumers cannot be ignored. The married samples were predominant, and most of them had some college or a bachelor's degree. Respondents with a monthly household income of 14,000 RMB and above occupied the largest proportion (30.94%), followed by those with 10,000–11,999 RMB and 12,000–13,999 RMB monthly household income. The higher monthly income and education may be because the study targeted consumers who had purchased green tea. According to Chen, et al. [59], tea consumption is positively correlated with consumers' income. Almost all of the respondents had more than three people living together. Additionally, 70.3% and 54.21% of the respondents had children aged 12 and below and elderly aged 65 and above, respectively. In terms of tea consumption frequency, the percentage of respondents who purchased green tea once every 1–2 months was 68.56%.

Table 3. Sociodemographic characteristics of the sample (n = 430).

Variable	Definition	Percentage (n = 430)
Gender	Male	45.54%
	Female	54.46%
Age	18–24	19.80%
	25–34	59.90%
	35–44	16.34%
	45–54	3.22%
	55–64	0.50%
	≥65	0.25%
Marriage	Married	72.03%
	Unmarried	27.97%
Education	Junior high school or below	0.25%
	High school	3.96%
	College or bachelor's degree	83.91%
	Post-graduate degree	11.88%
Members of household	≤2	8.17%
	3	40.84%
	4	28.47%
	≥5	22.52%
Are there children aged 12 and under in the household?	Yes	70.30%
	No	29.70%
Are there elderly people aged 65 and above in the household?	Yes	54.21%
	No	45.79%
Monthly household income (RMB)	≤2000	2.97%
	2001–3999	4.21%
	4000–5999	8.17%
	6000–7999	7.92%
	8000–9999	13.12%
	10,000–11,999	16.58%
	12,000–13,999	16.09%
	≥14,000	30.94%
Frequency	Once every half a month	13.86%
	Once a month	40.84%
	Once every 2 months	27.72%
	Two months and more	17.57%

3.2. Main Effect

Using the mixed logit model, this study set price and its cross terms as fixed parameters, and other attribute variables are set as random parameters. The log-likelihood values of the mixed logit model (−1629.2003 and −1619.7091) indicate that the regression results are generally significant.

Table 4 presents the results of the mixed logit model. In the main effects model, the parameters of the selected attributes are regressed to elicit the consumer preferences for attributes of the organic label, pesticide-free label, regional brand, and national brand. The results of the model estimation show a log-likelihood of −1629.2003, and the regression results are generally significant. The specific alternative constant ASC is significantly negative at the 1% level, indicating that choosing "neither A nor B" has a negative effect on consumer utility when compared with the combination of green tea attributes offered in the study. All of the green tea attribute combination options offered in this study could increase consumer utility. Price is negative and significant at the 5% level, indicating that consumers prefer lower-priced products. The higher the price of green tea, the more negatively it affects consumer utility. The three organic, pesticide-free, and national brand labels are significantly positive at the 1% level, indicating that consumers hold a positive preference for these three labels. The parameter estimation of different labels reveals that consumers have the highest preference for the organic label (1.282), followed by pesticide-free label (0.662) and national brand (0.459).

Table 4. Results of the mixed logit model.

Attributes	Main Effect		Main Effect with Interaction	
	Coefficient	SD	Coefficient	SD
PRICE	−0.0319 ***	0.005	−0.0258 ***	0.005
ORG	1.282 ***	0.055	1.576 ***	0.254
PEST	0.662 ***	0.054	0.923 ***	0.255
RGB	0.248 ***	0.073	0.332	0.238
NAB	0.459 ***	0.072	−0.0914	0.210
ASC	−4.385 ***	0.560	−3.602 ***	0.589
ORG × PEST	–	–	−0.710 *	0.380
ORG × RGB	–	–	0.0116	0.254
ORG × NAB	–	–	0.432 *	0.252
PEST × RGB	–	–	-0.204	0.250
PEST × NAB	–	–	0.696 ***	0.249
χ^2	1238.12		1226.94	
P	0.0000		0.000	
Log-likelihood	−1629.2003		−1619.7091	

Notes: * and *** indicate significance at the 10% and 1% levels, respectively. ASC = opt-out option; ORG = organic label; PEST = pesticide-free label; RGB = regional brand; NAB = national brand; SD = standard deviation.

In the main effect with the interaction model, the variable "ORG × PEST" is significantly negative at the 10% level, indicating that there is a substitution effect between the organic label and pesticide-free label. The variables "ORG × NAB" and "PEST × NAB" are significantly positive at the 10% level and the 1% level, respectively. When the organic label or the pesticide-free label is attached to the national brand, consumers' utility is enhanced.

3.3. Main Effect with Interaction in Trust

This section investigates the conjoint effect of trust in the organic and pesticide-free with the given attributes. Two averaged indices in Table 2 were used in a conjoint regression. The results are shown in Table 5.

Table 5. Main effect with interaction in trust.

Attributes	Coefficient	SD
PRICE	−0.0323 ***	0.005
ORG	−0.268 ***	0.360
PEST	−0.0697 **	0.365
RGB	0.0279	0.504
NAB	0.151	0.494
ASC	−4.425 ***	0.564
OTRU × ORG	0.238 **	0.101
OTRU × PEST	0.224	0.102
OTRU × RGB	0.267 *	0.141
OTRU × NAB	0.114	0.138
PTRU × ORG	0.159 *	0.084
PTRU × PEST	0.171 **	0.087
PTRU × RGB	−0.224 *	0.119
PTRU × NAB	−0.0395	0.115
χ^2	1220.76	
P	0.0000	
Log-likelihood	−1614.4741	

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. OTRU = Organic trust; PTRU = Pesticide-free trust; ASC = opt-out option; ORG = organic label; PEST = pesticide-free label; RGB = regional brand; NAB = national brand; SD = standard deviation.

The interaction term between organic trust and the organic label and regional brand is significantly positive. This indicates that the more consumers show trust in organic labels, the more they prefer organic labels and regional brands.

The interaction term between pesticide-free trust and the organic label, the pesticide-free label is significantly positive. This indicates that those who trust in pesticide-free will prefer organic labels too. Pesticide-free is an important attribute of organic labels. The interaction term between pesticide-free trust and the regional brand is significantly negative.

3.4. Heterogeneity Analysis Considering Other Consumer Factors

Heterogeneity exists in consumer preferences for organic and pesticide-free labels. To analyze the sources of heterogeneity, interaction terms of socio-demographics and consumption habits with each attribute of green tea were introduced in the model. Table 6 presents the results.

Table 6. Heterogeneity analysis considering socio-demographics and consumption habits.

Attributes	Coefficient	SD
PRICE	−0.0338 ***	0.00504
ORG	−1.604 **	0.627
PEST	−0.451	0.615
RGB	−0.383	0.836
NAB	−0.0907	0.807
ASC	−10.33 ***	1.477
sex × ORG	0.291 **	0.118
sex × PEST	0.0294	0.116
sex × RGB	0.242	0.155
sex × NAB	0.397 ***	0.153
sex × ASC	1.131 ***	0.264
age × ORG	0.0765	0.0897
age × PEST	−0.0886	0.0867
age × RGB	−0.0474	0.117
age × NAB	−0.0833	0.116
age × ASC	0.420 **	0.17
education × ORG	0.22	0.145
education × PEST	0.504 ***	0.144
education × RGB	−0.238	0.194
education × NAB	−0.123	0.184
education × ASC	0.0309	0.293
marriage × ORG	0.198	0.18
marriage × PEST	−0.185	0.175
marriage × RGB	−0.146	0.238
marriage × NAB	0.0585	0.234
marriage × ASC	0.175	0.372
household size × ORG	0.132 *	0.0693
household size × PEST	0.0599	0.0675
household size × RGB	−0.0441	0.0916
household size × NAB	0.0037	0.0891
household size × ASC	0.362 **	0.146
children × ORG	−0.0123	0.162
children × PEST	0.0458	0.158
children × RGB	0.430 **	0.216
children × NAB	0.105	0.209
children × ASC	0.678 **	0.335
elder × ORG	0.366 ***	0.119
elder × PEST	−0.193 *	0.116
elder × RGB	0.108	0.157
elder × NAB	−0.0531	0.155
elder × ASC	0.262	0.254

Table 6. *Cont.*

Attributes	Coefficient	SD
income × ORG	0.100 ***	0.0299
income × PEST	0.0187	0.0292
income × RGB	0.104 ***	0.0395
income × NAB	0.0447	0.0386
income × ASC	0.0799	0.0612
frequency × ORG	−0.022	0.0628
frequency × PEST	−0.0343	0.0616
frequency × RGB	0.029	0.0827
frequency × NAB	0.0502	0.0815
frequency × ASC	0.0222	0.134
χ^2	1206.68	
P	0.000	
Log-likelihood	−1569.3583	

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. ASC = opt-out option; ORG = organic label; PEST = pesticide-free label; RGB = regional brand; NAB = national brand; SD = standard deviation.

Considering socio-demographics, sex, household size, and income have a significant impact on the preference for organic labels. The "education × PEST" variable is significantly positive, while the "elder × PEST" variable is significantly negative. This implies that green tea with a pesticide-free label could attenuate the utility of consumers with elderly people over 65 years of age at home. The "income × RGB" and "children × RGB" are significantly positive, indicating that higher income consumers and those who with children under 12 years of age at home are more likely to buy green tea with a regional brand. Conversely, female consumers are more likely to buy green tea from a national brand. In addition, females, older, bigger household sizes, and consumers with children under 12 years of age at home are rather to choose the opt-out option. They might tend to keep the status quo.

3.5. Willingness to Pay

WTP can directly reflect the change in consumer utility when each attribute changes. The Hierarchical Bayes (HB) approach [60,61] was introduced in this study. Estimations were computed in Stata 16.0 using the command Bayesmixedlogitwtp developed by Baker [62]. Some studies have already used HB to estimate discrete choice models [63,64]. Table 7 shows the results.

Table 7. Estimated WTP: mean coefficients in 0.01 RMB.

Attributes	WTP	SD
PRICE	−6.812 ***	0.645
ORG	1.489 ***	0.171
PEST	0.871 ***	0.260
RGB	0.248	0.187
NAB	0.406 *	0.220
ASC	−4.477 ***	0.160

Notes: * and *** indicate significance at the 10% and 1% levels, respectively. WTP = Willingness to pay; ASC = opt-out option; ORG = organic label; PEST = pesticide-free label; RGB = regional brand; NAB = national brand; SD = standard deviation.

In terms of magnitudes, Chinese consumers have highly valued the organic label, with a mean WTP of 148.9 RMB/500 g among all attributes. Chinese consumers also showed a positive preference for the pesticide-free label with a mean WTP of 87.1 RMB/500 g. The reason may be that compared to pesticide-free labels, organic labels include not only food safety attributes (e.g., "no pesticide residue") but also environmental value attributes (e.g., "good for biodiversity" and "low pollution") [65]. In addition, the mean WTP for a national brand is 40.6 RMB/500 g.

Relative to the market price (101 RMB/500 g), the premium for the organic label reached 47.43%. In real life, the price premium of organic green tea over conventional green tea is approximately 50%, indicating that the WTP for organic green tea must be further improved.

4. Discussion

Chinese consumers' demand and preference for safer food have increased significantly because of health concerns [19]. This study confirms that both organic and pesticide-free labels can increase Chinese consumers' perceived utility. This finding is consistent with other studies [66,67], i.e., Chinese consumers have a positive preference for organic food. Organic labels contain not only health and safety attributes but also eco-attributes, such as being environmentally friendly. As society evolves and consumer environmental awareness rises, a growing number of Chinese consumers are motivated by environmental beliefs when buying organic products [68]. Researchers have compared consumer preferences for organic and pesticide-free labels in previous studies. Bernard and Bernard [26] examined consumers' preferences and WTP for organic, pesticide-free, non-GMO, and general products. They found no significant difference in consumer preferences between the organic label as a whole and its parts, and a strong substitution relationship between the whole and its parts. Consumers' WTP for the organic label as a whole is found to be greater than the WTP for each part individually. Grebitus, Peschel, and Hughner [37] examined U.S. consumers' preferences and WTP for pesticide-free labels using Medjool dates, finding that U.S. consumers had positive preferences for pesticide-free labels and were willing to pay more. By contrast, Edenbrandt [25] used rye bread as a subject, asserting that the pesticide-free label was not valuable and that people would only buy organic bread. This study demonstrates that the pesticide-free label is considered valuable on its own by Chinese consumers. The possible reason for this result is health concerns. Roos and Tjarnemo [69] noted that consumers were more concerned with attributes related to personal interests than other long-term benefits. Thogersen, et al. [70] confirmed that the positive attitude of Chinese consumers toward organic food is primarily motivated by consumers' concerns regarding the health value of organic food. Farias [71] demonstrated that the level of information on pesticide-free labels affected consumer preferences. As Chinese consumers become increasingly concerned about food quality and safety and health benefits, the pesticide-free label presents pesticide-related information more directly and visibly than the organic label, so that consumers have a clearer understanding of the quality and value of pesticide-free products. To sum up, both organic and pesticide-free labels have heterogeneous consumer groups and should be targeted to build markets according to their different attributes.

In real life, merchants will attach labels or additional features to goods to enhance the utility of the product itself and further gain more profits [72]. However, there is no unanimous conclusion in the academic community as to whether multiple labels necessarily enhance the utility of a product. Wang, et al. [73] proposed that consumers have a higher willingness to pay for food with both organic food and drug-free labels than organic food alone. The reason is that the more labels a food has, the more likely consumers believe the food is safer. The same idea also appears in Gabaix and Laibson [66,74] and Bertini, et al. [75] who propose that based on the quantity effect, consumers always perceive products with more attributes as superior to fewer attributes. However, Meas, et al. [76] proposed that whether more or fewer labels are better is not in the quantity but in the interaction between labels. He classified the interactions of labels into complementary effects and substitution effects. Several previous studies have shown a strong substitution effect between organic and pesticide-free labels [26]. The finding of this study is consistent with them. The organic label also contains the attribute of no pesticide residues, and there is a partial overlap in reflecting the value of the product; therefore, the overall value estimate for both labels will be less than the sum of the value estimates for the individual labels. Therefore, both labels need to be examined carefully and labeling decisions should not be based solely on the cost-benefit profile of a single label. In addition, this study also found a significant positive interaction effect between national brands and both organic and pesticide-free labels, showing strong complementary effects. According to Parguel et al. [77], brands can also act as a quality signal, and a high level of brand equity can represent a high level of product quality. National brands have higher visibility and better brand images than regional brands, and they can reflect the food quality from another perspective. When they are put together with the organic labels or pesticide-free labels, it does produce a one-plus-one effect. Compared with weak brands, strong brands are more likely to benefit from organic or pesticide-free labels. Therefore, well-known Chinese tea companies are encouraged to participate in organic label certification and to develop organic agriculture.

Consumers' trust in labeling is also a new issue in the area of study [78,79]. The interaction terms demonstrated consumer trust has a positive effect on enhancing label preferences. This finding is consistent with those of studies [32,80]. In an earlier study, Yin, et al. [81] revealed a large level of consumer distrust in organic labels; however, in recent years, with the continuous promotion of the Chinese government and the market, consumer perceptions of organic labels have increased significantly. There is also a deeper understanding and awareness of the connotations of organic labels, which also drives consumer preference for pesticide-free labels. This study also examined the role of socio-demographics in choice. Age, marriage, and green tea purchase frequency had almost no effect on the purchase of green tea. Consumers who were female, had high income, had a large household size, and had elderly above 65 years old at home were more likely to purchase organic green tea. Those with higher education were more willing to purchase pesticide-free green tea. Females, older, larger household sizes, and consumers with children under 12 years old in the household were more likely to maintain the status quo. However, socio-demographics alone are not sufficient to explain the differences in consumer behavior and more intrinsic factors such as consumer psychology should be considered [82].

This study has some research limitations. First, the CE method used provides consumers with a given product profile, and consumers who are not price sensitive may bias the results, which can be further demonstrated in the future by incorporating methods such as random Nth-price auction experiments. Second, China is the largest tea-producing country, with significant tea export and trade. To meet the expectations of different countries, tea producers will often put organic labels of other countries on their packaging, such as the EU, Japan, or Brazil; hence, the type of label preferred by consumers is also a potential consideration for future study.

5. Conclusions

This study focused on consumer preferences for organic labels and pesticide-free labels among Chinese consumers. The research chose green tea, a real product in the organic market to conduct the CE. It was confirmed that Chinese consumers have preferences for organic labels, pesticide-free labels, regional brands, and national brands. The highest premium for selected attributes was about 39.83% for organic labels, followed by pesticide-free labels (20.58%), and national brands (14.26%). In addition, this study also confirmed a substitution effect between the organic labels and pesticide-free labels; a complementary effect between organic labels and national brands, pesticide-free labels, and national brands. Trust was considered and found that consumers with higher scores in trust preferred green tea with organic labels or the regional brand. The socio-demographics were used to analyze the heterogeneity in consumer preferences. Female and consumers with higher income prefer organic green tea, and consumers with higher education prefer green tea without pesticide residues. Household size and whether there are elderly above 65 or children under 12 in the family also affect the preference. Conversely, age, marriage, and green tea purchase frequency have almost no effect on green tea purchase.

The findings of this paper yield several practical insights. First, considering that the pesticide-free label is not currently in use, such labeling may offer a viable alternative to effectively reduce the costs paid by SMEs for organic certification. For marketers, knowing consumers' preferences for pesticide-free attributes can also improve marketing strategy. For example, in certain markets, product packaging may consider using a pesticide-free label. Second, consumers have shown a highly positive preference for organic green tea, especially for when the organic label is placed alongside a national brand. Tea producers of well-known brands are encouraged to shift to sustainable production and organic certification to generate profits. Finally, trust is something that can contribute to the growth of organic green tea consumption. The government should adopt a responsible attitude and strengthen monitoring efforts to reduce food scandals, thus increasing consumer trust in organic food.

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