

Sustainable food consumption and production in the 21st century

Edited by

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and Umer Farrukh

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Sustainable food consumption and production in the 21st century

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Editorial: Sustainable food consumption and production in the 21st century

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Editorial on the Research Topic

Sustainable food consumption and production in the 21st century

The Research Topic “*Sustainable food consumption and production in the 21st century*” addressed issues of paramount importance within the field of food systems. Globally, food waste represents a major concern, occurring simultaneously with widespread malnutrition. Food production practices exert excessive pressure on natural resources such as water and land, while growing demand for animal products compounds environmental challenges. In the face of population expansion and an increasingly volatile climate, existing food production and consumption patterns proved unsustainable. The need for solutions addressing systemic sustainability weaknesses within global food systems was undeniable. This Research Topic served as a valuable forum for exploration, presenting 21 diverse contributions, including original research, reviews, and opinion pieces. The curated Research Topic sought to confront the complex challenges and identify potential solutions within the domain of sustainable food systems, demonstrating a holistic approach essential for understanding and addressing these critical issues affecting humanity worldwide.

Technological advancements have emerged as a driving force in transforming agricultural practices toward sustainability, enabling data-driven approaches that enhance production efficiency and environmental stewardship across diverse systems. Qi et al. demonstrate the role of digital technology in combating productivity losses by facilitating precise monitoring and timely actions that are essential within intensive dairy operations. The significance of verifiable sustainability practices gains prominence in Sarwar et al.’s exploration of an online platform, designed to create efficiencies in demonstrating environmental stewardship for Australian beef producers. Yuan et al. show how an Integrated Water-Fertilizer System promotes more judicious resource use among cotton growers. Further, their work illustrates a clear benefit of utilizing technological advances to quantify fertilizer use efficiency, thereby driving greater sustainability within the sector. These contributions point to the power of innovative technologies in supporting robust, evidence-based sustainable agriculture.

Enhancing sustainable food consumption requires a deep understanding of consumer behavior and the development of strategies to influence their choices toward environmentally responsible and ethical dietary practices. [Chen et al.](#)'s exploration of vegetarianism among Chinese urban and rural tourists reveals both a greater openness to plant-based diets and the complexities of navigating perceptions when adopting such choices. This aligns with [Erfanian et al.](#)'s analysis of plant-based meat acceptance, indicating that taste, perceived nutritional value, and texture have primary influence, suggesting avenues for tailoring product development and marketing. [Xiao et al.](#)'s focus on "ugly" produce presents a compelling counterpoint, indicating potential shifts in consumer attitudes around visual standards, as "naturalness" cues appear to mitigate negative bias in a potentially waste-reducing shift. Collectively, these studies reveal the interaction between internal motivations, product and marketing factors, and visual standards as important factors in sustainable food choices. This highlights the need for diverse communication and product strategies across a range of sustainable alternatives.

To achieve sustainability in food systems, it is imperative to adopt a comprehensive understanding of the environmental impact associated with both production and consumption practices, encompassing all aspects of their ecological footprint. A holistic understanding of the environmental impact of food production and consumption is essential for fostering sustainability. [Hatjiathanassiadou et al.](#)'s review emphasize the critical role of environmental footprinting tools, including carbon, water, and land-use metrics, when evaluating the sustainability of diets. Applying this rigorous assessment approach, [Sameshima et al.](#)'s examination of Japanese meals provides insights into the role of dietary choices in greenhouse gas emissions, highlighting the significance of protein sources. [Ma et al.](#)'s analysis of China's maize industry underscores the complexities of assessing sustainability, demonstrating the importance of including carbon emissions within productivity models. These studies advocate for incorporating comprehensive, standardized environmental measurements into policy making and decision support, informing dietary shifts and the promotion of sustainable agricultural practices with minimal ecological impact.

Achieving food security through sustainable practices demands proactive, data-driven approaches that anticipate future challenges and develop evidence-based strategies to address them effectively. [Mottaleb et al.](#)'s rigorous projections of growing wheat demand in China and India spotlight the crucial interplay between population dynamics and sustainable resource management, with clear implications for future food system planning. [Waseem et al.](#)'s exploration in Pakistan provides critical evidence linking crop and livestock diversification to improvements in food quality and access, informing region-specific policy responses. [Haq et al.](#)'s work highlights a strong linkage between sustainable climate change adaptation at the household level and gains in food security, underscoring the necessity of policies that integrate these factors. Overall, these studies emphasize the importance of evidence-based decision-making, context-specific solutions, and anticipatory actions for navigating complex future food security challenges within a sustainable framework.

Realizing sustainability goals within food production systems requires a strategic approach that involves the development of context-specific frameworks and the promotion of collaborative actions among various stakeholders, acknowledging the diverse challenges and opportunities across different settings. [Zhang and Zhu](#)'s findings reveal the benefits of market-oriented cooperation in bolstering the technical efficiency of smallholder farms in China, highlighting the significance of targeted cooperation for smaller operators. Turning to short food supply chains (SFSCs), [Balcom et al.](#)'s investigation of practices in Atlantic Canada demonstrates a commitment to environmental responsibility and economic viability within local systems. Conversely, [Su et al.](#)'s emphasis on developing robust, standardized systems to address online food markets reveal the critical role of policies in managing consumer protection and safeguarding quality, underscoring the distinct complexities posed by online sales channels. The studies provide evidence for leveraging various collaborative approaches alongside targeted policymaking to overcome challenges and ensure sustainability across diverse food production and distribution channels.

Strategic resource management underpins sustainable growth within the agricultural sector. [Dayananda et al.](#)'s work on village tank cascade systems highlights the critical role of water as a key limiting resource, requiring careful water-management systems and drought-resistant practices, especially in dry zones. In the Chinese context, [Ye et al.](#)'s investigation demonstrates that strategic integration of rural economies promotes agricultural total factor productivity. Their findings provide an understanding of how integrated development models contribute to enhanced efficiency and improved yields for sustainable food production. Both studies advocate for adopting systemic approaches to maximize sustainability, with interventions addressing both resource constraints and the broader rural sector.

Policy interventions in support of sustainable food systems demand evidence-based decision-making and multifaceted efforts aimed at understanding consumer behavior. [Nikravech](#)'s call for rigorous experimental designs emphasizes the need for reliable data that can accurately measure the impact of food waste policies. [Seymour](#)'s opinion piece advocates for expanding the definition of sustainable agriculture to incorporate animal-free organic practices, offering an inclusive approach to addressing food security. [Schäfer and Haack](#) underscore the challenge of overcoming established, efficiency-oriented systems in food service transitions, requiring interventions that span different governance levels. The rise of online food markets, as noted by [Su et al.](#), creates opportunities for transparency and quality control, necessitating policy interventions to create standardized systems. Lastly, [Shahbaz et al.](#)'s work emphasizes the significance of empowering female farmers and promoting innovation for responsible agriculture practices. Combined, these studies emphasize the interconnectedness of informed policy-making, inclusive practices, and targeted interventions targeting the behavior of both producers and consumers to foster sustainable change.

The breadth of research examined in this Research Topic demonstrates the inherent complexity of sustainable food systems and the necessity of adopting multi-pronged, systems-level

responses. Technology provides strategic solutions to resource management and productivity gains, while consumer research yields critical information to design both products and policies that encourage sustainable demand. From the granular view of village systems to national-level projections, the importance of integrating a wide range of scales—both geographic and temporal—for both analysis and future planning is self-evident. This diverse body of work reinforces the necessity of ongoing research tailored to both local realities and overarching environmental pressures. Through collaboration, evidence-based interventions, and an steadfast commitment to sustainability, it is possible to reshape food systems, achieving nutritional wellbeing while preserving the integrity of our planet for generations to come.

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Can the use of digital technology improve the cow milk productivity in large dairy herds? Evidence from China's Shandong Province

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Introduction: Improving milk productivity is essential for ensuring sustainable food production. However, the increasing difficulty of supervision and management, which is associated with farm size, is one of the major factors causing the inverse relationship between size and productivity. Digital technology, which has grown in popularity in recent years, can effectively substitute for manual labor and significantly improve farmers' monitoring and management capacities, potentially addressing the inverse relationship.

Methods: Based on data from a survey of farms in Shandong Province in 2020, this paper employs a two-stage least squares regression model to estimate the impact of herd size on dairy cow productivity and investigate how the adoption of digital technology has altered the impact of herd size on dairy cow productivity.

Results: According to the findings, there is a significant and negative impact of herd size on milk productivity for China's dairy farms. By accurately monitoring and identifying the time of estrus, coupled with timely insemination, digital technology can mitigate the negative impact of herd size on milk productivity per cow.

Discussion: To increase dairy cow productivity in China, the government should promote both small-scale dairy farming and focus on enhancing management capacities of farm operators, as well as large-scale dairy farms and increase the adoption of digital technologies.

KEYWORDS

herd size, milk production, productivity, digital technology, large-scale farms, sustainable foods production

Introduction

Population growth, rising incomes, and urbanization are driving growth in demand for livestock-derived foods across the globe, including dairy (Lagrange et al., 2015). Global cow milk production must increase in response to the rising demand for dairy products. However, dairy farming is increasingly blamed for environmental and climatic damage because it emits greenhouse gases (GHGs) (Herron et al., 2022). Improving cow productivity can be an effective strategy for sustainable milk production (Kelly et al., 2020) while reducing the associated environmental impacts (Lamkowsky et al., 2021; Faverdin et al., 2022).

Driven by rapid growth and technological innovation, global dairy farming has experienced profound structural change over the past decades, including rapid growth in the average size of primary production units and a shift toward fewer and larger farms in many countries (FAO (Food and Agriculture Organization of the United Nations), 2010). Such changes have significant consequences for farming productivity. One of the most debated findings in agricultural economics is the inverse relationship (IR) between farm size and agricultural productivity (Helfand and Taylor, 2021; Julien et al., 2021). The inverse relationship, first discovered by Chayanov during his study of the Russian peasantry (Chayanov, 1966), was subsequently detected by Sen (1962) in crop production in India. Since then, the inverse farm size-land productivity relationship has been widely discussed in academia and supported by empirical studies in many developing countries (Rada and Fuglie, 2019). IR is mainly caused by the increasing difficulty of supervision and management along with the expanding scale of the operation (Feder, 1985; Ferreira and Féres, 2020), an imperfection in market factors (Sheng et al., 2018), and measurement errors and omitted variables (Deininger et al., 2018a). Other studies have found that the inverse farm size-agricultural productivity relationship has reversed due to new technology adoption and institutional arrangements (Otsuka et al., 2016; Deininger et al., 2018b). For example, the latest breeding, tillage, and information technologies make labor supervision easier and may attenuate diseconomies of scale for large-scale farmers (Deininger and Byerlee, 2012). Moreover, coupled with the development of non-farm employment, the emergence of new institutional arrangements such as farm machinery services facilitates the substitution of machines for labor, resulting in a reversal of the inverse farm size-agricultural productivity relationship (Wang et al., 2016; Yamauchi, 2016).

Though livestock breeding and crop production differ, both confront the increasing difficulty of supervision and management as the farm size expands, but the literature is less clear on the existence of IR. Most of the extant literature on the relationship between herd size and dairy cow yield is based on the descriptive statistical analysis method, which discovered that the larger the herd size, the higher the dairy yield (Lerman, 2008; Yu, 2012; Krpalkova et al., 2016). While some studies have

found that larger herd size leads to higher dairy cow yield in the United States, there is no correlation between herd size and dairy cow yield outside of the Southern and Western regions (Weersink and Tauer, 1991). Some scholars have identified that milk production decreases with an increase in herd size (Brown and White, 1973), while others have empirically analyzed the determinants of dairy cow yield and concluded that herd size, in India, has a significantly positive impact on dairy cow yield (Kumar et al., 2020). Ma et al. (2019) found that with grazing dairy farms in New Zealand, an additional increase in stocking rate increased milk solids production per hectare by between 17 and 25% but decreased milk solids production per hectare cow by between 5 and 12%. They found that milking interval, dairy breed, farm labor, access to irrigation, and farm location were all important factors that increased milk solids production. Comparisons need to adjust as much for differences between farming systems (backyard, grazing, TMR) as access to critical inputs such as irrigation. Few studies have empirically analyzed the impact of herd size on dairy cow yield in China and so have missed the opportunity to identify potential causal relationships between herd size and cow yield.

To our knowledge, the role and impact of digital technology in improving cow yield and whether it differs in impact with herd size have not been well researched. Digital technology is a product or service included in or carried by information and communication technology (Lyytinen et al., 2016; von Briel et al., 2018) and comprises two main categories: precision farming technologies and software tools (Birner et al., 2021). In the dairy industry context, digital technology is known as Precision Dairy Farming or smart agriculture technology (Werkheiser, 2018; Eastwood et al., 2019). It may influence the dairy production process in two ways: First, digital technology automates operations and streamlines production steps and labor intensity, thus reducing the demand on operators' management abilities while increasing labor productivity (Barnes et al., 2019; Dela Rue et al., 2020; Yang et al., 2021). Second, digital technology collects data and automatically generates reports (Smith, 2020) to aid operators in decision-making (Huang et al., 2018; Parikoglou et al., 2022) and to improve management efficiency. However, the adoption of digital technologies remains relatively low in dairy farms around the world (Borchers and Bewley, 2015; Gargiulo et al., 2018). The barriers to adopting digital technologies include high initial investment costs and a lack of skilled labor (Pivoto et al., 2019; Bolfe et al., 2020). Compared to small-scale farmers, larger farmers are better able to adopt digital technologies (Lambert et al., 2015; Kolady et al., 2021) due to larger farmers needing more tools to manage their more complex production systems (Carrer et al., 2022) and economies of scale (Zhang et al., 2019; Mao et al., 2021). In China, digital technologies have gained popularity in dairy production systems incorporating TMR feeding (Cox, 2007). Such technologies include automatic cup removers and automatic teat cleaning with disinfection (Edwards et al., 2015), automatic temperature and weight

recording devices, milk component monitoring and milk conductivity indicators (Bewley, 2010; Eastwood et al., 2012), wireless identification devices, automatic farm management software (Eastwood et al., 2012) and cow estrus detection tools (Mayo et al., 2019). Except for cow estrus detection, other technologies have either a high or low penetration rate among farms of various sizes (Dong, 2017; Li, 2017; Peng and Li, 2020) with little observed impact on the relationship between herd size and milk yield. Chinese farms of different sizes diverge in their adoption of estrus detection technology, which is more prevalent among farms of more than 1,000 heads and less popular on farms of less than 1,000 heads (Peng and Li, 2020).

Furthermore, cow estrus monitoring is a crucial activity in dairy farming. In the event of a missed estrus, farmers require another estrous cycle (~21 days), which delays the conception of the cows and, consequently, their milk supply (Gaude et al., 2021). Currently, methods for monitoring estrus in cows include manual and automated inspection. Manual inspection is labor-intensive, and a lack of management leads to missed estrus. Automatic estrus detection, on the other hand, is a type of wearable information monitoring technology in which sensors like pedometers and collars are worn on the legs or necks of cows. The daily step data collected by the sensors is automatically obtained *via* signal receivers and sent to computer software, which then performs statistical analysis to build an information system for dynamic monitoring of cow estrus. Implementing automatic estrus detection in dairy cows can assist management in improving the detection rate and reduce the incidence of missed estrus (Rorie et al., 2002; Steeneveld et al., 2015).

Therefore, this paper aims to extend previous research by analyzing the impact of herd size on dairy cow productivity in China and take estrus detection technology as an example to explore the impact of the interaction between herd size and digital technology adoption on dairy cow productivity. China is an interesting case for two reasons. First, driven by the “Dual Circulation” strategy (Lin and Wang, 2021; Guo et al., 2022), the Chinese dairy sector needs a new focus to meet the strong domestic demand for dairy products, with domestic production as the mainstay and domestic and international supply reinforcing each other. According to the forecast of China’s Ministry of Agriculture and Rural Affairs, China’s cow milk production and dairy consumption will reach 43.89 million tons and 69.33 million tons by 2030, with a production-demand gap of 25.44 million tons (MEWEC (Market Early Warning Expert Committee, Ministry of Agriculture and Rural Affairs), 2021). Domestic milk production would need to be boosted by 58% to meet the “Dual Circulation” requirements. Second, there are two ways to increase domestic milk production. One approach is to increase the stock of dairy cows.

From 2010 to 2020, the dairy cow numbers fell from 12.108 million heads to 10.43 million heads (HF (Holstein Farmer), and

DC (dairy consultants), 2021). The main reason is that China’s dairy production is shifting from backyard farming to larger-scale dairy farm production. Thus, despite the considerable decline in dairy cow stock, the average size of dairy farms is expanding significantly. From 2010 to 2020, the average number of dairy cows farmed in China increased from 5.24 to 20.37 head of stock/ dairy farming households at an average annual growth rate of 14.54% (CAHVYED (China Animal Husbandry Veterinary Yearbook Editorial Department), 2021). The other approach is to increase dairy cow productivity. In recent years, China’s cow milk production growth has primarily depended on annual cow productivity increases.

Nevertheless, a gap remains in the level of dairy cow yield between China and developed countries. In 2020, China’s dairy cow yield was 8.3 tons/year, compared to 10.785 tons/year in the United States, 11.924 tons/year in Israel, and 10.702 tons/year in Canada (HF (Holstein Farmer), and DC (dairy consultants), 2021) in housed, intensive, total mixed ration (TMR) dairy systems. Cow milk production is affected by genetic and managerial factors (Norrington et al., 2012; Kato et al., 2022) and the system adopted. Chinese dairy farms have primarily introduced the world-recognized high-yielding breed, the Holstein, so the discrepancy between Chinese dairy yield and that of dairy-developed countries mainly stems from gaps in management among other aspects all else being equal.

This study makes the following marginal contributions: first, while most studies have focused on the impact of farm size on crop production (Aragón et al., 2022), few have paid attention to dairy farming in China (Xia et al., 2020). The negative relationship in crop plantation stems primarily from management supervision capacity and labor effort decrease as farm size increases (Feder, 1985; Ma et al., 2022), whereas dairy farming demands more refined management than crop production. This paper takes dairy farming as an example to fill the existing research gap. Second, it explores the impact of digital technology on the herd size-dairy cow productivity relationship, providing a new perspective for increasing dairy cow yield in China. Third, it empirically tests the impact of herd size on dairy cow productivity using the two-stage least squares (2SLS) regression model in an attempt to improve the accuracy and reliability of the estimation of the impact. In addition, it employs the quantile instrumental variable method for robustness testing.

Materials and methods

Research background

Changes in the size and structure of dairy production and dairy cow yield in China

Before the 1980s, dairy farming in China was concentrated in state-owned farms, with a breeding scale of about 1,000

heads (DAC (Dairy Association of China), 2002). With the development of the market economy and relevant policies, backyard farming evolved into the main pattern of dairy farming in China and remained unchanged for some time. After the Melamine incident in 2008, the Chinese government directed dairy farming toward large-scale, standardized, and intensive development, thereby changing the dominant production model of China's dairy sector (Mo et al., 2012). By 2016, the proportion of farming on a particular scale with an annual stock of more than 100 head exceeded 50%, indicating that the proportion of large-scale dairy farming in China surpassed that of backyard farming for the first time. After 2016, farming on a certain scale became China's primary production model for dairy farming. From 2016 to 2020, the proportion of dairy farms with an annual stock of more than 100 heads grew from 52.3 to 67.2% (DAC (Dairy Association of China), 2021), with an average annual growth rate of 6.9%.

China's dairy cow yield has also witnessed growth as the country's dairy cow systems evolved from backyard-oriented to a large-scale operation. During the 2008–2020 period, the dairy cow yield grew from 4.575 tons/year to 8.3 tons/year nationwide, registering an average annual growth rate of 5.09%. Since 2004, the Ministry of Agriculture has classified dairy farming modes into four categories/systems by the average annual stock of dairy cows: (1) backyard breeding of a stock of fewer than ten heads; (2) small-scale breeding of an annual stock of 10–50 heads; (3) medium-scale breeding of an annual stock of 51–500 heads; and (4) large-scale breeding of an annual stock greater than 500 heads. From 2008 to 2020, dairy cow production of different scales registered yield growth: (1) The average yield of backyard

dairy cows increased from 5.14 to 5.48 tons/year with an average annual growth rate of 0.54%; (2) The average yield of small-scale dairy cows increased from 5.16 to 5.61 tons/year with an average annual growth rate of 0.7%; (3) The average yield of medium-scale cows increased from 5.56 to 6.66 tons/year with an average annual growth rate of 1.52%; (4) The average yield of large-scale cows increased from 6.35 to 8.17 tons/year, with an average annual growth rate of 2.12% (PDNDRC (Price Department of National Development Reform Commission), 2021).

Shandong is one of the most critical dairy farming provinces in China. From 2016 to 2020, cow milk production in this province occupied about 7% of the total milk nationwide and ranked fourth in China, and its dairy cows accounted for about 8.5% of the national stock and ranked fifth in the country. In the past five years, the dairy herd size and cow yield have been improving rapidly in the province. The proportion of farms with more than 100 heads showed an average annual growth rate of 31.57%, ranking fourth nationwide, and the average annual growth rate of dairy cow yield was 15.04%, ranking second across China.

Use of estrus detection technology in dairy cows

The reproductive performance of dairy cows is critical to the profits of a farm because it affects the time interval between the parity of cows, which in turn affects cow milk production (Reith and Hoy, 2018). The estrus cycle of Holsteins generally lasts 18–23 days, with 21 days on average. The duration of estrus within each cycle is short, lasting 1.7–30.7 h (Dobson et al., 2008). Cows

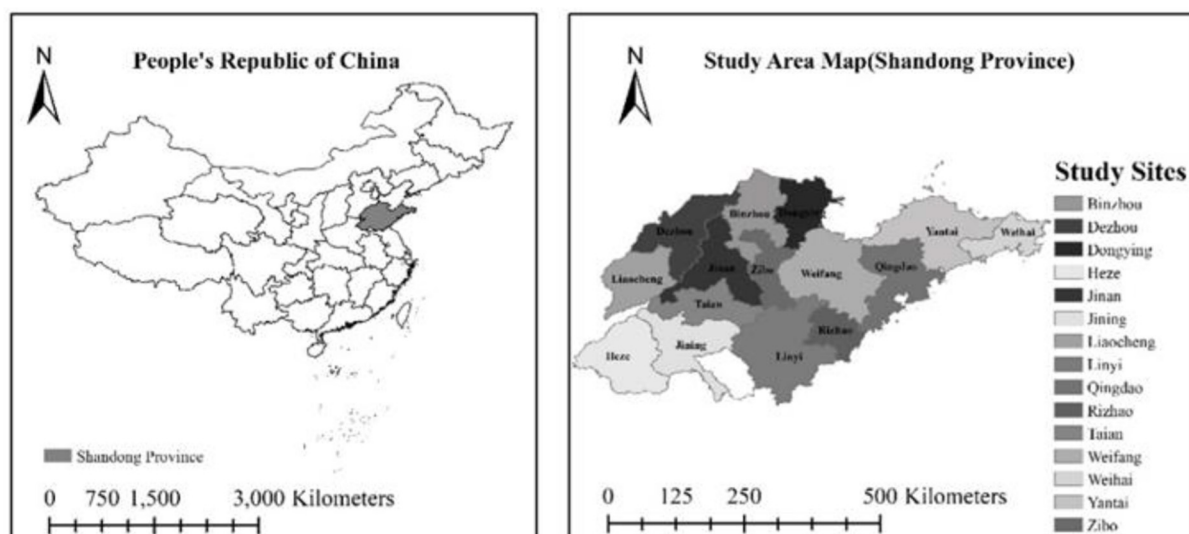


FIGURE 1
Map of the study area.

TABLE 1 Descriptive statistics results of model variables.

Variable name	Definition of variable	Mean value	SD	Minimum value	Maximum value
Dairy cow yield	Average daily milk production per cow (kg/head/day)	28.119	3.545	20	38
Herd size	Whole herd stock (head)	580.902	811.577	88	6,700
Adoption of digital technology	Adopted estrus detection technology = 1; Not adopted = 0	0.258	0.438	0	1
Proportion of hired workers	The proportion of hired workers to total workers (%)	0.763	0.216	0	1
Education level	Years of education (years)	10.766	3.006	0	19
Age	Age of operator (years)	47.912	8.386	22	76
Farming experience	Years of dairy farming (years)	15.207	6.233	3	40
Gender	1 = male; 0 = female	0.901	0.299	0	1
Fixed assets input	Depreciation of fixed assets (Yuan/head/day)	0.774	0.475	0.027	3.193
Amount of concentrated feed input	Daily concentrate feed input per cow (kg/head/day)	9.75	2.172	4	20
Labor input	Daily costs of employed labors and family laborers per cow (Yuan/head/day)	3.472	1.694	0	12.359
Breeding density	Land area per cow (mu/head)	0.178	0.204	0.01	2.381
Parity	Average years of usage per cow (years)	3.893	1.178	1.5	8.5
Breeds	The proportion of heads of Holstein breed cows to the whole herd (%)	0.961	0.112	0	1
Jiaodong area	Qingdao = 1; Dongying = 1; Linyi = 1; Weihai = 1; Rizhao = 1; Weifang = 1; Yantai = 1; otherwise = 0	0.586	0.493	0	1
Central area	Jinan = 1; Taian = 1; Jining = 1; Zibo = 1; Binzhou = 1; otherwise = 0	0.329	0.471	0	1
Western area	Dezhou = 1; Liaocheng = 1; Heze = 1; otherwise = 0	0.085	0.279	0	1

begin to produce milk only after timely and accurate detection of cows in estrus, timely breeding, the conception of cows, and successful delivery of calves. Farmers need to wait for the next estrus cycle (21 days on average) if they fail to detect the estrus, and the increased inputs during cows' missed conception will result in the farm incurring economic losses. Therefore, detecting estrus is a crucial management factor affecting the reproductive performance of dairy cows (Dolecheck et al., 2015; Endo, 2022).

Historically, cow estrus monitoring was accomplished mainly through manual labor, such as external observations of cow activity and rectal and vaginal examinations. These methods, which rely on the experience of farmers, are time-consuming and labor-intensive with a high human cost. In addition, cow estrus frequently occurs at night, when observers are most fatigued, making manual monitoring difficult and possibly resulting in missed estrus. Manual monitoring has become even more challenging as herd sizes grow, with detection accuracy often falling below 50% (Roelofs et al.,

2010). Since then, automatic estrus detection has gradually replaced manual detection (Homer et al., 2013). Automatic estrus detection is designed on the principle that cow activity increases when a cow is in estrus. The adult cow will wear a pedometer to identify its number and track its movement. When approached by a cow, the sensor automatically collects data about it and transmits it to a computer, which sends the movement data to a computerized estrus monitoring and analysis system to generate a report. Breeders schedule timely breeding according to the estrus report form. Pedometer estrus monitoring can be as accurate as 80%–90% or even 100% (Stevenson et al., 2014).

Small and medium-sized farms in China still detect cow estrus manually, whereas large-scale farms have utilized cow estrus monitoring systems (Liu et al., 2019). The Chinese self-designed automated estrus monitoring system is still in its early stages, and companies such as Afimilk and SCR from Israel, Delaval from Sweden, and Nadap from The Netherlands have all developed market-ready products (Cao et al., 2013).

TABLE 2 Empirical results on the impact of herd size on the dairy cow yield.

Variable	(1)		(2)		(3)	
	OLS		2SLS		2SLS	
	Coefficient	SE	First stage	SE	Second stage	SE
Average size of county-level farms in 2017	–	–	0.179***	0.044	–	–
Herd size	0.032**	0.013	–	–	–0.197**	0.078
Adoption of digital technology	0.052***	0.015	0.338***	0.075	0.130***	0.033
Proportion of hired workers	0.080***	0.03	1.211***	0.118	0.387***	0.114
Years of education	0.050*	0.027	0.274**	0.112	0.102**	0.044
Age	–0.031	0.042	–0.122	0.181	–0.069	0.07
Breeding experience	0.024	0.015	0.002	0.07	0.028	0.02
Gender	–0.015	0.023	0.036	0.11	0.023	0.028
Fixed assets input	0.050***	0.012	–0.123**	0.058	0.021	0.021
Feed input	–0.018	0.033	0.074	0.149	0.019	0.043
Labor input	0.049***	0.016	–0.249***	0.067	–0.029	0.032
Breeding density	–0.029**	0.011	–0.085	0.053	–0.039*	0.02
Parity	0.013	0.024	–0.319***	0.114	–0.075	0.049
Breeds	0.023	0.049	0.665**	0.306	0.223**	0.092
Western area	0.043*	0.024	0.319	0.207	0.170**	0.086
Jiaodong area	0.059***	0.015	–0.049	0.073	0.031	0.026
Constant term	2.999***	0.22	5.307***	0.946	4.516***	0.646
Observed value	284					
R ²	0.338					

SE, standard errors.

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

However, the imported estrus monitoring systems are costly and necessitate specific computer skills on the part of the breeders (Luo et al., 2019).

Econometric model

To examine the impact of herd size on dairy cow yield, we developed the following econometric model.

$$\ln y_i = \beta_0 + \beta_1 \ln size_i + \gamma X_i + \varepsilon_i \quad (1)$$

In model (1), we denote cow yield by the explained variable y_i , referred to as daily milk production per cow for farm i . The $size_i$ is herd size, referring to a farm's total cow numbers. X_i refers to other factors that influence cow yield. We choose basic characteristics of operators and farming features as control variables based on extant research. These include the operator's age; years of education; years of farming; gender; the proportion of hired workers, expressed as the ratio of the number of hired workers to the total number of workers; fixed asset input; feed input per cow; farming density; cow parity; breed, expressed as

the proportion of the number of Holsteins to the entire number of cows; the economic region where the farm is located. The ε_i in Equation (1) is a random disturbance term whereas β_0 , β_1 and γ are model parameters to be estimated. Our focus is β_1 , and a negative and statistically significant β_1 would suggest the existence of an inverse herd size-dairy cow yield relationship.

To further test the role of digital technology on the impact of herd size on dairy cow yield, this paper creates an interaction term of herd size and whether digital technology is applied based on model (1) and constructs the model as follows.

$$\ln y_i = \alpha_0 + \alpha_1 \ln size_i + \alpha_2 DT_i * \ln size_i + \alpha_3 DT_i + \delta X_i + \mu_i \quad (2)$$

In model (2), DT_i is a dummy variable for 'whether digital technology is applied'. Value is taken as 1 when digital technology is applied and 0 when not applied. μ_i is a random disturbance term. α_0 , α_1 , α_2 , α_3 and δ are model parameters to be estimated. α_1 , α_2 , α_3 are the parameters of our interest. A positive and statistically significant α_2 indicates the dairy cow

TABLE 3 Empirical results on the impact of digital technology adoption on the relationship between herd size and dairy cow yield by OLS.

Variable	Coefficient	SE
Herd size	0.036**	0.016
Herd size *adoption of digital technology	−0.009	0.017
Adoption of digital technology	0.109	0.106
Proportion of hired workers	0.075**	0.032
Years of education	0.050*	0.027
Age	−0.033	0.042
Breeding experience	0.025	0.015
Gender	−0.015	0.023
Fixed assets input	0.050***	0.012
Feed input	−0.017	0.033
Labor input	0.049***	0.016
Breeding density	−0.028**	0.011
Parity	0.013	0.024
Breeds	0.021	0.05
Western area	0.044*	0.024
Jiaodong area	0.060***	0.015
Constant term	2.978***	0.228
Observed value	284	
R ²	0.339	

SE, standard errors.

*** $p < 0.01$.

** $p < 0.05$.

* $p < 0.1$.

yield gap between small and larger farms diminishes when digital technology is used.

The key explanatory variables of herd size in models (1) and (2) are theoretically endogenous variables that may lead to endogenous problems and estimate bias in the model. We use the two-stage least squares (2SLS) regression model to solve endogenous problems. We chose the “average size of county-level farms in 2017” as the instrumental variable. This variable meets the necessary condition for being an instrumental variable for the herd size: the average size of county-level farms in 2017 directly influences the size of a single farm in the county in 2020 but does not directly affect the dairy cow yield on a single farm in the county. In equation (2), for the interaction term between digital technology and herd size, we take the interaction term between digital technology and “average size of county-level farms in 2017” as the instrumental variable. In the empirical process, the model underwent the endogenous test and the validity test of the instrumental variables.

To ensure the reliability of the estimation, we adopt two methods for the robustness tests. The first is to change the dependent variable. We transformed the dependent variable

of the average daily cow yield in 2020 into the average daily cow yield in spring and winter in 2020. That is because cows dislike heat, and milk production is generally low in summer and autumn, while the average daily yield is high in spring and winter. The second is to change the estimation method. We use the instrumental variable quantile regression method.

Data sources and variable definitions

This paper incorporates data from a survey of dairy farms in Shandong Province in 2020 for empirical research. Due to the dispersed distribution of dairy farms in each county, we gathered the managers/owners of dairy farms to the animal husbandry station of each county and recruited the trained graduate students as enumerators to conduct one-on-one interviews with them. The interview lasted about an hour, and the enumerators filled out questionnaires covering the basic characteristics of the farm manager/owner as well as the farm’s cost and benefits in 2019 and 2020, including total milk production, price and quantity of milk sold, cost of feeding the entire herd of cows, amount of feed input, depreciation of fixed assets, labor input and adoption of digital technology, in particular estrus detection technology.

We first used stratified random sampling in the survey and selected 15 cities with relatively more large-scale dairy farming households, considering regional distribution and development disparities. Then, based on the number of dairy farming households of each county in the 15 cities, we selected 1–5 counties with more farming households and conducted a census of dairy farming households in each of these counties. The 15 cities selected in Shandong Province are shown in [Figure 1](#). Zaozhuang is excluded due to relatively few dairy farmers in the city. The survey obtained a total of 361 samples, of which 324 were valid, accounting for 89.75% of all samples.

The most important three variables used in this analysis are cow yield, herd size, and adoption of digital technology. Cow yield is measured in daily milk production per cow reported by farm manager/owner. We define herd size as the highest number of cows per farm during the year. Many studies use the number of milking cows to define herd size ([Huettel and Jongeneel, 2011](#); [Dong et al., 2016](#)). However, this is not the case in China. Our definition of herd size follows China Agricultural Product Cost-Benefit Compilation, published by the National Development and Reform Commission. The adoption of digital technology is a dummy variable equal to one if the farm adopts dairy cow estrus detection technology and zero otherwise, directly reported by manager/owner. The analysis also controls for a large number of farm characteristics. The labor input includes hired labor and family labor expressed as daily costs per cow. The cost of family labor is reported by the farm manager/owner. The proportion of hired workers and breeds are expressed

TABLE 4 Empirical results on the impact of digital technology adoption on the relationship between herd size and dairy cow yield by 2SLS.

Variable	(1)		(2)		(3)	
	First stage		Herd size *adoption of digital technology		Second stage	
	Herd size				Dairy cow Yield	
	Coefficient	SE	Coefficient	SE	Coefficient	SE
Average size of county-level farms in 2017	0.168***	0.051	−0.041	0.037	–	–
Average size of county-level farms in 2017*	0.036	0.088	0.312***	0.064	–	–
adoption of digital technology						
Herd size	–	–	–	–	−0.235**	0.092
Herd size *adoption of digital technology	–	–	–	–	0.133*	0.079
Adoption of digital technology	0.127	0.522	4.467***	0.377	−0.693	0.477
Proportion of hired workers	1.216***	0.119	0.194**	0.086	0.412***	0.123
Years of education	0.273**	0.113	0.191**	0.081	0.086*	0.045
Age	−0.115	0.182	−0.220*	0.131	−0.036	0.066
Breeding experience	0.003	0.070	0.068	0.050	0.02	0.021
Gender	0.032	0.110	0.079	0.080	0.009	0.028
Fixed assets input	−0.127**	0.059	−0.039	0.042	0.017	0.022
Feed input	0.077	0.150	0.050	0.108	0.018	0.043
Labor input	−0.249***	0.067	−0.073	0.048	−0.029	0.033
Breeding density	−0.086	0.053	0.026	0.038	−0.047**	0.019
Parity	−0.316**	0.115	−0.100	0.083	−0.071	0.048
Breeds	0.665**	0.307	0.146	0.221	0.229***	0.088
Western area	0.325	0.208	−0.119	0.150	0.205**	0.097
Jiaodong area	−0.050	0.074	0.010	0.053	0.027	0.026
Constant term	5.331***	0.949	0.600	0.685	4.668***	0.69
Observed value	247		247		247	

SE, standard errors.

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

in percentages. Fixed assets input includes total mixed ration (TMR), milking machines, feeding machines and some transport machines, measured by the depreciation. Education is expressed as the manager's years of school and farming experience as the number of years the manager has raised dairy cows. We define breeding density as the total raising land area divided by total cow numbers. The amount of concentrated feed is expressed in quantity. Parity is expressed as the average years the milking cows used. We also controlled the regional difference and expressed in dummy variables.

The definitions and descriptive statistics of the variables used in this paper are shown in Table 1. On average, the milk production per cow is 28.119 kg /day. The average herd size is 580 cows. 25.8% of dairy farms have adopted digital technology, 76.3% have hired workers, and 90.1% of the operators are male. The operators' average age, education level and dairy farming experience are 47.912 years of age, 10.766 years of education and 15.207 years of dairy farming, respectively. In terms of expenditures, the daily depreciation of fixed assets per cow is

0.774 yuan (0.112 US dollars; 2019 dollars). In terms of variable costs, a milking cow receives 9.75 kg of concentrate feed per day. Furthermore, the daily wage for employed and family laborers is 3.472 yuan per cow. The land area per cow is 0.178 Mu (1 Mu = 1/15th of a hectare). The average parity of the cows is 3.893 gestations per cow, and 96.1% of dairy farms use Holstein cows. Furthermore, 32.9% of the farms are located in the central area, 8.5% in the western area, and 58.6% in the Jiaodong area.

Results and discussion

The impact of herd size on the dairy cow yield

Column (1) in Table 2 reports the ordinary least squares (OLS) estimation results of model (1). The coefficient of Herd size is positive and significant at a 1% level, and a 1% increase in herd size increases the dairy cow yield by 3.2%, suggesting that small farms will increase dairy cow yield by

TABLE 5 Robustness test: the impact of herd size on the dairy cow yield by change the dependent variable.

Variable	(1)		(2)	
	2SLS		2SLS	
	First stage		Second stage	
	Coefficient	SE	Coefficient	SE
Average size of county-level farms in 2017	0.178***	0.044	–	–
Herd size	–	–	–0.194**	0.08
Adoption of digital technology	0.331***	0.076	0.109***	0.034
Proportion of hired workers	1.206***	0.119	0.385***	0.116
Years of education	0.287**	0.115	0.106**	0.045
Age	–0.114	0.182	–0.046	0.073
Breeding experience	–0.001	0.07	0.029	0.021
Gender	0.035	0.11	0.025	0.025
Fixed assets input	–0.123**	0.058	–0.001	0.022
Feed input	0.087	0.151	0.033	0.046
Labor input	–0.246***	0.067	–0.014	0.033
Breeding density	–0.08	0.053	–0.041*	0.021
Parity	–0.310***	0.115	–0.08	0.05
Breeds	0.652**	0.307	0.198**	0.09
Western area	0.322	0.208	0.145*	0.08
Jiaodong area	–0.053	0.074	0.005	0.031
Constant term	5.226***	0.96	4.442***	0.643
Observed value	245		245	

SE, standard errors.

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

enlarging their herd size in China. The coefficients on the adoption of digital technology (estrus detection technology), Proportion of hired workers, Years of education, fixed asset input, and labor input are all positive and significant, indicating that implementing these practices could also increase dairy cow yield. The coefficient of breeding density is significantly negative, consistent with Ma et al. (2019). In addition, dairy cow yields were higher on farms in the western and Jiaodong areas.

It should be noted that there is a causal relationship between herd size and cow yield but that using the OLS estimation may lead to biased results. Therefore, we used the two-stage least squares (2SLS) regression model. Before doing so, we first tested the validity of the instrumental variables. The Hausman test results reported that the null hypothesis is rejected at a 1% level of significance, indicating that the herd size is considered an endogenous variable. We further conducted weak instrumental variable tests. The Cragg-Donald Wald F -statistic was 14.527, significantly greater than the threshold for the weak instruments test formalized by Stock and Yogo (2005). The above results proved that the model does not have a weak instrumental variable problem. Therefore, the instrumental variable selected

in this paper, namely “average size of county-level farms in 2017”, is reasonable.

Column (2) of Table 2 presents the first stage regressions of the 2SLS model (1). The estimated effect of the average size of county-level farms in 2017 on herd size is positive and significant. This implies that the larger the average size of county-level farms in 2017, the larger the herd size. As for the magnitude, a 1% increase in average size of county-level farms in 2017 is associated with a 0.181% increase in herd size.

Column (3) of Table 2 reflects the second stage estimation results of 2SLS model (1), which reveal that herd size contributes negatively and statistically significantly to dairy cow yield. When controlling for other factors, a 1% increase in herd size reduced the dairy cow yield by a 19.7%. This indicates that under current conditions where technology, fixed input, and factor input are constant, expanding herd size will result in a decline in the average dairy cow yield in China. That is because management ability and practices are primary milk production determinants (Bewley et al., 2001b). Most large-scale farms evolved from small-scale farms in China, while the large-scale farmers’ managerial ability did not improve simultaneously

TABLE 6 Robustness test: the impact of digital technology adoption on the relationship between herd size and dairy cow yield by change the dependent variable.

	(1)		(2)		(3)	
	First stage		Herd size *adoption of digital technology		Second stage	
	Herd size				Dairy cow yield	
	Coefficient	SE	Coefficient	SE	Coefficient	SE
Average size of county-level farms in 2017	0.167**	0.049	−0.041**	0.020	–	–
Average size of county-level farms in 2017* adoption of digital technology	0.035	0.096	0.308**	0.104	–	–
Herd size	–	–	–	–	−0.235**	0.094
Herd size *adoption of digital technology	–	–	–	–	0.145*	0.083
Adoption of digital technology	0.127	0.557	4.473***	0.613	−0.785	0.501
Proportion of hired workers	1.210***	0.151	0.183**	0.067	0.413***	0.125
Years of education	0.287**	0.101	0.208**	0.080	0.087*	0.045
Age	−0.107	0.194	−0.212	0.148	−0.011	0.072
Breeding experience	0.000	0.069	0.062	0.053	0.021	0.022
Gender	0.031	0.093	0.078	0.082	0.01	0.025
Fixed assets input	−0.126**	0.057	−0.037	0.039	−0.005	0.023
Feed input	0.090	0.121	0.067	0.078	0.03	0.046
Labor input	−0.246**	0.095	−0.066	0.050	−0.014	0.034
Breeding density	−0.081	0.065	0.035	0.053	−0.051**	0.021
Parity	−0.307**	0.132	−0.087	0.097	−0.076	0.049
Breeds	0.652**	0.221	0.127	0.181	0.206**	0.089
Western area	0.328	0.262	−0.114	0.106	0.183**	0.091
Jiaodong area	−0.054	0.077	0.003	0.058	0.001	0.031
Constant term	5.248***	1.042	0.501	0.752	4.612***	0.677
Observed value	245		245		245	

SE, standard errors.

*** $p < 0.01$.

** $p < 0.05$.

* $p < 0.1$.

(Hu et al., 2019). In recent years, dairy cow farming has scaled up very quickly in China, while dairy farmers have also not improved their management capacity despite expanding herd size (Liu et al., 2018), resulting in farms growing in size but attenuating their cow productivity. This is consistent with previous findings, suggesting that milk production decreases with an increase in herd size (Brown and White, 1973). The drop in milk production is greatest for those rapidly expanded farms. The reasons for this drop included lack of production ability and incorrect management practices (Speicher et al., 1978). In addition, other control variables which significantly impact dairy cow yield include the adoption of digital technology, the proportion of hired workers, years of education, breeds and the economic region where the farm is located still present a positive and significant influence on dairy cow yield. Breeding density has a negative and significant influence on dairy cow yield.

Moderating effect of digital technology

To verify that the adoption of digital technology reduces the demand for management capacity and improves management efficiency, as well as to mitigate the inverse herd size-cow yield relationship further, we empirically analyze the impact of technology adoption on the herd size-cow yield relationship based on model (2). The estimated results are presented in Tables 3, 4. Table 3 reports the OLS estimation results, which indicate that herd size positively contributes to dairy cow yield. However, according to these results, neither digital technology adoption has a significant impact on the dairy cow yield nor does the adoption of digital technology significantly impact the herd size-dairy yield relationship. To address the endogenous problem of the model, we further develop a two-stage least squares (2SLS) regression model. Before that, it was necessary to pass the endogeneity test of herd size and

TABLE 7 Robustness test: influence of herd size on cow yield at different quartiles.

	25th		50th		75th	
	Coefficient	SE	Coefficient	SE	Coefficient	SE
Herd size	−0.254**	0.11	−0.248**	0.117	−0.241*	0.141
Adoption of digital technology	0.147***	0.039	0.140***	0.052	0.134*	0.081
Proportion of hired workers	0.517***	0.197	0.467***	0.168	0.413***	0.154
Years of education	0.126**	0.059	0.107*	0.058	0.088	0.076
Age	0.028	0.088	−0.05	0.071	−0.133	0.081
Breeding experience	0.023	0.03	0.024	0.024	0.025	0.026
Gender	−0.035	0.04	0.001	0.032	0.039	0.038
Fixed assets input	0.033	0.027	0.006	0.033	−0.022	0.05
Feed input	0.017	0.057	0.045	0.054	0.074	0.073
Labor input	−0.038	0.042	−0.043	0.042	−0.048	0.046
Breeding density	−0.070***	0.024	−0.043**	0.02	−0.016	0.022
Parity	−0.056	0.05	−0.1	0.07	−0.146	0.113
Breeds	0.201	0.165	0.229*	0.121	0.259	0.168
Western area	0.147	0.105	0.185	0.125	0.226	0.198
Jiaodong area	0.052*	0.029	0.028	0.033	0.003	0.049
Constant term	4.321***	0.701	4.751***	0.795	5.207***	1
Observed value	247		247		247	

SE, standard errors.

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

the weak instrumental variable test. The Hausman test results showed that the null hypothesis is rejected at a 1% significance level; the Cragg-Donald Wald F -statistic was 7.069, significantly higher than the threshold of the Stock-Yogo weak instrumental variable. According to the results of the above tests, the herd size is an endogenous variable, and the instrumental variables selected in this paper are reasonable.

Columns (1) and (2) in Table 4 report the results for the first stage regression [model (2)]. Column (1) shows that the average size of county-level farms in 2017 positively and significantly impacts herd size. Column (2) shows a positive and significant effect of the interaction between the average size of county-level farms in 2017 and the adoption of digital technology on the interaction between herd size and adoption of digital technology. The results suggest that the average size of county-level farms in 2017 increased the herd size.

Table 4 column (3) reports the second stage estimates of the 2SLS model (2). The regression shows that herd size significantly negatively affects dairy cow yield, and 1% increase in herd size leads to a reduction of 23.5% in dairy cow yield. The negative impact of herd size on dairy cow yield diminishes with the adoption of digital technology. As mentioned above, the reason for the negative effect of herd size on dairy cow yield is that dairy farmers have expanded herd size but have not improved their managerial ability. However, as herd size increases, herd management is the biggest challenge (Bewley

et al., 2001a). The adoption of digital technology can help to reduce the requirements for managerial ability and improve managerial efficiency (Eastwood et al., 2012, 2016; Cabrera et al., 2020). Farmers operating larger farms are more likely to adopt digital technology (Läpple et al., 2015; Min et al., 2020) to take advantage of economies of scale (Pierpaoli et al., 2013; Tamirat et al., 2018). Therefore, the adoption of digital technology can attenuate the negative impact of herd size on dairy cow yield. This is supported by the literature, which indicates that larger farms adopting new technologies or management practices can increase milk production (Khanal et al., 2010) due to a scale-bias toward technology adoption (Abeni et al., 2019). China is experiencing a rapid digital transformation of agriculture (Cui et al., 2022; Shen et al., 2022). Large-scale farms have advantages in adopting digital technology (Xie et al., 2021). These suggest that the impact of herd size on dairy milk yield may change as China transforms.

Robustness tests

Tables 5, 6 present the results of the two-stage least squares (2SLS) regressions for the first robustness tests. Column (1) of Table 5, and columns (1) and (2) of Table 6 report the first-stage estimation results. Column (1) of Table 5 and column (1) of Table 6 shows that the average size of county-level

TABLE 8 Robustness test: Influence of digital technology adoption on the relationship between herd size and dairy cow yield at different quantiles.

	25th		50th		75th	
	Coefficient	SE	Coefficient	SE	Coefficient	SE
Herd size	−0.224**	0.089	−0.237***	0.088	−0.252**	0.108
Herd size *adoption of digital technology	0.207***	0.067	0.223***	0.071	0.242***	0.093
Adoption of digital technology	0.105***	0.034	0.067***	0.024	0.024	0.028
Proportion of hired workers	0.411***	0.141	0.392***	0.117	0.370***	0.114
Years of education	0.087*	0.046	0.056	0.041	0.02	0.047
Age	0.048	0.071	−0.01	0.062	−0.077	0.079
Breeding experience	0.006	0.027	0.007	0.022	0.008	0.022
Gender	−0.025	0.047	−0.014	0.036	−0.002	0.038
Fixed assets input	0.042*	0.022	0.014	0.023	−0.019	0.035
Feed input	−0.01	0.06	0.037	0.047	0.091*	0.054
Labor input	−0.018	0.032	−0.022	0.03	−0.027	0.037
Breeding density	−0.056**	0.022	−0.037**	0.017	−0.014	0.02
Parity	−0.039	0.04	−0.067	0.045	−0.099	0.073
Breeds	0.128*	0.077	0.217**	0.095	0.318	0.207
Western area	0.146**	0.074	0.201*	0.111	0.265	0.194
Jiaodong area	0.051*	0.028	0.017	0.028	−0.021	0.041
Constant term	2.875***	0.32	3.253***	0.278	3.685***	0.33
Observed value	247		247		247	

SE, standard errors.

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

farms in 2017 positively and significantly impacts herd size. Column (2) of Table 6 shows that the interaction between average size of county-level farms in 2017 and the adoption of digital technology has a positive and significant impact on the interaction between herd size and the adoption of digital technology. These results are consistent with the above results, indicating that our results are robust.

The regression result in column (2) of Table 5 shows significantly negative coefficients for herd size, implying that statistically significant negative impact of herd size on dairy cow yield corroborating the regression results above and indicating that the research conclusions are robust. The regression result in column (3) of Table 6 shows that herd size significantly influences dairy cow yield, with digital technology significantly attenuating the negative impact of herd size on dairy cow yield, which is consistent with the previous empirical results, indicating the robustness of our findings. In addition, we performed an endogeneity test of herd size and the weak instrumental variable test. The results of the Hausman test indicated that the null hypotheses should be rejected for all models. The Cragg-Donald Wald F -statistic exceeds the threshold for the weak instrumental variable test formalized by Stock and Yogo, indicating our estimations do not suffer from weak instrumental variable problems.

Tables 7, 8 present the estimation results for the second robustness test. Table 7 reports the regression results of the quantile instrumental variables method for the influence of

herd size on dairy cow yield. The impact of herd size on dairy cow yield is significantly negative at different quantiles, once again confirming that the main results of this paper are robust. In addition, Table 8 reports the regression results of the quantile instrumental variable method for the influence of digital technology adoption on herd size and dairy cow yield. First, the regression results show that herd size has a significantly negative impact on dairy cow yield, and the adoption of digital technology can significantly mitigate the negative impact of herd size on dairy cow yield, indicating that the above research findings are robust. Second, the regression coefficient of the interaction term of herd size and technology adoption was the largest at the 75th quantile and showed a increasing trend as the quantile increased, indicating that the digital technology adoption on farms with high cow yield had a greater mitigating effect on the negative impact of herd size on dairy cow yield.

Conclusions

Increasing cow milk productivity is essential for ensuring sustainable milk production. However, the impact of herd size on milk productivity is complicated. Based on research data from dairy farms of certain scales in Shandong Province in 2020, this paper used a two-stage least squares (2SLS) regression model to explore the influence of herd size on dairy cow yield and

further discussed the impact of digital technology adoption on the herd size-dairy cow yield relationship, citing dairy cow estrus monitoring technology as an example. The main findings are as follows: first, herd size significantly negatively impacts dairy cow yield; second, the adoption of digital technology can attenuate the negative impact of herd size on dairy cow yield.

According to the findings of this paper, our estimates are in line with previous studies that found a negative influence of farm size on land productivity in developing countries. However, the government has provided a series of large-scale oriented subsidies for dairy farms since 2008, resulting in the rapid development of scale in China's dairy sector. The large-scale farms that grew fast from small-scale farms have not upgraded their management and other aspects, resulting in stagnation in China's milk production. Thus, a possible policy option would be to promote small-scale dairy farming to enhance dairy cow yield. Furthermore, the results of this paper also show that the adoption of digital technology can mitigate the negative impact of herd size on dairy cow yield. This is consistent with extant studies that new technologies may change the negative influence of farm size on land productivity. It means large-scale farms' managerial ability could be offset by adopting digital technologies. The role of digital technologies in improving dairy yield is important. As a result, the government should encourage large-scale farms rapidly expanding from small-scale farms to use digital technologies to boost their dairy cow yields. Further research suggestions prompted from the conclusion of this paper include using continuous multi-period panel data to explore the impact of herd size on dairy cow yield. This paper uses cross-sectional data, so the author will extend this work and conduct a follow-up survey on dairy farms to analyze the dynamic influence of herd size on dairy cow yield. Also, while estrus monitoring was chosen as an example for digital technology, the influence of the adoption of different digital technologies on the herd size-cow yield relationship can be compared in further studies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

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Conceptualization and investigation: YQ and JH. Data curation, formal analysis, methodology, visualization, and writing—original draft: YQ. Funding acquisition, project administration, and resources: JH. Supervision: JH and NS. Validation: NS and QZ. Writing—review and editing: JH, NS, and QZ. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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A pathway towards the development and evolution of consumer behavior: Policy directions for sustainable development and improvement of nutrition

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Introduction: The virtuality, concealment, uncertainty and complexity of online trading make the online food trading market have security risks, while the lack of information, information asymmetry and imperfect market system make the "lemon problem" in the market increasingly obvious.

Methods: In order to clearly understand and manage the "lemon problem" in the online food trading market, we built an evolutionary game model involving the seller, buyers and online food trading platform, deeply analyzed the formation process of the "lemon problem" in the online food trading market, and revealed the influencing factors and effects of each subject's strategy choice from the perspectives of subsidy, punishment, cost, and benefit.

Results: Findings of this study reveal that: (1) In the online food trading market, the strategy of the seller, buyer and platform will be stable in six situations, and the "lemon problem" will emerge with the development and evolution of the online food trading market. (2) The strategy of each subject in the online food trading market will be affected by variables like cost difference between positive performance and negative performance of the seller, punishment from the buyer with positive participation to the seller with negative performance, subsidy from the platform with positive regulation to the seller with positive performance, etc., and different factors have different influence directions and degrees on the subject strategy. (3) In the online food trading market, cost, punishment, subsidy and benefit have different effects on the subject's strategy. Among them, cost and cost difference have the most significant impact on the subject's strategy, followed by punishment and benefit difference, and subsidy and additional benefit have less impact on the subject's strategy.

Discussion: Based on our study findings, it is proposed that by constructing a complete and standardized system of online food trading market from the aspects of examination and verification institution, reward and punishment institution, and supervision institution, it will be able to provide reference for managing the “lemon problem” in the online food trading market, promoting the sustainable development of the market, and ensuring the safety of online food.

KEYWORDS

sustainable food production, formation mechanism, influencing factors, evolutionary game, online food trading market, lemon problem

Introduction

In recent years, driven by the upsurge of “Internet +” and “platform economy,” the food supply chain closely related to consumer life has been constantly changing, and the marketing mode represented by Internet platform sales has gradually emerged. At present, people’s lives are full of various online food trading platforms, such as Meituan Takeout, Eleme, Koubei, and Jingdong To Home from China, Grubhub, Ubers Eats, and DoorDash from United States, Deliveroo and Just Eat from United Kingdom, Delivery Hero from Germany, and Swiggy from India (1). During the COVID-19 pandemic, in order to reduce the spread of the virus, some countries adopted partial or complete blockade measures, such as closing schools, workplaces, entertainment places, restaurants, etc. (2), which had a significant impact on people’s food purchasing methods and consumption habits (3), and changed consumers’ dietary preferences from offline eating to online delivery (4). In this process, people’s demand for online food services such as takeout catering and fresh food e-commerce is also expanding. Globally, online food trading market revenue increased by 27% in 2020, reaching 136.4 billion dollars. Furthermore, a 79% increase in total orders between 2020 and 2021, across its 17 operating countries including UK, Germany, Canada, and Netherlands (5). In 2021, China’s total income in food delivery is 27.3 billion dollars, and the United States’ total income is 15 billion dollars. The China Sharing Economy Development Report (2022) shows that in 2021, online takeout revenue will account for 21.4% of China’s catering industry revenue, up 4.5% year on year (6). According to the Research on NPS User Experience of Fresh Food in 2021 by iiMedia Research, the scale of China’s fresh food e-commerce industry in 2021 will be 458.5 billion yuan, an increase of 46.2% over 2020 (7).

Online food trading is a new economic model based on emerging information technologies such as the Internet, big data, artificial intelligence, and blockchain, which has different characteristics and patterns from traditional food trading. While expanding the market scale and creating social and economic

benefits, the “lemon problem”¹ also comes into being (8–11). The virtuality, concealment, uncertainty, and complexity of online trading make it increasingly obvious that food is not fresh, delivery is not timely, after-sales service is poor, false promotion, and other issues (12), which has aroused widespread concern of the government and society. In order to meet the new challenges of online food security, countries have taken a series of response measures. Among them, German consumers have a series of rights and interests protection policies, such as the right of inspection (unsatisfied food users can return goods on the spot). The United States government has established a special food safety website to uniformly and authoritatively disclose food safety information. Japan’s Food Hygiene Law clearly stipulates online food, and food safety is subject to the double strict supervision of law and public opinion. China’s food safety regulatory authorities have successively issued such rules and regulations as the Food Safety Law, the Measures for the Investigation and Punishment of Illegal Acts of Online Food Safety, and the Measures for the Supervision and Administration of Food Safety in Online Catering Services, which clearly stipulate the food safety responsibilities and obligations of online food trading platforms, food producers, and food operators (13, 14). However, the problem of online food safety has not been fundamentally solved. The reality of many businesses, difficult supervision, limited number of technical and law enforcement personnel makes it difficult to solve the “lemon problem” in the online food trading market. In 2020, China’s 12315 platform, an Internet platform dedicated to handling consumer complaints, received 65,800 online food complaints (7). For a long time, consumers will lose confidence in the market due to their inability to distinguish the quality of food. High quality businesses will be difficult to obtain income matching the quality of food due to consumers’ distrust. Food trading platforms will face difficulties such as low customer retention rate, high churn rate, and low profits. Eventually, the online food trading market will be full of low-quality businesses, and food quality also has high safety risks (15).

1 The lemons problem refers to concerns concerning the value of an investment or product that develop as a result of unequal knowledge possessed by the buyer and supplier.

Online food trading involves government, food suppliers, food consumers, food trading platforms, media, and other subjects, as well as production, transportation, sales, after-sales, and other links. In the transaction process, many factors, such as cost and income, will affect the strategic choice behavior of each subject. In relevant research, scholars believe that the lack of information, information asymmetry and imperfect market system will lead to the “lemon problem” in the online food trading market (16), and the “lemon problem” in the market can be alleviated with the help of blockchain technology, reputation mechanism, and regulatory mechanism (17, 18). However, will the “lemon problem” in the online food market definitely exist? What factors will affect the “lemon problem?” What is the relationship between the behavior of each subject in the market and the “lemon problem?” How to alleviate and manage the “lemon problem” in the online food trading market? We do not know these. To effectively solve the lemon problem in the online food trading market, it is necessary to analyze the formation mechanism of formation of the “lemon problem” and clarify the key factors affecting the development and evolution of the online food trading market. Only by recognizing and solving problems can the interests and needs of food suppliers, food consumers, and other subjects be met, and the online food trading market can achieve long-term, healthy and sustainable development.

Under the above background, we analyzed the online food trading market and built an evolutionary game model with the seller, buyer and platform as the main body. By depicting the interaction between the subjects in the online food trading market and revealing the influencing factors and effects of each subject’s strategy choices, we hope to provide reference for managing the “lemon problem” in the online food trading market, promoting the sustainable development of the market, and ensuring the online food safety.

Literature review

Food safety concerns the health of the people and the long-term stability of society (19). With the continuous optimization and improvement of network information technology and network infrastructure, Internet thinking and network development mode have permeated all areas of social life, and the online food market has developed rapidly. The online food trading has changed the consumption mode, trading mechanism and circulation link of traditional food, and has also increased the difficulty of food safety management while facilitating consumers. In the relevant research on online food safety, scholars mainly focus on the causes and governance of online food safety problems.

On the one hand, the causes of online food safety problems. With the continuous expansion of the scale of online food trading market, the market has shown new

features such as prominent platform effect (forming a new economic development model with platform organization and its data control right as the core), data oriented consumption (individual consumption behavior is affected by data information), and increased information asymmetry (information asymmetry mastered by various subjects) (12). In this process, problems such as weak performance of platform responsibilities, imperfect market credit evaluation system, lagging government regulatory capacity, and acute contradiction between the platform and the seller have become increasingly prominent (11, 20). The characteristics of online food trading, such as spatial inconsistency, time inconsistency, and food non-standard, will lead to information asymmetry among governments, enterprises, and consumers (21). The high information asymmetry, high externality, high liquidity, and high risk of online food trading (22), as well as the trusted product characteristics of food safety and the self-interest motivation of various stakeholders in the process of food trading, make food safety problems prone to occur in the market (23). However, excessive dispersion of food producers, low market access threshold for food sellers, lack of platform food safety supervision system, and difficulty in tracing the food transportation process will further increase the online food safety problem (24). Among them, the lack of safety awareness of food sellers is the fundamental reason for the existence of online food safety problems (19). The failure of the market reputation mechanism, the imperfect government supervision mechanism, the low threshold for market entry, the imperfect platform information generation and release mechanism, and the opaque platform credit evaluation mechanism are the main reasons for the “lemon problem” in the online food trading market (16, 25).

On the other hand, the governance of online food safety problems. The governance of online food safety problems involves multiple subjects and links, and has many characteristics, such as open structure, complementary functions, subject cooperation, consultation and interaction, and self-regulation. At present, scholars mainly explore the governance of online food safety from the perspective of government, media, online food trading platform, and consumers.

Government

The government is the direct subject of online food safety governance and plays an important role in the formulation of food safety system (26, 27). The government can alleviate the food safety problem by increasing the inspection probability of enterprises and improving the punishment of self-discipline (28). In relevant research, Ortega et al. found that Chinese consumers have the highest willingness to pay for government certification programs, followed by third-party certification,

traceability systems, and product specific information labels (29). A strict monitoring system can not only improve consumers' welfare, but also restore consumers' trust and increase social welfare. However, in the online food trading market, there are many and scattered food suppliers, heavy food safety supervision tasks, backward food safety supervision technology, and other problems, which make the defects of the government's single governance of the online food trading market increasingly prominent (30, 31). Among them, Deng believed that the single government supervision model is a system obstacle to produce food safety risks. It is an inevitable choice for the reform of the food safety supervision model to move from a single government supervision model to a social co governance model (32). Hu pointed out that at present, China's food safety supervision is faced with such dilemmas as endogenous conflict of policy objectives, structural mismatch of resources and powers, and adverse incentive of regulatory behavior (33). In view of the problems existing in government governance, scholars have given relevant solutions. Among them, Liu and Ma believed that the government should strengthen food safety education to enable the public to have basic knowledge (34). Wei and Yao pointed out that the government should improve the security system of data governance, clarify the operator access mechanism, limit the monopoly of network giants, build a cooperative rights protection mechanism, and reform the regulatory governance system (12). Yang et al. believed that the government should increase punishment, reduce supervision costs, strengthen self-discipline of enterprises, guide the public to participate in governance, and build a multi-agent collaborative governance mechanism (35).

Media

In order to effectively solve the failure of government regulation and improve the problem of insufficient government regulation, some scholars introduced media to participate in the governance of online food safety problems. Cao et al. studied the role of new media in government food safety supervision and found that efficient and accurate new media supervision can effectively restrain food enterprises' adulteration behavior and urge the government to perform due diligence supervision (36). Chen et al. believed that the media would take the lead in exposing food safety problems, grasp the guidance of public opinion, and help government regulators to strengthen supervision (37). Zhang et al. found that strengthening third-party supervision is conducive to promoting government regulatory authorities to strengthen supervision and improve enterprise food safety governance (38). Xie et al. found that the sensitivity of producers to perceived reputation loss, the subjective value judgment of media participation in social governance, and the government's normalization of regulatory penalties are three important constraints for media participation in social governance of food safety (39). Zhang et al. found

that reducing the cost of media supervision will not only stimulate the enthusiasm of consumers to complain, but also improve the efficiency of food safety supervision, so that food safety risks are kept at a low level for a long time (40). However, the media have the characteristics of timeliness and low cost and high income, which makes it difficult for them to fully understand the whole process of food events, and it is easy for them to report in a partial way (21, 41).

Online food trading platform

In the online food trading market, the online food trading platform is the bridge connecting food sellers and food buyers, and the main carrier of online food sales. Compared with the government, food sellers, food buyers, media, and other subjects, online food trading platforms have more advantages in information acquisition, collation, and analysis. They are direct participants in online food safety governance and have the rights and obligations to manage online food trading market (42, 43). Cheng and Dong pointed out that the online food trading platform should give play to its own advantages in technology, information and resources, take the initiative to undertake food seller information review, food information disclosure and other work, so as to ease the regulatory pressure of the government (44). Zhang et al. found that the daily supervision and management of online food trading platform on food safety is crucial to improve the level of food safety supervision on the platform (24). Although the online food trading platform can improve the supervision efficiency of the market, the lack of direct judicial punishment power and the market behavior of pursuing profit maximization will also make the platform "fail" in the process of online food safety governance (45). Therefore, in the online food trading market, it is necessary to strengthen the government's supervision on the platform and strengthen the platform's supervision responsibility (21).

Consumers

With the continuous occurrence of food safety incidents, consumers' safety awareness has gradually increased and participated in the governance of online food safety problems. Wang and Miao found that consumers' participation in supervision will affect the production decisions of food enterprises, and enterprises will eventually transform to producing high-quality products (46). Wang and Sha believed that consumers' education level and objective cognitive ability had a positive impact on online food safety risk prevention and control (47). Niu and Wu believed that the public should be encouraged to supervise and report, and the public interest litigation system and punitive compensation system should be established and improved (48). Zhu and Rong found that the increase of consumers' real evaluation and complaints about

rights protection can effectively promote manufacturers to provide high-quality products (49).

With the deepening of research, scholars found that the single subject regulation could not meet the needs of the rapid development of online food trading market. Therefore, it is very important to integrate the government, media, consumers, platforms, industry associations, and other subjects into the collaborative governance framework of online food safety through legalization, marketization, and other ways, and improve the collaborative governance capability through communication and cooperation (50, 51).

Game theory is a theory that uses rigorous mathematical models to study the optimal decision-making problem under the condition of conflict confrontation (52). In previous studies, Liu et al. built a signaling game model between online food trading platforms and sellers based on signaling game theory, and analyzed the formation conditions and results of different equilibria (53). Zhang et al. constructed a principal-agent model from the perspective of food sellers and food buyers, revealed the equilibrium evolution path of food quality and safety, and proved that the flooding of unsafe food in the market is the inevitable result of non-optimal equilibrium under the asymmetric information environment (23). Evolutionary game theory is a theory that combines game theory analysis with dynamic evolutionary process analysis. This method can help understand the dynamic process of group evolution, and explain why and how groups will reach this state. It has been widely used in management, economics, biology and many other fields (54). For example, in terms of environmental governance, Chu et al. built an evolutionary game model involving the central government, local governments and pollution enterprises, hoping to provide solutions for regional haze governance from the perspective of environmental regulation (55). In terms of online public opinion management, Wen constructed a game model for the evolution of online public opinion in colleges and universities involving the media, college students, universities and the government, and found that the main factors affecting the balance of the game system were the government's supervision, the willingness of online media to report, the attention of colleges and universities to public opinion events, and college students' self-awareness (56).

In recent years, scholars have also applied evolutionary game theory to online food safety governance. Liu constructed a static game payment matrix between the government and enterprises, and found that the combination of incentives and government supervision can effectively guide food enterprises to produce safe food (57). Xu et al. established an evolutionary game model involving suppliers and manufacturers, and found that the quality input strategy of food suppliers and manufacturers is closely related to the quality input-output ratio of both parties (58). Zhu and Sun built a tripartite evolutionary game model involving the government, food enterprises, and third-party testing institutions, and analyzed the interaction mechanism

of strategy choices among different actors and the evolution trend of each subject's strategy choices under different parameter changes (59). Wang et al. constructed an evolutionary game model of the behavior of the government and the seller involved in the platform supervision, and analyzed the strategies of the government and the seller under different supervision strengths of the platform (60). Cao et al. built a game model involving the government, the platform and the seller to discuss the collaborative supervision of the government and the platform on online food safety (61).

Therefore, this article constructs a tripartite evolutionary game model with the seller, buyer, and food trading platform, and analyzes the formation process and impact mechanism of the "lemon problem" in the online food trading market. The main contributions of this article are as follows: First, previous studies mainly analyzed online food safety from the theoretical level. However, this article focuses on the "lemon problem" in the online food trading market, and intuitively shows the formation process of the "lemon problem" in the online food trading market from the perspective of dynamic evolution, which can provide new evidence for the existence of the "lemon market." Second, previous studies mainly focused on the relationship between the government, food sellers, and food trading platforms in the online food trading market, and mostly used the government and food trading platforms to regulate the behavior of food sellers. However, as direct participants in food transactions, food buyers' behavior also has an important impact on the development and evolution of the market. Therefore, this article mainly analyzes the direct participants in the online food trading market, food sellers, food buyers, and food trading platforms, hoping to have a clearer understanding of the strategic choice of each subject. Third, previous studies mostly analyzed the conditions that affect the subject's strategic choice behavior, and emphasized the role of supervision, but rarely conducted a comprehensive and in-depth analysis of the factors that affect the subject's behavior. Therefore, based on the relevant conditions (stability conditions of evolutionary equilibrium) that affect the choice of the subject's strategy, this article conducts an in-depth analysis of the factors that affect the choice of the subject's strategy, and clarifies the extent and effect of different factors such as cost, punishment, subsidy, and income on each subject, which can provide a scientific basis for the online food trading platform and the government to formulate relevant institutional systems and policy measures.

Evolutionary game model in the online food trading market

Basic assumptions

Without considering the environment of online food trading market, it is assumed that seller, buyer, and online food

trading platform can constitute a complete online food trading market based on the functions of each subject in the market. Assuming that each participant is a finite rational individual with information asymmetry among them, the following assumptions are made for the tripartite subjects based on evolutionary game theory.

Game subject 1: Seller

With the rise of online food trading, the number of users participating in food transactions has gradually increased, and people's willingness and ability to pay has also grown, which will greatly promote the benefits of food seller. Under the supervision of the online food trading platform, the food seller will take initiative to provide quality products and services to the buyer in order to maintain user stickiness and attract more buyers. At the same time, with the development of online food trading market, the phenomenon of serious homogenization of products, unclear supply information, and uneven quality levels has become increasingly severe, and platforms problems such as high commissions (the platform will charge the seller a higher sales commission after the sale of products) and overbearing treaties (unfair treaties imposed on the seller and buyer by the platform to escape responsibility and obtain more benefits) have become increasingly prominent, which makes some sellers choose to provide low-quality products to obtain higher profits. Therefore, the seller's strategy in the online food trading market is {positive performance, negative performance}. Among them, the seller will provide the buyer with high-quality products when choosing "positive performance," and provide the buyer with low-quality products when choosing "negative performance." Suppose that the probability of the seller choose "positive performance" is x ($0 \leq x \leq 1$), the probability of choose "negative performance" is $1 - x$, where x is the function of time t , and the initial willingness of the seller is x_0 ($0 \leq x_0 \leq 1$). In the case of the seller choose negative performance, the production cost of food is C_1 . In the case of the seller choose positive performance, the seller would put more effort M into producing food, and the cost is $M + C_1$. In the case of the buyer choose positive participation, the basic benefit of the seller with positive performance is R_1 , and the basic benefit of the seller with negative performance is R_2 . In the case of the buyer choose negative participation, the basic benefit of the seller with positive performance is R_3 , and the basic benefit of the seller with negative performance is R_4 . When the online food trading platform choose "positive regulation," the seller with positive performance will receive extraneous benefit R_5 .

Game subject 2: Buyer

In the online food trading market, the seller provides the buyer with a diverse range of products. When buyer faces low-quality products, on the one hand, they will adopt various methods to safeguard their legitimate rights and interests, and on the other hand, they will adopt an indifferent attitude due to process, cost, their own knowledge level, and other reasons.

Furthermore, some buyers will release false information for personal benefit, and such speculative behavior will seriously affect the order of the online food trading market. Therefore, the buyer's strategy in the online food trading market is {positive participation, negative participation}. Among them, the buyer will participate in platform governance and maintain their rights when choosing "positive participation", and the buyer will not participate in platform governance when choosing "negative participation." Suppose that the probability of the buyer choose "positive participation" is y ($0 \leq y \leq 1$), and the probability of choose "negative participation" is $1 - y$, where y is the function of time t , and the initial willingness of the buyer is y_0 ($0 \leq y_0 \leq 1$). In the case of the seller choose positive performance, the basic benefit of the buyer is R_6 . In the case of the seller choose negative performance, the basic benefit of the buyer with negative participation is R_7 , and the basic benefit of the buyer with positive participation is $R_7 + N$. Among them, N is the punishment imposed by the buyer with positive participation on the seller with negative performance. When the buyer choose "positive participation," they need to identify the quality of food and take certain measures to defend their rights, which will require certain cost C_2 . When the online food trading platform choose "positive regulation," the buyer with positive participation will receive extraneous benefit R_8 .

Game subject 3: Online food trading platform

In the rapid development process of the online food trading market, the online food trading platform may invest a lot of resources to regulate the seller's behavior and audit the food quality. Meanwhile, in order to attract more sellers and reduce the operating cost of platform, the online food trading platform may take a laissez-faire attitude toward the speculative behavior of the seller. Therefore, the strategy of the online food trading platform is {positive regulation, negative regulation}. Among them, when the platform choose "positive regulation," they will manage the behavior of the seller and buyer, while when the platform choose "negative regulation," they will not respond to the behavior of the seller and buyer. Suppose that the probability of the platform choose "positive regulation" is z ($0 \leq z \leq 1$), the probability of choose "negative regulation" is $1 - z$, where z is the function of time t , and the initial willingness of the platform is z_0 ($0 \leq z_0 \leq 1$). In the case of positive regulation, the online food trading platform will give subsidies H to the seller with positive performance, and subsidies I to the buyer with positive participation, the platform will give punishment J to the seller with negative performance, and punishment K to the buyer with negative participation. When the online food trading platform choose "positive regulation," they will supervise the behavior of seller and buyer, which will incur certain regulation cost C_3 . In addition, when the seller choose "positive performance," the platform will receive the perceived benefit R_9 due to the improvement of reputation, user scale and brand value. And when the buyer choose "positive participation," the food trading platform will receive the perceived benefit R_{10} .

In the online food trading market, when food sellers provide low-quality products, buyers passively protect their rights, and online food trading platforms allow food sellers to speculate, there will be more and more low-quality food sellers in the market, and promote a large number of high-quality food sellers to leave the market. At this time, the phenomenon of “bad money drives out good money” will appear in the online food trading market, which is also known as the “lemon problem.” The formation process of the “lemon problem” in the online food trading market is shown in **Figure 1**, the relevant parameters and their meanings are shown in **Table 1**.

Construction of tripartite game model

Based on the above analysis assumptions, a benefit matrix of the tripartite game model is constructed with the seller, the buyer and the online food trading platform as the tripartite subjects. The benefits of all subjects under different scenarios are shown in **Table 2**. Among them, when the strategy of the seller, buyer and platform is {positive performance, positive participation, positive regulation}, the seller's benefit is $R_1 + R_5 + H - M - C_1$, the buyer's benefit is $R_6 + R_8 + I - C_2$, and the platform's benefit is $R_9 + R_{10} - H - I - C_3$.

When the seller, buyer and platform choose different strategies, they will get different benefits, as shown below.

Seller

The expected benefit when the seller choose “positive performance” is:

$$E_x = y(R_1 - R_3) + z(R_5 + H) + R_3 - M - C_1$$

The expected benefit when the seller choose “negative performance” is:

$$E_{1-x} = y(R_2 - N - R_4) - zJ + R_4 - C_1$$

The average expected benefit of the seller is:

$$\bar{E}_a = xE_x + (1-x)E_{1-x}$$

The replicator dynamic equation of the seller is:

$$U(x) = \frac{dx}{dt} = x(E_x - \bar{E}_a) = x(1-x)[y(R_1 + R_4 - R_2 - R_3 + N) + z(R_5 + H + J) + R_3 - R_4 - M]. \quad (1)$$

Buyer

The expected benefit when the buyer choose “positive participation” is:

$$E_y = x(R_6 - R_7 - N) + z(R_8 + I) + R_7 + N - C_2$$

The expected benefit when the buyer choose “negative participation” is:

$$E_{1-y} = x(R_6 - R_7) - zK + R_7$$

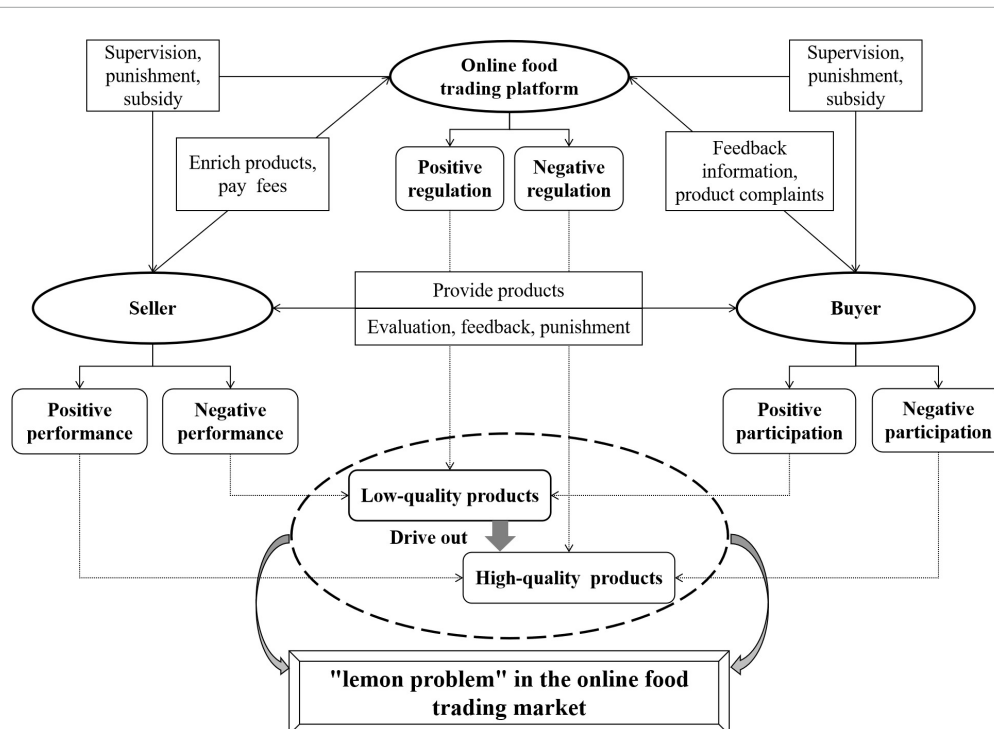


FIGURE 1
Formation process of the “lemon problem” in the online food trading market.

TABLE 1 Symbols and meanings of parameters.

Symbols	Description
M	Cost difference between positive performance and negative performance of the seller
N	Punishment from the buyer with positive participation to the seller with negative performance
H	Subsidy from the platform with positive regulation to the seller with positive performance
I	Subsidy from the platform with positive regulation to the buyer with positive participation
J	Punishment from the platform with positive regulation to the seller with negative performance
K	Punishment from the platform with positive regulation to the buyer with negative participation
R_1	Basic benefit of the seller with positive performance when the buyer choose positive participation
R_2	Basic benefit of the seller with negative performance when the buyer choose positive participation
R_3	Basic benefit of the seller with positive performance when the buyer choose positive participation
R_4	Basic benefit of the seller with negative performance when the buyer choose negative participation
R_5	Extraneous benefit of the seller with positive performance when the platform choose positive regulation
R_6	Basic benefit of the buyer when the seller choose positive performance
R_7	Basic benefit of the buyer with negative participation when the seller choose negative performance
R_8	Extraneous benefit of the buyer with positive participation when the platform choose positive regulation
R_9	Perceived benefit of the platform when the seller choose positive performance
R_{10}	Perceived benefit of the platform when the buyer choose positive participation
C_1	Input cost when the seller choose negative performance
C_2	Input cost when the buyer choose positive participation
C_3	Input cost when the platform choose positive regulation
x	Probability of the seller choose positive performance
y	Probability of the buyer choose positive participation
z	Probability of the platform choose positive regulation

The average expected benefit of the buyer is:

$$\bar{E}_b = yE_y + (1 - y)E_{1-y}$$

The replicator dynamic equation of the buyer is:

$$U(y) = \frac{dy}{dt} = y(E_y - \bar{E}_b) = y(1 - y)[z(R_8 + I + K) + N(1 - x) - C_2]. \quad (2)$$

Online food trading platform

The expected benefit when the online food trading platform choose “positive regulation” is:

$$E_z = x(R_9 - H - J) + y(R_{10} - I - K) + J + K - C_4$$

TABLE 2 Benefit matrix of the tripartite game of seller, buyer, and platform.

Seller	Buyer	Online food trading platform	
		Positive regulation _z	Negative regulation _{1-z}
Positive performance x	Positive participation y	$R_1 + R_5 + H - M - C_1$ $R_6 + R_8 + I - C_2$ $R_9 + R_{10} - H - I - C_3$	$R_1 - M - C_1$ $R_6 - C_2$ $R_9 + R_{10}$
	Negative participation $1 - y$	$R_3 + R_5 + H - M - C_1$ $R_6 - K$ $R_9 + K - H - C_3$	$R_3 - M - C_1$ R_6 R_9
	Negative performance $1 - x$	$R_2 - N - J - C_1$ $R_7 + R_8 + N + I - C_2$ $R_{10} + J - I - C_3$	$R_2 - N - C_1$ $R_7 + N - C_2$ R_{10}
	Negative participation $1 - y$	$R_4 - J - C_1$ $R_7 - K$ $J + K - C_3$	$R_4 - C_1$ R_7 0

The expected benefit when the online food trading platform choose “negative regulation” is:

$$E_{1-z} = xR_9 + yR_{10}$$

The average expected benefit of the online food trading platform is:

$$\bar{E}_c = zE_z + (1 - z)E_{1-z}$$

The replicator dynamic equation of the online food trading platform is:

$$U(z) = \frac{dz}{dt} = z(E_z - \bar{E}_c) = z(1 - z)[x(-H - J) + y(-I - K) + J + K - C_3]. \quad (3)$$

Stability analysis

By combining Formulae 1–3, the replicator dynamic system of the online food trading market can be obtained.

$$\begin{cases} U(x) = x(1 - x)[y(R_1 + R_4 - R_2 - R_3 + N) + z(R_5 + H + J) + R_3 - R_4 - M] \\ U(y) = y(1 - y)[z(R_8 + I + K) + N(1 - x) - C_2] \\ U(z) = z(1 - z)[x(-H - J) + y(-I - K) + J + K - C_3] \end{cases} \quad (4)$$

When $U(x) = 0 \cap U(y) = 0 \cap U(z) = 0$ in Formula 4, the equilibrium points of the replicator dynamic system can be obtained: $E_1(0,0,0)$, $E_2(0,0,1)$, $E_3(0,1,0)$, $E_4(0,1,1)$, $E_5(1,0,0)$, $E_6(1,0,1)$, $E_7(1,1,0)$, $E_8(1,1,1)$, and $E_9(x^*, y^*, z^*)$. In Su et al. (62), Xiao et al. (63), and other studies, scholars believe that the Evolutionary Stable Strategy (ESS) of the multi group evolutionary game must also be a pure strategy Nash equilibrium, that is, in an asymmetric game, the mixed strategy equilibrium must not be an evolutionary stability

equilibrium. Therefore, this article will only analyze eight pure strategy equilibrium points, that is, do not discuss $E_9(x^*, y^*, z^*)$. The stability of each equilibrium point in the tripartite evolutionary game can be determined according to the Lyapunov stability theory, that is, when the replicator dynamic system is evolutionary stable, the eigenvalue of its Jacobian matrix is negative (64).

By calculating the partial derivatives of $U(x)$, $U(y)$ and $U(z)$ for x , y , and z , respectively, the Jacobian matrix of replicator dynamic system of online food trading market can be obtained. The eigenvalues can be calculated by substituting the values of x , y , and z at each equilibrium point into Formula 5. For example, the eigenvalues of $E_1(0,0,0)$ is $\lambda_1 = R_3 - R_4 - M$, $\lambda_2 = N - C_2$, $\lambda_3 = J + K - C_3$. The eigenvalues of each equilibrium point are shown in Table 3.

$$J = \begin{bmatrix} (1-2x) \left[\begin{array}{l} y(R_1 + R_4 - R_2 - R_3 + N) + \\ z(R_5 + H + J) + R_3 - R_4 - M \end{array} \right] & & \\ -y(1-y)N & & \\ z(1-z)(-H-J) & & \\ x(1-x)(R_1 + R_4 - R_2 - R_3 + N) & & \\ (1-2y) \left[\begin{array}{l} z(R_8 + I + K) + \\ N(1-x) - C_2 \end{array} \right] & & \\ z(1-z)(-I-K) & & \\ x(1-x)(R_5 + H + J) & & \\ y(1-y)(R_8 + I + K) & & \\ (1-2z) \left[\begin{array}{l} x(-H-J) + y(-I \\ -K) + J + K - C_3 \end{array} \right] & & \end{bmatrix} \quad (5)$$

For each equilibrium point, if its eigenvalues λ_1 , λ_2 , λ_3 are all negative, then it is the evolutionary stable point of the system. According to the actual operation of the online food trading market, $C_2 > 0$ and $H + I + C_3 > 0$ can be known by analyzing the equilibrium points. That is to say, the two equilibrium

TABLE 3 Eigenvalues of equilibrium point.

Equilibrium point	λ_1	λ_2	λ_3
$E_1(0,0,0)$	$R_3 - R_4 - M$	$N - C_2$	$J + K - C_3$
$E_2(0,0,1)$	$R_5 + H + J$ $+ R_3 - R_4 - M$	$R_8 + I + K + N - C_2$	$-(J + K - C_3)$
$E_3(0,1,0)$	$R_1 + N - R_2 - M$	$-(N - C_2)$	$J - I - C_3$
$E_4(0,1,1)$	$R_1 + R_5 - R_2 + N$ $+ H + J - M$	$-(R_8 + I + K$ $+ N - C_2)$	$-(J - I - C_3)$
$E_5(1,0,0)$	$-(R_3 - R_4 - M)$	$-C_2$	$K - H - C_3$
$E_6(1,0,1)$	$-(R_5 + H + J$ $+ R_3 - R_4 - M)$	$R_8 + I + K - C_2$	$-(K - H - C_3)$
$E_7(1,1,0)$	$-(R_1 + N - R_2 - M)$	C_2	$-H - I - C_3$
$E_8(1,1,1)$	$-(R_1 + R_5 - R_2$ $+ N + H + J - M)$	$-(R_8 + I + K - C_2)$	$H + I + C_3$

TABLE 4 Asymptotical stability conditions for the replicator dynamic system at equilibrium points.

Equilibrium point	Asymptotical stability conditions	Number
$E_1(0,0,0)$	$R_3 - R_4 - M < 0, N - C_2 < 0, J + K - C_3 < 0$	①
$E_2(0,0,1)$	$R_5 + H + J + R_3 - R_4 - M < 0,$ $R_8 + I + K + N - C_2 < 0, -(J + K - C_3) < 0$	②
$E_3(0,1,0)$	$R_1 + N - R_2 - M < 0, -(N - C_2) < 0,$ $J - I - C_3 < 0$	③
$E_4(0,1,1)$	$R_1 + R_5 - R_2 + N + H + J - M < 0,$ $-(R_8 + I + K + N - C_2) < 0, -(J - I - C_3) < 0$	④
$E_5(1,0,0)$	$-(R_3 - R_4 - M) < 0, -C_2 < 0, K - H - C_3 < 0$	⑤
$E_6(1,0,1)$	$-(R_5 + H + J + R_3 - R_4 - M) < 0,$ $R_8 + I + K - C_2 < 0, -(K - H - C_3) < 0$	⑥

points $E_7(1,1,0)$ and $E_8(1,1,1)$ are unstable. If it is to achieve the evolution stability, the asymptotical stability of equilibrium points $E_1(0,0,0)$, $E_2(0,0,1)$, $E_3(0,1,0)$, $E_4(0,1,1)$, $E_5(1,0,0)$, and $E_6(1,0,1)$ need to be analyzed. The asymptotical stability conditions for each equilibrium point are shown in Table 4.

According to Table 4, we can know that many factors, such as the seller's benefit, the seller's cost, the buyer's cost, the platform's cost, the platform's subsidy and punishment to the seller, the platform's subsidy and punishment to the buyer, and the buyer's punishment to the seller, will affect the eigenvalues of each equilibrium point. The stability of each equilibrium point in the asymptotic stability conditions ①–⑥ will be analyzed below (Table 5).

According to Table 5, under each asymptotic stability condition, there may be multiple equilibrium points in the replicator dynamic system. Specific conditions are as follows:

In the case of condition ①, except that E_1 is the stable point of the Jacobian matrix of the replicator dynamic system, other equilibrium points are all unstable points. At this time, {negative performance, negative participation, negative regulation} is the evolutionary stability point of the system.

In the case of condition ②, there is only E_2 as a stable point in the system. At this time, {negative performance, negative participation, positive regulation} is the evolutionary stability point of the system.

In the case of condition ③, E_3 is the stable point, that is, {negative performance, active participation, negative regulation} is the evolutionary stable point of the system. In addition, the stability of E_5 and E_6 is uncertain. The specific conditions are as follows: When conditions ③ and ⑤ are met simultaneously, E_3 and E_5 are stable points and E_6 is unstable point. When conditions ③ and ⑥ are met simultaneously, E_3 and E_6 are stable points and E_5 is unstable point. In general, under condition ③, there are at most two stable points in the system.

In the case of condition ④, E_4 is the stable point, and the stability of E_5 and E_6 is uncertain. The specific conditions are as follows: When conditions ④ and ⑤ are met simultaneously, E_4 and E_5 are stable points and E_6 is unstable point. When

TABLE 5 Stability of each equilibrium point under each asymptotic stability condition.

		E_1	E_2	E_3	E_4	E_5	E_6
①	Plus or minus	—	?? +	? + —	?? +	+ —	?? +
	Stability	ESS	Unstable	Unstable	Unstable	Unstable	Unstable
②	Plus or minus	— +	—	? + ?	? + ?	+ — ?	+ — ?
	Stability	Unstable	ESS	Unstable	Unstable	Unstable	Unstable
③	Plus or minus	? + ?	? + ?	—	? — +	? — ?	?? ?
	Stability	Unstable	Unstable	ESS	Unstable	Uncertain	Uncertain
④	Plus or minus	?? +	? + ?	— ? +	—	? — ?	?? ?
	Stability	Unstable	Unstable	Unstable	ESS	Uncertain	Uncertain
⑤	Plus or minus	+ ? ?	+ ? ?	?? ?	?? ?	—	— ? +
	Stability	Unstable	Unstable	Unstable	Uncertain	ESS	Unstable
⑥	Plus or minus	?? +	+ ? ?	?? ?	?? ?	? — +	—
	Stability	Unstable	Unstable	Uncertain	Uncertain	Unstable	ESS

conditions ④ and ⑥ are met simultaneously, E_4 and E_6 are stable points and E_5 is unstable point. In general, under condition ④, there are at most two stable points in the system.

In the case of condition ⑤, E_5 is the stable point, and the stability of E_3 and E_4 is uncertain. The specific conditions are as follows: When conditions ⑤ and ③ are met simultaneously, E_5 and E_3 are stable points and E_4 is unstable point. When conditions ⑤ and ④ are met simultaneously, E_5 and E_4 are stable points and E_3 is unstable point. In general, under condition ⑤, there are at most two stable points in the system.

In the case of condition ⑥, E_6 is the stable point, and the stability of E_3 and E_4 is uncertain. The specific conditions are as follows: When conditions ⑥ and ③ are met simultaneously, E_6 and E_3 are stable points and E_4 is unstable point. When conditions ⑥ and ④ are met simultaneously, E_6 and E_4 are stable points and E_3 is unstable point. In general, under condition ⑥, there are at most two stable points in the system.

By analyzing the stability of the equilibrium points in the asymptotical stability conditions ①–⑥, it can be found that there may be multiple stable points in the replicator dynamic system under various asymptotic stability conditions. Specifically, when condition ① or condition ② is met, there will be only one stable point in the system. When condition ③ and ⑤, ③ and ⑥, ④ and ⑤, ④ and ⑥ are met respectively, there will be two stable points in the system.

The formation and evolution of the “lemon problem” in the online food trading market

Parameter setting

For different sellers, buyers and online food trading platforms, the initial strategic choice behavior may be affected in many ways and show some differences. In order to avoid

this impact, this article refers to the method of setting the initial value of the system in the previous evolutionary game analysis (65), and sets the initial willingness of each subject to low, medium, and high levels, that is $x_0, y_0, z_0 \in \Omega(0.2, 0.5, 0.8)$. By combining the initial willingness of the three subjects, 27 different scenarios can be obtained. For the convenience of comparison, the following only explores the cases where the initial willingness of each subject are consistent.

In the process of assigning values to each variable, first, we set the variable parameters according to the stability of condition ①, that is, each variable needs to meet $R_3 - R_4 - M < 0, N - C_2 < 0, J + K - C_3 < 0$ at the same time. After constant debugging, we finally determined the parameters of condition ①. Then, for the convenience of exploring the changing situation of each subject in the online food trading market, this article takes the condition ① as the base, with reference to the actual operating structure and interest relationship of the online food trading market, and assign values for variables ①, ②, ③, ④, ⑤, ⑥, ③ and ⑤, ③ and ⑥, ④ and ⑤, and ④ and ⑥ for different situations. For example, for condition ②, it is difficult to satisfy $R_5 + H + J + R_3 - R_4 - M < 0, R_8 + I + K + N - C_2 < 0, -(J + K - C_3) < 0$ by substituting the variable parameters in condition ①. To this end, it is necessary to compare the difference between condition ① and condition ②, and adjust on the basis of the relevant parameters of condition ①. It is found by comparison that: condition ② can be met when M, C_2 , and C_3 are adjusted, condition ③ can be met when M and N are adjusted, condition ④ can be met when M and J are adjusted, condition ⑤ can be met when R_3 is adjusted, condition ⑥ can be met when K and C_2 are adjusted, condition ③ and ⑤ can be met when M, N, C_2 , and R_3 are adjusted, condition ③ and ⑥ can be met when M, N, K, C_2 , and R_3 are adjusted, condition ④ and ⑥ can be met when M, J , and R_3 are adjusted, condition ③ and ⑥ can be met when M, N, J, K, C_2 , and R_3 are adjusted. The

specific assignment of each variable under different conditions is shown in **Table 6**.

Simulation analysis

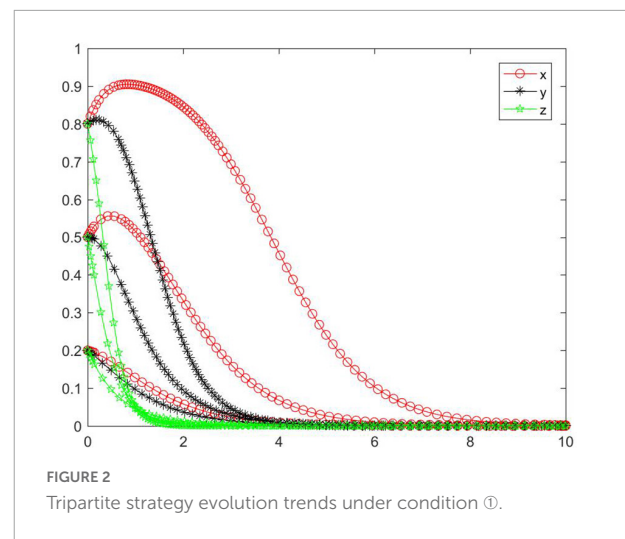
In the online food trading market, many conditions will occur if the system is to reach evolutionary stable equilibrium. The following simulates and analyzes the strategic choice behaviors of each subject under different conditions.

Simulation analysis under asymptotical stability condition ①

In the case of condition ①, the strategy of the tripartite subjects will eventually stabilize in {negative performance, negative participation, negative regulation} (**Figure 2**). In the case of condition ①, the strategy tend of platform will rapidly reach a negative state, while the seller and buyer will reach a negative state relatively slowly. As the initial willingness increases, the speed and probability of each subject evolving to a negative state gradually decrease. With medium and high initial willingness, the seller's strategy will first evolve to a positive state and then to a negative state, and the higher the initial willingness, the more obvious the seller's evolving trend will be toward a positive state. Combined with condition ①, we can know that M , N , J , K , C_2 , C_3 , and R_4 will have an impact on the strategic choice behavior of all subjects, and the initial willingness will promote all subjects to choose positive strategy to a certain extent.

Simulation analysis under asymptotical stability condition ②

In the case of condition ②, the strategy of the tripartite subjects will eventually stabilize in {negative performance, negative participation, positive regulation} (**Figure 3**). In the case of condition ②, the strategy of the seller and buyer will rapidly evolve to a negative state, and the lower the initial willingness, the greater the speed and probability of the subject evolving to a negative state. For the online food trading



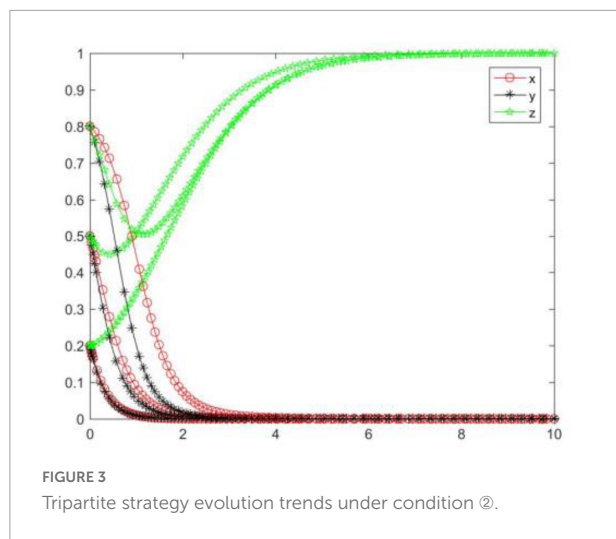
platform, its strategy will evolve to a negative state first and then to a positive state, and the higher the initial willingness, the more obvious the trend of the platform evolving toward a negative state. Combining conditions ① and ②, we can know that M , N , H , I , J , K , C_2 , C_3 , R_3 , and R_4 will have an impact on the strategic choice behavior of all subjects, and the change of M , C_2 , and C_3 will promote the platform's strategy to stabilize in a positive state.

Simulation analysis under asymptotical stability condition ③

In the case of condition ③, the strategy of the tripartite subjects will eventually stabilize in {negative performance, positive participation, negative regulation} (**Figure 4**). In the case of condition ③, the strategy of the platform will rapidly evolve to a negative state, and the lower the initial willingness, the greater the speed and probability of the subject evolving to a negative state. The seller evolves relatively slowly toward a negative state. In the case with high initial willingness, the seller also has a tendency to evolve to a positive state. The buyer's strategy will evolve toward a positive state. In the case

TABLE 6 Variable assignment in the online food trading market.

Conditions	M	N	H	I	J	K	C_2	C_3	R_1	R_2	R_3	R_4	R_5	R_8
①	2	1	1	1	1	1	2	3	22	21	2	1	1	1
②	5	1	1	1	1	1	5	1	22	21	2	1	1	1
③	5	3	1	1	1	1	2	3	22	21	2	1	1	1
④	10	1	1	1	5	1	2	3	22	21	2	1	1	1
⑤	2	1	1	1	1	1	2	3	22	21	4	1	1	1
⑥	2	1	1	1	1	5	8	3	22	21	2	1	1	1
③ and ⑤	4	2	1	1	1	1	1	3	22	21	6	1	1	1
③ and ⑥	11	9	1	1	1	5	8	3	22	21	10	1	1	1
④ and ⑤	10	1	1	1	5	1	2	3	22	21	12	1	1	1
④ and ⑥	11	2	1	1	5	5	8	3	22	21	6	1	1	1



with medium initial willingness, the speed and probability of the buyer evolving to a positive state are greater, followed by low initial willingness. And with high initial willingness, the buyer is the slowest to evolve to a positive state, and its strategy will fluctuate to a certain degree in the early period. Combining conditions ① and ③, we can know that $M, N, I, J, K, C_2, C_3, R_1$, and R_2 will have an impact on the strategic choice behavior of all subjects, and the change of M and N will promote the buyer's strategy to stabilize in a positive state.

Simulation analysis under asymptotical stability condition ④

In the case of condition ④, the strategy of the tripartite subjects will eventually stabilize in {negative performance, positive participation, positive regulation} (Figure 5). In the case of condition ④, the seller's strategy will quickly evolve to a negative state, and the lower the initial willingness, the greater the speed and probability that the subject tends to reach a negative state. The strategy of the buyer and platform gradually evolve to a positive state. With increasing initial willingness, the speed and probability of the buyer evolving to a positive state gradually increase, while the speed and probability of the platform evolving to a positive state gradually decrease. Combining conditions ① and ④, we can know that $M, N, H, I, J, K, C_2, C_3, R_1, R_2, R_5$, and R_8 will have an impact on the strategic choice behavior of all subjects, and the change of M and J can promote the strategy of the buyer and platform to be stable in a positive state.

Simulation analysis under asymptotical stability condition ⑤

In the case of condition ⑤, the strategy of the tripartite subjects will eventually stabilize in {positive performance, negative participation, negative regulation} (Figure 6). In the case of condition ⑤, the strategy of the buyer and platform gradually evolves to a negative state, and the lower the initial

willingness, the higher the speed and probability of the subject evolving toward a negative state. The seller's strategy gradually evolves to a positive state, and the higher the initial willingness, the faster and more likely the subject evolves to a positive state. Combining conditions ① and ⑤, we can know that M, H, K, C_2, C_3, R_3 , and R_4 will have an impact on the strategic choice behavior of all subjects, and the change of R_3 will promote the seller's strategy to stabilize in a positive state.

Simulation analysis under asymptotical stability condition ⑥

In the case of condition ⑥, the strategy of the tripartite subjects will eventually stabilize in {positive performance, negative participation, positive regulation} (Figure 7). In the case of condition ⑥, the buyer's strategy quickly evolves to a negative state, and the lower the initial willingness, the greater the speed and probability of the subject evolving toward a negative state. The strategy of the seller and the platform gradually evolve to a positive state. With the increase of initial willingness, the speed and probability of the seller's strategy evolving to a positive state gradually increase, while the speed and probability of the online food trading platform evolving to a positive state gradually decrease. Combining conditions ① and ⑥, we can know that $M, H, I, J, K, C_2, C_3, R_3, R_4, R_5$, and R_8 will have an impact on the strategic choice behavior of all subjects, and the change of K and C_2 can promote the strategy of the seller and the platform to be stable in a positive state.

Simulation analysis under asymptotical stability conditions ③ and ⑤

In the cases of conditions ③ and ⑤, the strategy of the tripartite subjects will eventually stabilize in {negative performance, positive participation, negative regulation} and {positive performance, negative participation, negative regulation} (Figure 8). It can be seen that, in the cases of conditions ③ and ⑤, the strategy of the online food trading platform rapidly evolves to a negative state, and the lower the initial willingness, the higher the speed and probability of the subject evolving toward a negative state. The strategy of the seller and the buyer diverge as the system evolves. In the case of low and high initial willingness, the seller's strategy is eventually positive, and the buyer's strategy is negative; when the initial willingness is medium, the seller's strategy evolves to be at a negative state, and the buyer's strategy evolves to a positive state. Combining conditions ① and ③, ⑤, we can know that $M, N, H, I, J, K, C_2, C_3, R_1, R_2, R_3, R_4$ will have an impact on the strategic choice behavior of all subjects, and the change of M, N, C_2 , and R_3 can promote the strategy of the seller and the buyer to be stable in different states.

Simulation analysis under asymptotical stability conditions ③ and ⑥

In the cases of conditions ③ and ⑥, the strategy of the tripartite subjects will eventually stabilize in {negative

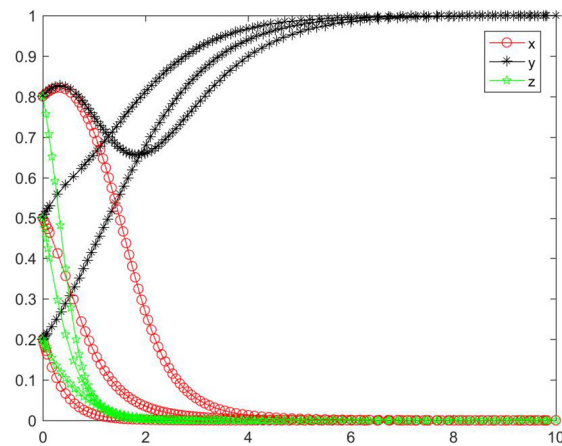


FIGURE 4
Tripartite strategy evolution trends under condition ③.

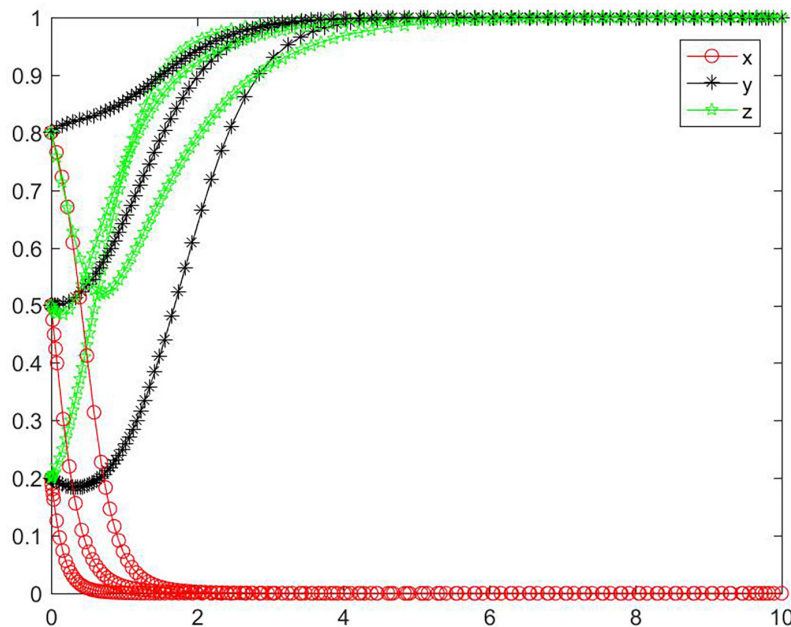


FIGURE 5
Tripartite strategy evolution trends under condition ④.

performance, positive participation, negative regulation} and {positive performance, negative participation, positive regulation} (Figure 9). When the initial willingness is low and medium, the strategy of the seller and the platform evolve to a negative state, and the buyer's strategy evolves to a positive state. When the initial willingness is high, the strategy of the seller and the online food trading platform evolves to a positive state, and the buyer's strategy evolves to a negative state. Combining conditions ① and ③, ⑥, we can know that M , N , H , I , J , K , C_2 , C_3 , R_1 , R_2 , R_3 , R_4 , R_5 , and R_8 will have an impact on the strategic choice behavior

of all subjects, and the change of M , N , K , C_2 , and R_3 can promote the strategy of seller, buyer and platform to be stable in different states.

Simulation analysis under asymptotical stability conditions ④ and ⑤

In the cases of conditions ④ and ⑤, the strategy of the tripartite subjects will eventually stabilize in {negative performance, positive participation, positive regulation} and {positive performance, negative participation, negative regulation} (Figure 10). When the initial willingness is low and

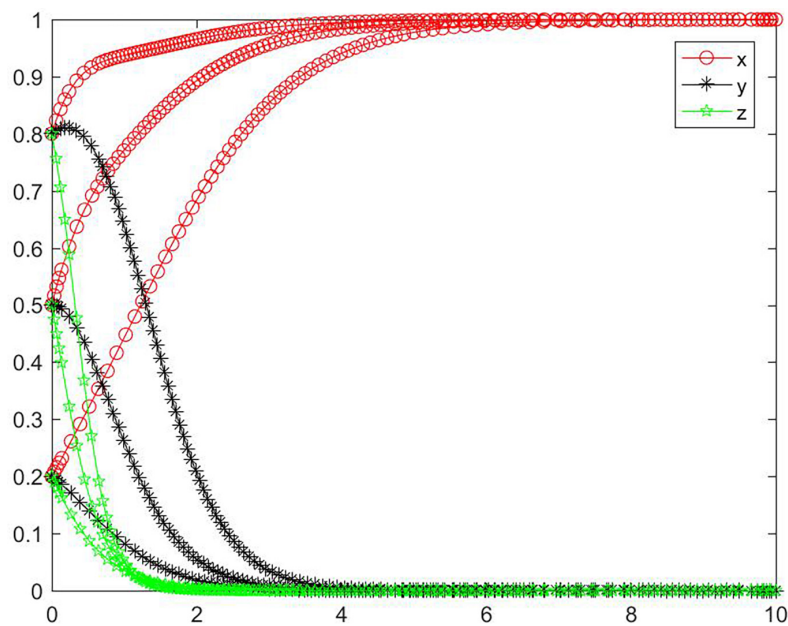


FIGURE 6
Tripartite strategy evolution trends under condition ⑤.

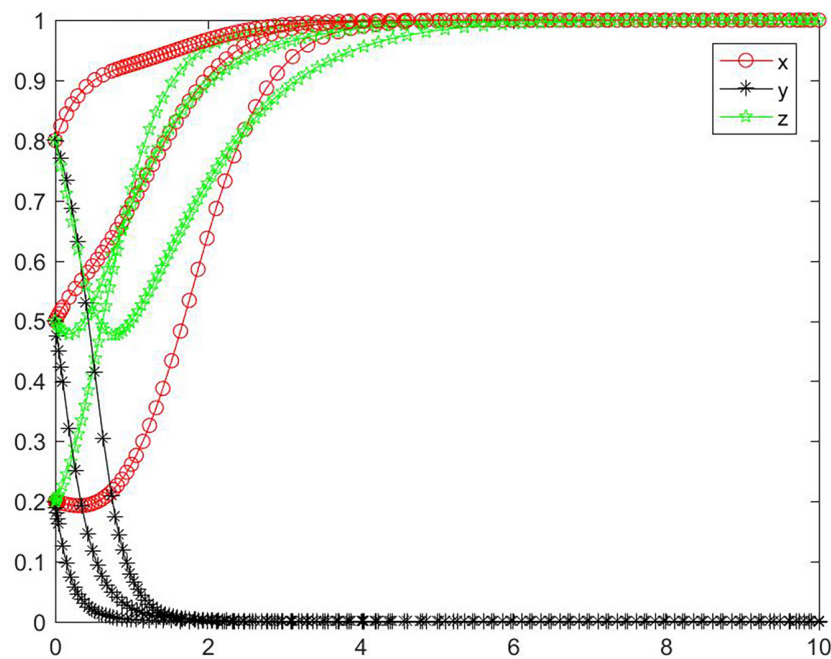


FIGURE 7
Tripartite strategy evolution trends under condition ⑥.

medium, the strategy of the seller evolve to a positive state, and the strategy of the buyer and the platform evolve to a negative state. When the initial willingness is high, the strategy of the buyer and the platform evolve to a positive state, and the seller's strategy evolves to a negative state. Combining conditions ①

and ④, ⑤, we can know that M , N , H , I , J , K , C_2 , C_3 , R_1 , R_2 , R_3 , R_4 , R_5 , and R_8 will have an impact on the strategic choice behavior of all subjects, and the change of M , J , and R_3 can promote the strategy of seller, buyer and platform to be stable in different states.

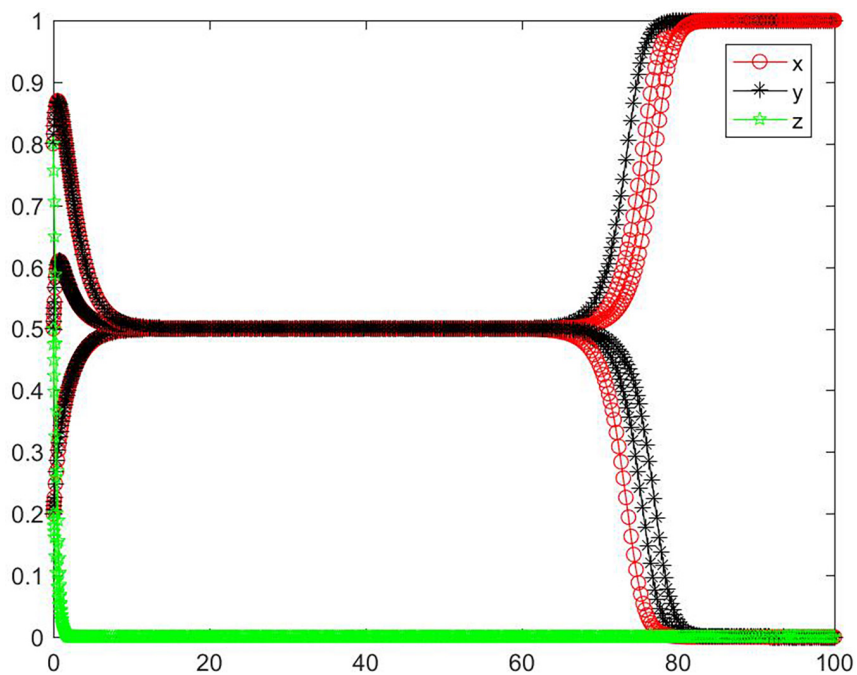


FIGURE 8
Tripartite strategy evolution trends under conditions ③ and ⑤.

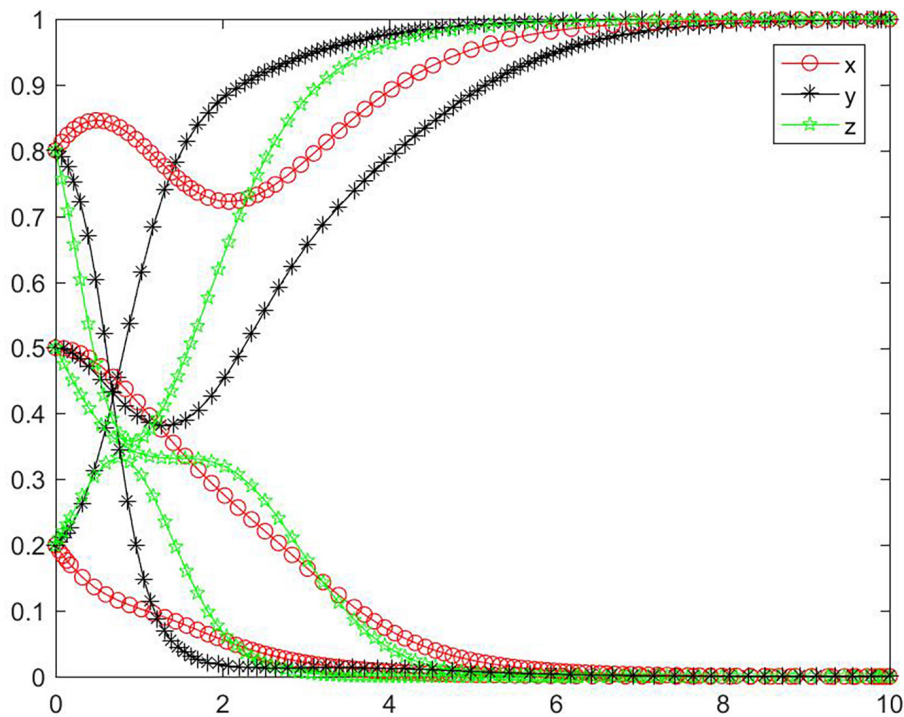


FIGURE 9
Tripartite strategy evolution trends under conditions ③ and ⑥.

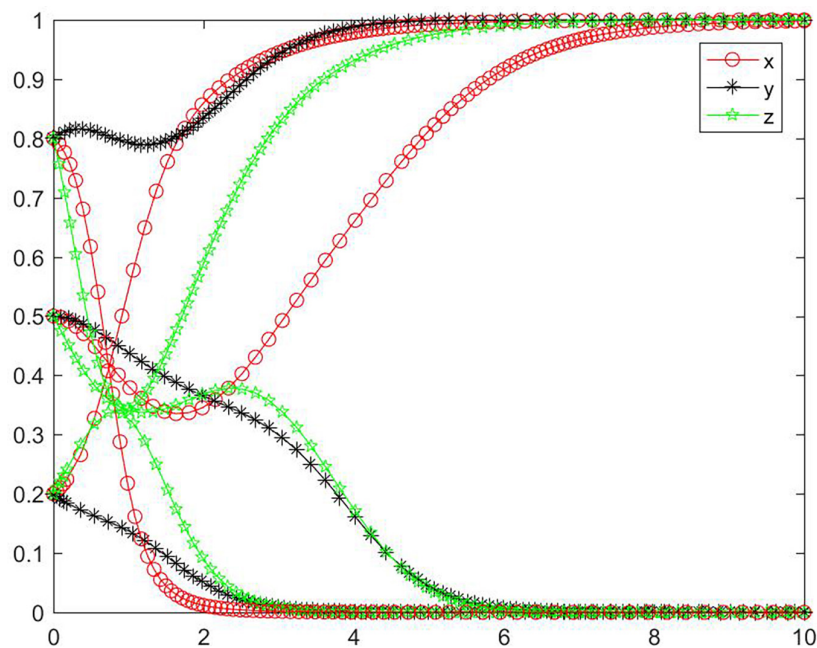


FIGURE 10
Tripartite strategy evolution trends under conditions ④ and ⑤.

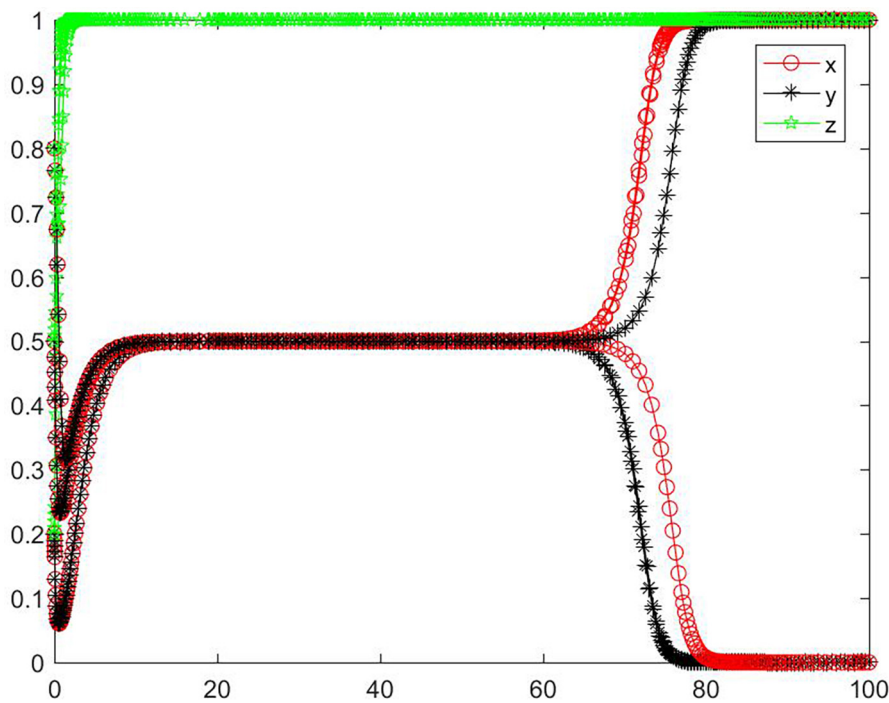


FIGURE 11
Tripartite strategy evolution trends under conditions ④ and ⑥.

Simulation analysis under asymptotical stability conditions ④ and ⑥

In the cases of conditions ④ and ⑥, the strategy of the tripartite subjects will eventually stabilize in {negative performance, positive participation, positive regulation} and {positive performance, negative participation, positive regulation} (Figure 11). When the initial willingness is low and medium, the strategy of the seller and the platform evolve to a positive state, and the buyer's strategy evolves to a negative state. When the initial willingness is high, the strategy of the buyer and the online food trading platform evolve to a positive state, and the seller's strategy evolves to a negative state. Combining conditions ① and ④, ⑥, we can know that M , N , H , I , J , K , C_2 , C_3 , R_1 , R_2 , R_3 , R_4 , R_5 , and R_8 will have an impact on the strategic choice behavior of all subjects, and the change of M , N , J , K , C_2 , and R_3 can promote the strategy of the platform to be stable in a positive state, and promote the strategy of seller and buyer to be stable in different states.

Analysis of the formation mechanism of the “lemon problem” in the online food trading market

Under different conditions, the strategy of seller, buyer, and platform in the online food trading market will eventually stabilize in six situations.

In the cases of {negative performance, negative participation, negative regulation}, {negative performance, negative participation, positive regulation}, {negative performance, positive participation, negative regulation}, {negative performance, positive participation, positive regulation}, the seller will eventually choose negative strategy. That is to say, with the development of the online food trading market, more and more sellers on the market will choose to

provide low-quality products, and the seller who choose to provide high-quality products will gradually be crowded out of the market, eventually leading to the “lemon problem” in the online food trading market.

In the case of {positive performance, negative participation, negative regulation}, the seller will eventually choose positive strategy, the buyer and the platform will choose negative strategy. Although the seller will choose positive strategy in this case, satisfying this scenario requires that the benefits the seller adopts positive strategy obtains are far greater than those of the seller adopting negative strategy. In actual situations, when the buyer and the online food trading platform choose negative strategy, the seller may obtain higher benefits from providing low-quality products.

In the case of {positive performance, negative participation, positive regulation}, the seller and the platform will choose positive strategy, while the buyer will choose negative strategy. However, in order to meet this scenario, it will be more costly for the buyer to positively participate, and the platform will also have to impose severer punishment on negative buyer. In reality, the cost of for buyer with positive participation is relatively low, and the platform is more to encourage buyer to choose negative performance than to impose higher punishment on the buyer. Because high punishment will cause a large number of buyer withdraw from the market, and make the entire online food trading market disappear.

In general, during the development and evolution of the online food trading market, the “lemon problem” will occur and will not disappear. To solve the “lemon problem” in the online food trading market, it is necessary to analyze the factors affecting the development and evolution of the online food trading market and formulate the corresponding measures to suppress and reduce the occurrence of the “lemon problem.”

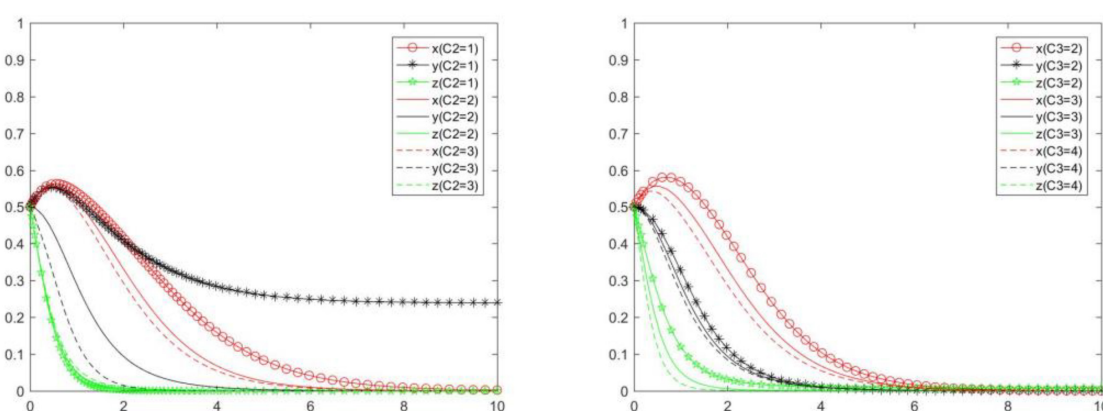


FIGURE 12
Tripartite strategy evolution trends when C_2 and C_3 change.

Influencing factors analysis of the “lemon problem” in the online food trading market

Through the analysis of asymptotical stability conditions ①–⑥, it is found that the strategy of each subject in the online food trading market will be affected by variables like M , N , H , I , J , K , C_2 , C_3 , R_1 , R_2 , R_3 , R_4 , R_5 , and R_8 . In the above research, we only analyzed the changes of each subject's strategic behavior under the common changes of multiple factors. In order to analyze the strategy choice behavior of each subject in depth and find the core elements that affect the strategy change of each subject, this article makes specific analyses of the factors on the basis of asymptotical stability condition ①.

Cost of positive strategy

In order to explore the influence of C_2 and C_3 on the choice of each subject's strategy, we will analyze the evolution law of each subject's strategy under scenarios $\{C_2 = 1, C_2 = 2, C_2 = 3\}$, $\{C_3 = 2, C_3 = 3, C_3 = 4\}$. Compare and analyze the

evolution law of each subject's strategy when C_2 and C_3 change (Figure 12). We can know the following.

When C_2 changes, the strategies of the seller and buyer will change significantly, and the platform will change little. Specifically, with the increase of C_2 , the probability and speed of the seller and buyer to choose positive strategy will gradually decrease, and the probability and speed of the platform to choose positive strategy will gradually increase. In other words, C_2 will have a negative impact on the positive strategy choice of the seller and the buyer, and will have a positive impact on the positive strategy choice of the online food trading platform. The reason is that if a large amount of investment cannot be exchanged for the same or more benefits, the buyer's enthusiasm for participating in market governance and rights protection will also be greatly reduced. The reduction of the buyer's willingness to defend their rights will reduce the supervision of the seller's behavior and make them tend to choose negative strategy. At this time, in order to maintain market order and retain more users, the food trading platform will choose positive strategy.

When C_3 changes, the strategies of the seller, buyer, and platform will change to some extent. Specifically, with the increase of C_3 , the probability and speed of the seller, buyer, and platform to choose positive strategy will gradually decrease.

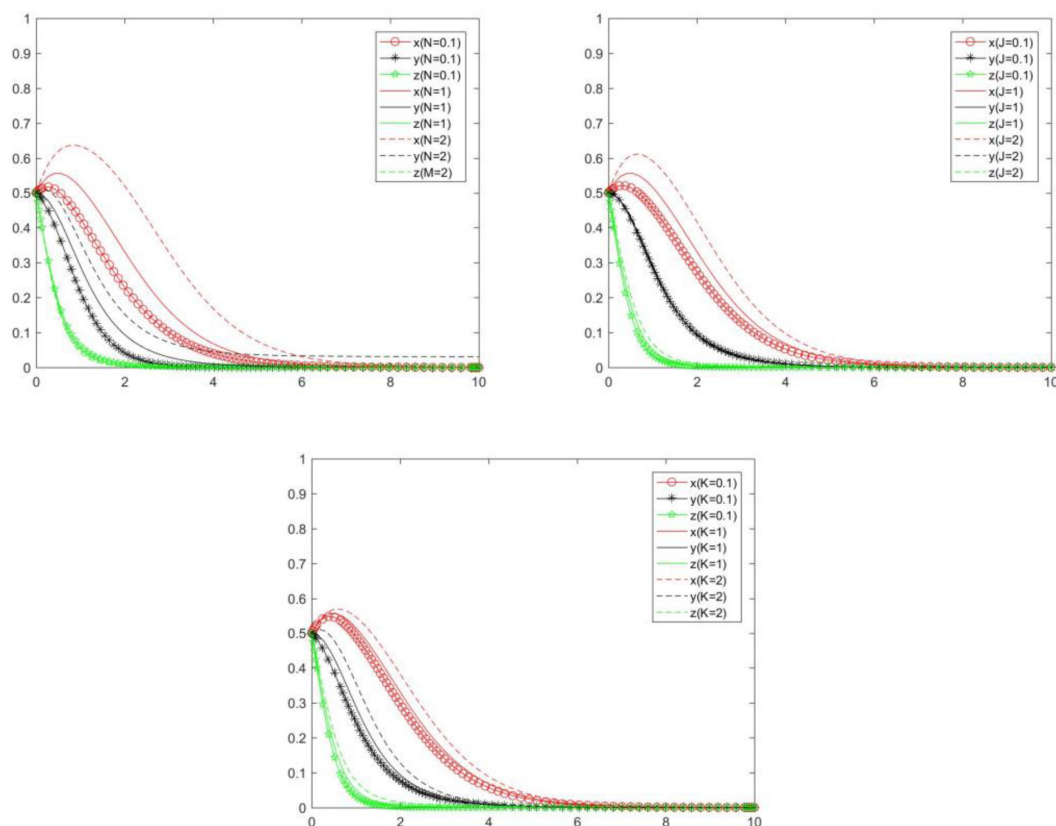


FIGURE 13
Tripartite strategy evolution trends when N , J , and K change.

In other words, C_3 will have a negative impact on the positive strategy choice of the seller, buyer, and platform. The reason is that when the platform increases the regulation cost, it will restrict the behavior of the seller and buyer from many aspects, and will transfer the cost to the seller and buyer, which will reduce the enthusiasm of the seller and buyer and drive them to withdraw from the online food trading market.

Punishment of positive strategy

In order to explore the influence of N , J , and K on the choice of each subject's strategy, we will analyze the evolution law each subject's strategy under scenarios $\{N = 0.1, N = 1, N = 2\}$, $\{J = 0.1, J = 1, J = 2\}$, $\{K = 0.1, K = 1, K = 2\}$. Compare and analyze the evolution law of each subject's strategy when N , J , and K change (Figure 13). We can know the following.

When N changes, the strategies of the seller and buyer will change significantly, and platform will change slightly. Specifically, with the increase of N , the probability and speed of the seller and buyer to choose positive strategy will gradually increase, and the probability and speed of the platform to choose

positive strategy will gradually decrease. In other words, N will have a positive impact on the positive strategy choice of the seller and buyer, and will have a negative impact on the positive strategy choice of the online food trading platform.

When J changes, the seller will change significantly, the online food trading platform will change slightly, and the buyer will not change. Specifically, with the increase of J , the probability and speed of the seller and platform to choose positive strategy will gradually increase. In other words, J will have a positive impact on the positive strategy choice of the seller and platform.

When K changes, the seller, the buyer, and the online food trading platform will change to some extent. Specifically, with the increase of K , the probability and speed of the seller, buyer, and platform to choose positive strategy will gradually increase. In other words, K will have a positive impact on the positive strategy choice of the seller, buyer and platform.

In general, a certain degree of punishment will prompt relevant subjects to choose positive strategy. Because the benefits obtained in the process of punishment will urge the subject who implements punishment to choose positive strategy, while

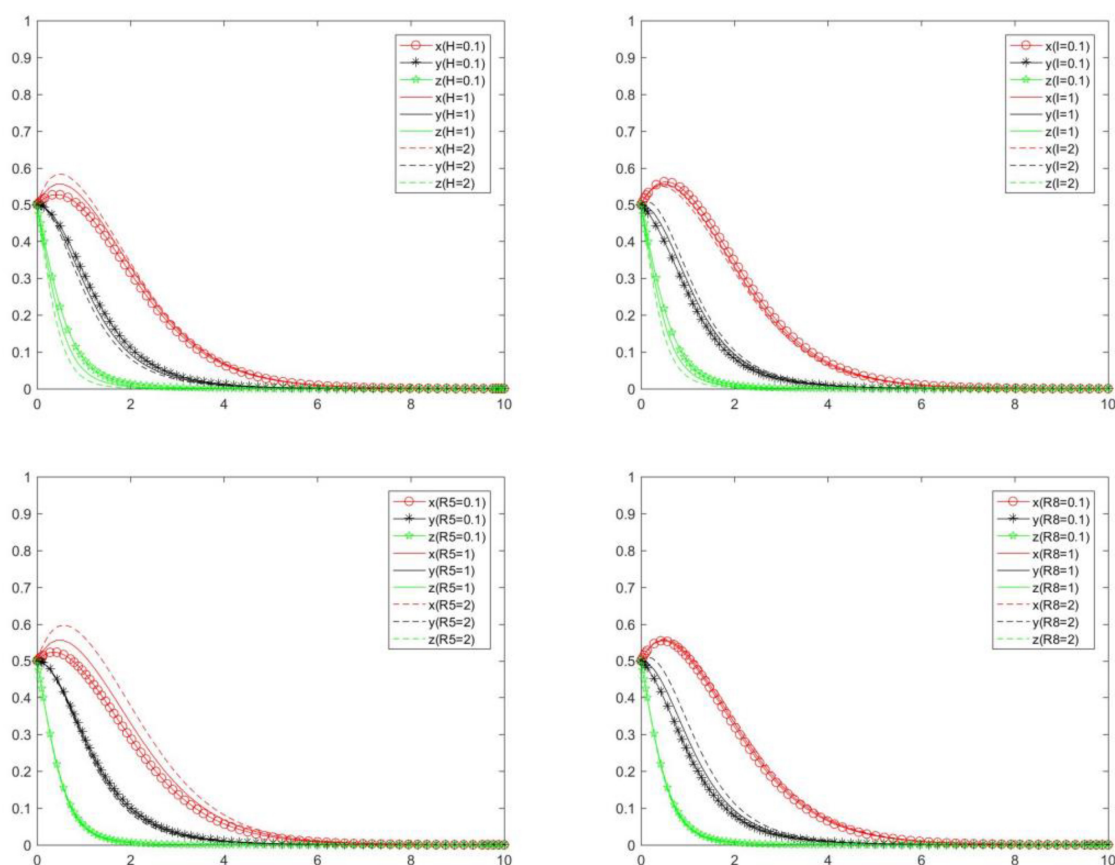


FIGURE 14
Tripartite strategy evolution trends when H , I , $R5$, and $R8$ change.

the subject who accepts punishment will also choose positive strategy in order to avoid losses.

Subsidy and extraneous benefit of positive strategy

In order to explore the influence of H , I , R_5 , and R_8 on the choice of each subject's strategy, we will analyze the evolution law of each subject's strategy under scenarios $\{H = 0.1, H = 1, H = 2\}$, $\{I = 0.1, I = 1, I = 2\}$, $\{R_5 = 0.1, R_5 = 1, R_5 = 2\}$, $\{R_8 = 0.1, R_8 = 1, R_8 = 2\}$. Compare and analyze the evolution law of each subject's strategy when H , I , R_5 and R_8 change (Figure 14). We can know the following.

When H , I , R_5 , and R_8 change, the strategies of the seller, buyer and platform will change slightly. This is mainly because the decision on how much subsidy and additional benefit the subject can obtain is made by other subjects rather than itself. From the perspective of interests, other entities will not provide them with more subsidies, which will not make major changes due to changes in H , I , R_5 , and R_8 .

With the increase of H , the probability and speed of the seller to choose a positive strategy will gradually increase, while the probability and speed of the buyer and platform to choose a positive strategy will gradually decrease. That is to say, H will have a positive impact on the positive strategy choice of the seller, and will have a negative impact on the positive strategy choice of the buyer and the online food trading platform.

With the increase of I , the probability and speed of the seller and platform to choose a positive strategy will gradually decrease, while the probability and speed of the buyers to choose a positive strategy will gradually increase. That is to say, I will have a negative impact on the positive strategy choice of the seller and platform, and will have a positive impact on the positive strategy choice of the buyer.

With the increase of R_5 , the probability and speed of the seller to choose a positive strategy will gradually increase, while the probability and speed of the buyer and platform to choose a positive strategy will gradually decrease. That is to say, R_5 will have a positive impact on the positive strategy choice of the seller, and will have a negative impact on the positive strategy choice of the buyer and platform.

With the increase of R_8 , the probability and speed of the seller and buyer to choose a positive strategy will gradually increase, while the probability and speed of the platform to choose a positive strategy will gradually decrease. That is to say, R_8 will have a positive impact on the positive strategy choice of the seller and buyer, and will have a negative impact on the positive strategy choice of the platform.

Cost and benefit difference between positive strategy and negative strategy

The analysis shows that R_1 , R_2 , R_3 , and R_4 do not directly affect the evolution game of the system, but affect the system through the benefit difference between the positive and negative performance of the seller, that is, affect the evolution law of the system through $R_1 - R_2$ and $R_3 - R_4$. Figure 15 shows the tripartite strategy evolution trends when R_1 and R_2 change and $R_1 - R_2$ unchanged, and Figure 16 shows the tripartite strategy evolution trends when R_3 and R_4 change and $R_3 - R_4$ unchanged.

In order to explore the influence of M , $R_1 - R_2$, and $R_3 - R_4$ on the choice of each subject's strategy, we will analyze the evolution law of each subject's strategy under scenarios $\{M = 1, M = 2, M = 3\}$, $\{R_1 - R_2 = 0.1, R_1 - R_2 = 1, R_1 - R_2 = 2\}$, $\{R_3 - R_4 = 0.1, R_3 - R_4 = 1, R_3 - R_4 = 2\}$. Compare and analyze the evolution law of each subject's strategy when M , $R_1 - R_2$, and $R_3 - R_4$ change (Figure 17). We can know the following.

When M , $R_1 - R_2$, and $R_3 - R_4$ change, the seller's strategy changes most significantly, followed by the buyer, and the platform's strategy changes less. The reason is that when the cost difference and benefit difference between the positive and negative performance of the seller are large, the seller will quickly react and choose strategies that are beneficial to itself, and the seller's different strategies will also have an impact on the buyer and cause them to change indirectly.

With the increase of M , the probability and speed of the seller to choose a positive strategy will gradually decrease, and the probability and speed of the buyer and platform to choose a positive strategy will gradually increase. That is to say, M will have a negative impact on the positive strategy choice of the seller, and will have a positive impact on the positive strategy choice of the buyer and platform.

With the increase of $R_1 - R_2$ and $R_3 - R_4$, the probability and speed of the seller to choose a positive strategy will gradually increase, and the probability and speed of the buyer and platform to choose a positive strategy will gradually decrease. That is to say, $R_1 - R_2$ and $R_3 - R_4$ will have a positive impact on the positive strategy choice of the seller, and will have a negative impact on the positive strategy choice of the buyer and platform.

Conclusion and policy implications

Conclusion

Through systematic analysis of the structure and operation mode of the online food trading market, this article takes the

seller, buyer, and online food trading platform as tripartite subjects and constructs a tripartite evolution game model. With the help of MATLAB software, it is possible not only to simulate the formation process of the “lemon problem” in the online food trading market dynamically, but also to conduct an in-depth analysis of the strategic choice behavior of each subject. In general, the following conclusions can be drawn.

Through the analysis of the stable points of evolution of the seller, buyer, and online food trading platform, it is found that the “lemon problem” occurs with the development and evolution of the online food trading market and will not dissipate. In the online food trading market, the strategy of the tripartite subjects will stabilize in six situations. And the “lemon problem” occurs in all six situations. In the research of Zhang

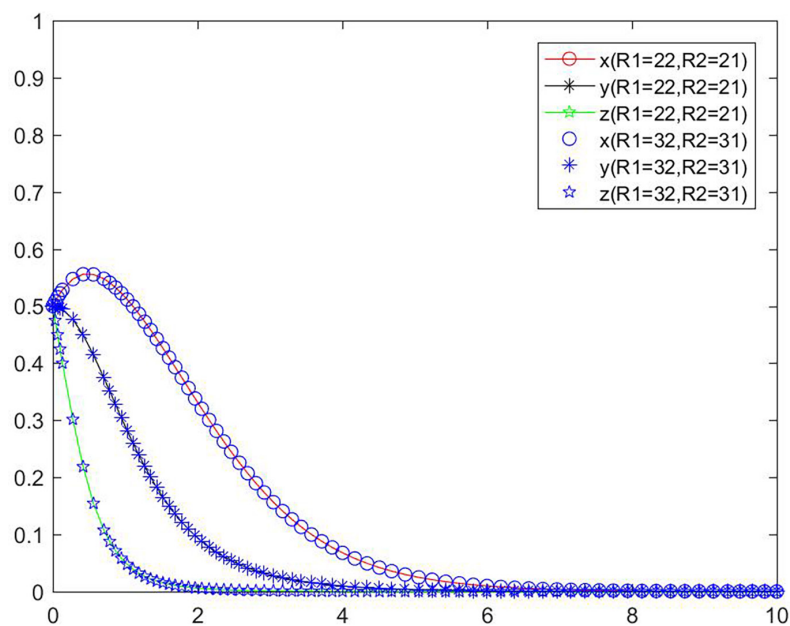


FIGURE 15

Tripartite strategy evolution trends when R_1 and R_2 change and $R_1 - R_2$ unchanged.

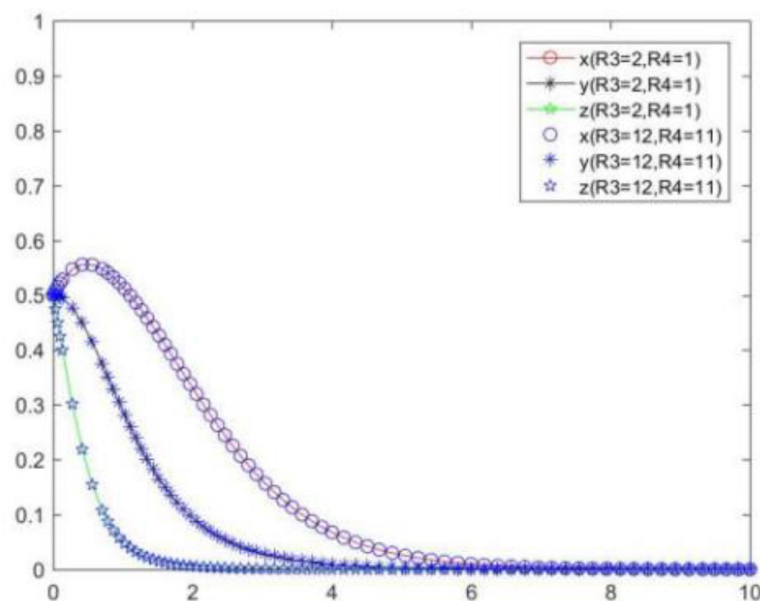


FIGURE 16

Tripartite strategy evolution trends when R_3 and R_4 change and $R_3 - R_4$ unchanged.

et al., it was also pointed out that under the network trading environment of asymmetric information, the characteristics of trusted products of food safety and the self-interest motives of various stakeholders in the food supply chain make unsafe food flooding the market an inevitable result (23). In order to control the “lemon problem” in the online food trading market, it is necessary to deeply analyze the factors that affect the development and evolution of the market, and use advanced technical means and effective management mechanisms to alleviate the problem of information asymmetry in the market (66, 67).

In the online food trading market, different factors have different influence directions on the subject strategy. For the seller, N , H , J , K , $R_1 - R_2$, $R_3 - R_4$, R_5 , and R_8 will have a positive impact on the seller's positive strategy choice, while M , I , C_2 , and C_3 will have a negative impact on the seller's positive strategy choice. For the buyer, M , N , I , K , and R_8 will have a positive impact on the buyer's positive strategy choice, while H , C_2 , C_3 , $R_1 - R_2$, $R_3 - R_4$, and R_5 will have a negative impact on the buyer's positive strategy choice. For the online food trading platform, M , J , K , and C_2 will have a positive impact on the

platform's positive strategy choice, while N , H , I , C_3 , $R_1 - R_2$, $R_3 - R_4$, R_5 , and R_8 will have a negative impact on the platform's positive strategy choice. Clarifying the impact of different factors on each subject can not only help understand the strategic choice behavior of each subject in the online food trading market, but also help and guide the subject's behavior from various aspects. For example, we can change M , J , K , and C_2 to promote the platform to choose a positive strategy.

In the online food trading market, different factors have different influence degrees on the subject strategy. Among them, M , N , H , I , J , K , C_2 , C_3 , $R_1 - R_2$, $R_3 - R_4$, and R_5 will have a significant impact on the seller's strategic choice behavior, M , N , K , C_2 , C_3 , and R_8 will have a significant impact on the buyer's strategic choice behavior, H and C_3 will have a significant impact on the platform's strategic choice behavior. Analyzing the degree of influence of different factors on the subject's strategy can help us clearly identify the key factors that affect the subject's strategy choice and point out the direction for the subsequent development of solutions. However, the degree of influence mentioned in this article is more the result of the comparison among multiple subjects, rather than quantitative comparison.

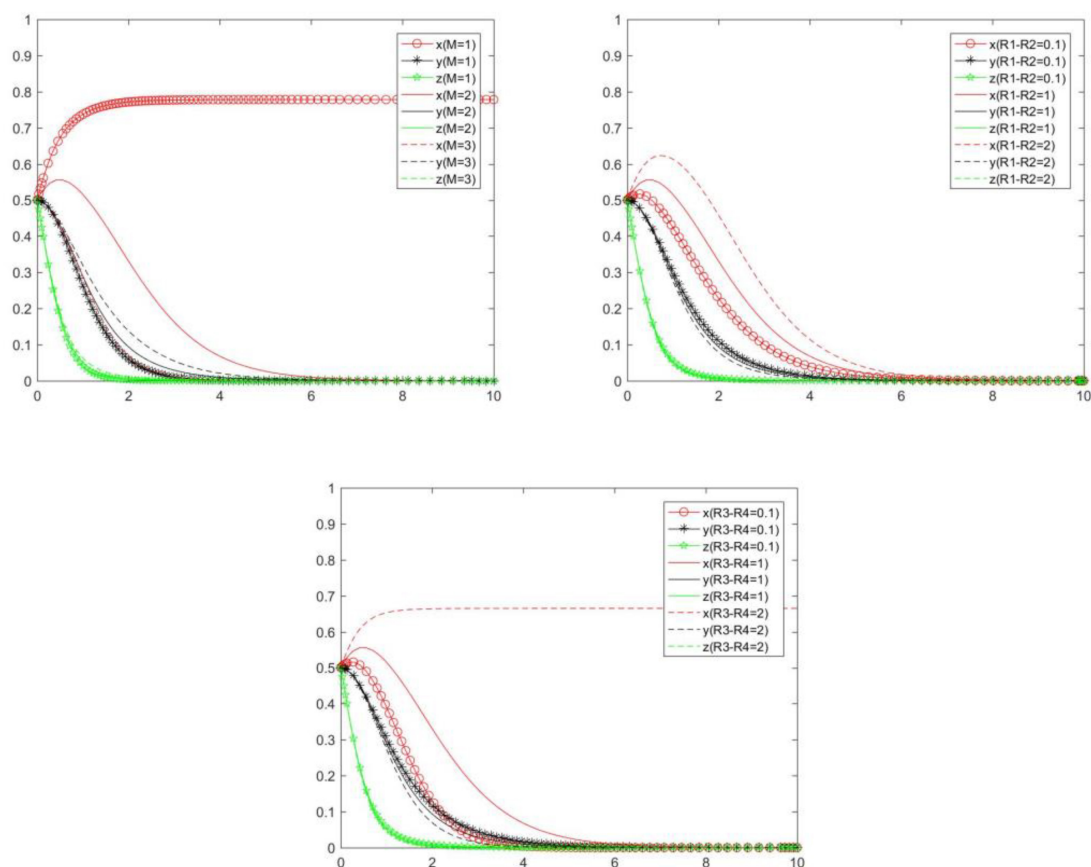


FIGURE 17
Tripartite strategy evolution trends when M , $R_1 - R_2$, and $R_3 - R_4$ change.

In order to more clearly identify the differences between the impact degrees, we will collect realistic data from various aspects in the future to verify and deepen relevant conclusions.

In the online food trading market, cost, punishment, subsidy and benefit have different effects on the subject's strategy. Among them, cost and cost difference have the most significant impact on the subject's strategy, followed by punishment and benefit difference, and subsidy and additional benefit have less impact on the subject's strategy. Therefore, if we want to build a good and sustainable online food trading market, we need to focus on cost reduction and reveal food quality and safety information at the lowest management cost (68). At present, establishing a good institution (such as signal detection mechanism, reputation mechanism, and reward and punishment mechanism) has become an inevitable requirement for the healthy development of online food trading market (53). However, most of the supervision in the market is ex-post supervision, and although the incentive forms are diverse, there is no clear and scientific basis, which requires comprehensive management of the online food trading market from various aspects.

Policy implications

In order to effectively suppress the “lemon problem” in the online food trading market, provide consumers with rich and diverse, healthy and safe food, and bring more benefits to food suppliers and food trading platforms, this paper presents the following suggestions.

- (1) In order to reduce the input cost of tripartite subjects and improve the quality of information in the market, the online food trading market should establish a complete and standardized examination and verification institution. In the online food trading market, the performance cost of the seller, the participation cost of the buyer, and the regulation cost of the online food trading platform will have influence on the strategic choices of the subjects. On the one hand, a complete examination and verification institution will effectively reduce the cost of information screening for the buyer and the online food trading platform and will encourage the buyer and the platform to adopt positive strategy. On the other hand, it will increase the input cost of the low-quality seller, reduce the competitive pressure of the high-quality seller, and further encourage the seller to adopt positive strategy. Specific improvements can be made in the following aspects.
 - ① The quality of information should be strictly controlled from the food source and a complete food seller qualification examining and verifying mechanism should be established. In order to have a general examination of

user credibility, creation ability, and consumption ability of product, the online food trading platform can connect user information with bank credit information system, higher education information network, enterprise credit information query platform, etc.

- ② The online food trading market should refine the sale rules of products and standardize the product examining and verifying process to raise the threshold for products entering the market. For example, for certain products, the platform may require the food seller to provide information such as the creation time, place, raw materials, technology, and process of food production, which can not only ensure the safety of products, but also provide a evidence for subsequent accountability and verification.

- ③ The online food trading market should improve public rules for examining and verifying reports. The online food trading market can release regulatory information and examine and verify information to users in its reports. Well-designed examining and verifying reports and information releasing rules can improve accountability efficiency, promote platform information transparency, and awe dishonest users.

- (2) In order to encourage and restrict the behaviors of the subjects, the online food trading market should establish an appropriate and flexible reward and punishment institution. In the online food trading market, the subsidy received by the seller with positive performance, the punishment for the seller with negative performance, the subsidy received by the buyer with positive participation, and the punishment for the buyer with negative participation will not only affect each subject's own strategic choice, but will also affect the behavior of other subjects. Generally speaking, subsidy institution can encourage the positive strategic behavior of the subject, and the punishment institution can restrain the negative strategic behavior of the subject. The establishment of an appropriate and flexible reward and punishment institution can not only regulate the behavior of the subjects but also ensure the orderly operation of the online food trading market at the same time. Specific improvements can be made in the following aspects.

- ① Based on the credit file of the seller, the online food trading platform should establish a complete institution integrating signal recognition, detection, and processing, so that the platform can accurately determine the information transacted by the seller. At the same time, the credit records of the food seller also need to be made, which can provide a basis for the platform to set specific standards for reward and punishment.

- ② To make a clear distinction between reward and punishment, the online food trading platform should raise the reward for high-quality food sellers and the punishment for low-quality food sellers. At the same

time, the platform should also improve its accuracy and efficiency in detecting information from the seller. For the food seller who have been providing high-quality products for a long time, the online food trading platform can reduce the proportion of their trading commission fee, reduce their advertising and bidding rank fees. For the dishonest food seller, the platform will charge a certain amount of punishment fees and restrict some of their behaviors when the platform detects that he is selling low-quality products at high prices. For the food seller with fraudulent behaviors and food quality problems, the platform may disclose this illegal operation information to all users and remind consumers to be cautious when buying.

- ③ The online food trading market can constantly innovate its reward and punishment institution, try to introduce institutions such as expert identification, user reward reporting, media reward monitoring, guide the seller to operate in good faith, and then construct an honest, high-quality, and professional online food trading market environment.
- (3) In order to effectively reduce the supervision cost of each subject and improve the supervision efficiency, the online food trading market should establish a supervision institution involving multi-party participation. In the online food trading market, the buyer and online food trading platform will supervise the behavior of seller, and the online food trading platform will supervise the seller and buyer. However, affected by the differences in the user's knowledge level, the subjectivity of product evaluation and the externalities of product, although all subjects will invest more time and energy to identify products, it is often difficult to achieve the expected supervision goals. To effectively solve the lemon problem in the online food trading market, it is necessary to continuously update the supervision methods and supervision concepts, and actively introduce different supervision subjects to participate in the management (11, 69–71). Specific improvements can be made in the following aspects.
- ① The public and platform should be encouraged to participate in supervision. On the one hand, it is necessary to introduce the online food trading platform to participate in the supervision, give full play to the initiative of each platform, continuously improve the supervision awareness and supervision technology of each platform, so as to build a supervision institution that includes access rules, transaction rules, evaluation rules, etc. On the other hand, the public supervision function should be given full play, a variety of complaint channels can be established to encourage the public to complain and provide suggestions to the supervision institution.
- ② It is necessary to clarify the government's supervisory responsibilities. In the online food trading market, government participation in supervision can not only

more effectively regulate the behavior of the platform and the seller, but also provide more security for food quality and safety (60, 72–74). In the process of supervision, the government should not only have different supervision models and supervision content according to the actual situation, but also actively guide and encourage other subjects to participate in supervision. At the same time, the government should also pay attention to the standards of legislation and law enforcement, not to over-regulate and over-restrict the development of the online food trading market.

③ Industry associations and internal supervision institutions should be established. In the online food trading market, leading enterprises in the food industry and well-known food bloggers (experts in the food field) can take the lead in establishing industry associations with other users, and promote the self-discipline management of the online food trading market through industry associations. The industry associations can take advantage of the regulatory power, information acquisition and professional technology to internally discuss multiple topics such as market access thresholds, marketing methods, product and service pricing, capital management, and information disclosure, and share the discussion results with the online food trading platform and government (25, 75).

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

FS and SF: conceptualization. FS and JC: methodology, software, and writing—original draft preparation. XZ: validation. FS: formal analysis, resources, data curation, and funding acquisition. JC: investigation. FS, XZ, SF, and SA: writing—review and editing. All authors read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Do urban tourists prefer vegetarianism? An urban-rural comparison of vegetarian consumption in China

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The adoption of a vegetarian diet might have public health and environmental benefits. However, little is known about urban and rural Generation Z tourists' attitudes toward vegetarianism or vegetarian consumption within the Chinese urban and rural settings. Hence, to address this gap, the present study adopted a sequential and mixed research approach based on a survey ($n = 212$) and laddering interviews ($n = 20$) to validate post-millennial tourists' motives for adopting a vegetarian diet. The results identified the top four motives as environmental protection and resource conservation, ethical consideration, personal taste and choice, and personal healthcare issues. The top four barriers to vegetarianism were unavailability and limited choice, peer pressure, traditional prejudice/habit, and the inability to change. The results also demonstrated that both rural and urban tourists adopt vegetarianism mainly for environmental protection and ethical consideration, a subtle difference between them is that urban vegetarians emphasized ethical considerations more but rural ones emphasized food and variety. Urban consumers considered unavailability and limited choice as the topmost barriers to being vegetarian, while rural vegetarians found traditional prejudice to be restricting. Due to traditional dietary habits and peer influence, rural tourists face many more challenges when adopting a vegetarian diet. Understanding the perceived benefits and barriers to being vegetarian in different regions will not only enrich the theory of food nutrition but also expand Generation Z tourists' consumption behavior and practices.

KEYWORDS

vegetarian, Generation Z, rural, urban, contrast

Introduction

Tourism and food consumption have become a new focal point of Chinese economic growth within the country's economic reform. Since 1978, China's urban-rural duality has also come to be reflected in the consumption patterns of residents, particularly food consumption. Based on food consumption data from the National Bureau of Statistics of

China, grains account for the highest proportion, followed by meat; however, the demand for meat has increased year by year. Though the consumption of meat among urban residents is relatively high, it shows a downward trend year by year (1). In the past 10 years, even as urbanization has continued, the urban-rural differences persist and the food consumption structure between them is gradually widening. Urban residents have a higher tendency to consume fruits and vegetables rather than merely meat. Several studies showed that urban residents widely exposed to the newest concepts of food nutrition, personal healthcare, and environmental protection are easily inclined to accept vegetarianism (1, 2). Thus, are there any differences in vegetarians among urban and rural populations, and do urban residents have a higher proclivity toward vegetarianism than rural ones?

This study aimed to address this issue, and the goal of this research is to investigate the differences between urban and rural vegetarianism by analyzing the motivations, benefits, and barriers to following a vegetarian diet during travel. In the present study, vegetarian refers to individuals who eat a diet consisting wholly of vegetables, fruits, grains, nuts, and sometimes eggs or dairy products, and they do not consume meat, fish, and poultry. Well-planned vegetarian diets have proved to be healthy and nutritionally adequate and they can provide enough nutrition for people at all stages of life (3, 4). There are quite a large number of benefits to following a vegetarian diet. According to a survey by Izmirli and Phillips, a meat-free diet can directly lower the intake of calories as compared with non-vegans, and this can assist people who want to lose weight (5). Second, vegetarians tend to have fewer intakes of fat, saturated fat, and cholesterol (6). Finally, vegetarian diets contain rich nutrition, such as vitamins, folate, photochemical, potassium, fiber, and protective compounds, all of which are beneficial for human beings (7, 8).

Although there are benefits to consuming vegetarian products, the proportion of the vegetarian population in China is still small; among 1.3 billion people at present, only 3.8% of the population consider themselves vegetarian (6).

Generation Z, born between 1995 and 2010, gradually became the main influence on the food consumption market, and they play an important role in vegetarian consumption in China (9). Generation Z advocates freedom and is obsessed with tourism. They are loyal fans of rural tours, RV tours, camping, outdoor tours, and music tours. However, because vegetarianism is not yet widespread in China, choices are very limited, and finding enough comfortable vegetarian food becomes a primary concern during the journey. In addition, because of China's typical urban-rural duality (10), the vegetarian consumption gap between them is still widening. Thus, the purpose of the present study is to contrast the perception of vegetarian diets between urban and rural Generation Z tourists and explore their attitudes, motivations, driving factors, and barriers to following a vegetarian diet. In this context, the key research questions are:

- (a) What are the most commonly perceived benefits of vegetarianism for urban and rural Chinese Generation Z tourists?
- (b) What are the most commonly perceived barriers to vegetarianism for urban and rural Chinese Generation Z tourists?
- (c) What are the main differences in terms of perceived benefits and barriers between them and why?

This study is important because it attempts to identify the new generation's attitude toward a vegetarian diet, by investigating their perception of the benefits and barriers to adopting a vegetarian diet. From the perspective of nutrition and dietetics, the information from this study could be beneficial for enhancing nutritional interventions and contributing to the reduction of certain chronic lifelong diseases in Chinese societies (11).

Literature review

This study aimed to undertake a contrast analysis of post-millennial tourists' attitudes toward vegetarianism, including perceived benefits and barriers. This section provides a brief review of perceived benefits and barriers.

Motivations and perceived benefits of vegetarian consumption

As people become more and more concerned about health, environmental protection, and animal welfare, vegetarianism has increased and has drawn increasing attention from theory and practice, in particular psychology research, though it is still at an early stage. Psychological processes regarding vegetarianism involve cognitive, emotional, and motivational aspects and vegetarian identity. This study aimed to investigate the factors influencing post-millennials' motivation for adopting vegetarianism.

Studying their motivation provides a new way of understanding the driving forces behind their vegetarian choice (12). Table 1 presents a general summary of nine representative studies examining the consumers' motivations for adopting vegetarian diets. Among them, two studies chose a qualitative approach and had open-ended questions to identify the motivations, and the remaining seven studies adopted quantitative research methodology using a closed-ended questionnaire for examining respondents' motivations.

Based on previous research, the most frequently mentioned motivations for adopting a vegetarian diet included ethical considerations, environmental protection, health, individual taste, and religious reasons (13–15). The ethical reason, also referred to as moral reason, indicates that people

TABLE 1 List of previous researches on the benefits and motivations of vegetarian diet.

References	Research sample	Research method	Results: Main motive(s)
Waldmann et al. (13)	154 vegans Germany	Quantitative Questionnaire: Closed-format question Research was carried out through Journal advertising	Among all the 154 respondents, 48.7% (75 persons) were driven by health-related reasons, 41.6% (64 persons) were motivated by ethical-moral issue, these two motives occupied majority, the other motives were selected relatively limited. Among them, only 2 persons chose hygiene motivator and only 1 person chose Environment-related reasons (13)
Fox and Ward (14)	33 participants from US, Canada and the UK.	Qualitative Questionnaire: open-format question It conducted online survey of open-ended questions, and then a follow-up e-mail interviews with 18 participants	Result indicated that health and ethical issue were the top driving factors for participants' vegetarianism, and only one case was environmental-related motivator (14).
Dyett et al. (15)	100 vegans United States of America	Quantitative Close-format question Data collected through Printed advertisement	Results shows that 47% of the participants chose vegan diet for health-related motivation, 40% of them for moral motivation, 9% of them for religious beliefs, 2% chose it for environmental motivation, and the last 2% chose it for family or other type of reason (15).
Rothgerber (16)	315 vegans and 200 vegetarians	Quantitative Questionnaire Close-format question Collect on internet	Among 315 vegans, 177 persons (56.2%) were driven by ethical motives, 40 persons (12.7%) were driven by personal health-related issue, and the last 98 chose (31.1%) vegan diet for other motives (16).
Radnitz et al. (17)	246 vegans United States of America, Canada and other countries	Quantitative Questionnaire: Close-format question Data collected by Vegan events and social media	Researchers just explored two kinds of motivations: Ethical reasons and health-related reasons. And result showed that 81.7% (201 persons) chose ethical motivators and 19.3% (45 persons) chose health-related motives (17).
Kerschke-Risch (18)	852 vegans Germany	Quantitative Questionnaire: Close-format question Data collected through Internet, and the sample method was snowball sampling	Participants were asked to rank different factors related to their influence on their decisions for quitting meat, Likert list was adopted for "1 means no influence at all" to "5 means very strong influence". The result showed that the index score of climate protection was 3.8, the index score of health-related reason was 3.2 and the index score about factory farming (ethical consideration) was 4.4 (18).
Janssen et al. (19)	329 vegans Germany	Quantitative Open-ended question	Among all the 329 vegans, 89.7% were driven by animal-related reasons, 69.3% were motivated by personal health related motivations and 46.8% were driven by environmental related motivations (19).
Dorard and Mathieu (20)	49 vegetarians and 52 omnivores France	Quantitative research close-ended questionnaires Data collected by Facebook	Results indicated that compared with the omnivores, the motivations of vegetarians were more related with health ($p = 0.001$) and natural content ($p < 0.0001$), less related with weight control motivations ($p = 0.015$) (20).
North et al. (21)	701 participants 371 vegans, 99 Vegetarian and 231 Omnivore Australia	Qualitative Open-ended question Data collected through Online survey of Qualtrics	The participants were divided into three groups, and similar motivation among them is health-related reason. The second one is environmental protection, and the animal welfare was also cited most by vegans and vegetarians. Taste and enjoyment for diet were also identifies as motivation (21).

should consider the following when determining their dietary preferences: animal welfare, animal right, and their suffering during livestock production (13). Environmental concern includes the ecological reason for choosing a vegetarian diet, advocating environmental protection, resource-saving, and the greenhouse effect (14), which were also classified under ethical

reason in the past. Health-related reasons uphold that a vegetarian diet is beneficial for personal health while compared with omnibus or purely meat consumption (15), arguing that it can prevent people from common illnesses and is good for personal fitness (16, 17). Of the three motives, ethical and environmental motives were considered to be of public interest,

and the health-related motive was assumed to be guided to a greater extent by self-interest (18).

However, some researchers also pointed out that the classification of motives to adopt vegetarianism into just two groups was not feasible, for there might be other kinds of motives that might have been overlooked, such as personal taste and food choice, personal interests, and family lifestyle (19). These multiple motives may complement and reinforce each other for stimulating people to adopt a vegetarian diet. Based on the above, motivations can be classified as those driven by personal health, personal taste, environmental protection, personal interest, and ethical consideration (20, 21). Thus, we propose the following hypothesis:

H₁: Personal health, personal taste and choices, environmental protection and resource conservation, personal interests, and ethical consideration are positively related to Generation Z tourists' willingness to follow a vegetarian diet.

This classification and differentiation have been described and explained by Greenebaum, who also stated that ethical and environmental-related vegetarians are different from personal-related vegetarians (22). The latter were considered self-interest-oriented and hedonistic vegetarians, while the former was marked as public-interest-oriented and altruistic vegetarians, and they may have quite a different understanding and feeling about adopting a vegetarian diet. In fact, in most cases, ethical and environmental protection-related motivations occupied a majority of the vegetarian community. Especially in China, which is considered an oriental traditional country favoring collectivism, people are encouraged to put public interest, including environmental protection and animal welfare, as their first priority (23). Under these circumstances, we propose the following hypothesis.

H₂: Of all the benefits, ethics-related and environmental protection-related motives have a stronger positive effect on willingness to be vegetarian.

Although vegetarianism is not mainstream in China, there is a growing trend toward reducing meat consumption. Especially for urban Generation Z, who have been living in cities or towns for a long time, being exposed to the concepts of environmental protection, animal protection, and personal healthcare, and fully understanding the benefits of vegetarianism and vegetarian consumption, they were more motivated by the perceived benefits of vegetarian consumption (24). In addition, urban areas have a long history of vegetarianism compared to rural areas. Thus, based on the above, we propose the following hypothesis.

H₃: The positive influence of ethics-related and environmental protection-related motives is stronger for tourists in urban areas than those in rural areas.

Perceived barriers to vegetarian consumption

In 2003, Lea and Worsley surveyed the perceived benefits and barriers to the consumption of a vegetarian diet in Australia (25). In this study, over 1,000 south Australians were randomly selected and required to fill out a questionnaire consisting of 49 questions, among which 25 questions were about personal barriers and 24 items were about benefits. Of the 1,000 respondents, 70.6% of them completed the questionnaire. It was found that only 1.5% of them identified themselves as vegans and 7.2% as semi-vegans (25). And the main barrier for them to adopt a vegetarian diet was the enjoyment of eating meat and the unwillingness to give it up. The second barrier was the lack of enough information about vegetarianism. Traditional beliefs that people are meant to eat meat were the third barrier to meat consumption. Health concerns were also noted as a barrier for vegetarians who did not eat any meat. Overall, respondents' enjoyment of eating meat and their unwillingness to change their diet were considered the biggest barriers to the consumption of a vegetarian diet. Lea and Worsley (25) study concluded that there were many Australians who were quite interested in vegetarianism, and they strongly believe that vegetarian consumption was positively related to health benefits. Because the enjoyment of meat is the biggest barrier to adopting the vegetarian diet, it was suggested that the most feasible and suitable way was to provide both meat- and plant-based diet instead of completely eliminating meat input (25).

In 2006, Lea et al. conducted a study exploring people's attitudes toward the consumption of a plant-based diet. More than 1,000 adult respondents were selected randomly and 51% of them completed the questionnaire. Of these 62% demonstrated high or somewhat interest in consuming a plant-based diet (26). The main perceived barrier to adopting a plant-based diet was the lack of enough information and consumers had relatively few choices. Other common barriers included people's unwillingness or inability to change their family's diet, and they were also reported to have relatively low availability of plant-based options while eating out. This research also showed that as a community, they may be unfamiliar with the notion of a plant-based diet, which was an unexpected prevalent barrier to plant-based consumption.

Wieliczki also examined the main perceived barriers to vegetarianism in universities (27). The research explored how university students had enough knowledge about vegetarianism and also identified the biggest differences in the field of perceived barriers between vegetarians and omnivores. The respondents were 96 students selected using a convenience sample. The most frequently mentioned barriers to a vegetarian diet were: (a) All my family members eat meat, (b) I enjoy eating meat, (c) My friends eat meat, (d) I need more information about vegetarian food and diet, (e) I am unwilling to change my taste and habit,

TABLE 2 List of previous research on the barriers to vegetarian consumption.

References	Research sample	Research method	Results: Main barrier(s)
Lea and Worsley (25)	1,000 south Australians Australians	Quantitative Closed-format question	Main barriers included a) Enjoy meat eating b) unwilling to change their current diet or routine c) traditional concept that people are ‘meant’ to eat meat d) limited choices (25).
Lea et al. (26)	USA	Quantitative Closed-format question	Main barriers included a) lack of information about plant-based diets, b) unable or inability to change current food diet and eating habit C) few plant-based options (26).
Wieliczki (27)	96 subjects United States of America	Quantitative Closed-format question	Ten most common perceived barriers identified, in order, are: a) my family members prefer meat eating b) I like meat eating) my friends eat meat d) I am in need of more information about vegetarian diets e) I am unwilling to change my eating habits f) I think humans are meant to eat meat g) there’s limited vegan diet choices when I eat out h)I don’t have enough will power, i) my family/spouse/partner won’t eat vegetarian foods, and j) it is inconvenient (27).
Radnitz et al. (17)	246 vegans USA, Canada and other countries (not further specified by the authors)	Quantitative Closed-format question Data collected by Vegan events and social media	<ul style="list-style-type: none"> • Unable to change the current diet • Lack of enough choice of substitute • Inconvenient (17).
Mullee et al. (28)	2436 participants Belgium	Quantitative Online questionnaire with multiple-choice questions	Key barriers for not being vegetarian included inadequately tasty, lack of interest and awareness and limited choices (28).
Rosenfeld and Tomiyama (29)	579 participants United States	Quantitative Closed-format question	Key barriers including inadequately tasty, inadequately nutritious, inconvenient consumption, high price and socially stigmatizing (29).
Beningfield et al. (30)	458 participants South Africa	Quantitative Closed-format question Cross-sectional study	Most frequently perceived barriers identified, they are: a) I like eating meat b) Except meat, I don’t know eat what c) Somebody else decides what I eat everyday d) My Family members eat meat e) Eating meat is favorable in my culture f) I think humans are meant to eat meat h) I don’t want people to think I am strange i)Limited vegetarian choice when I eat out (30).

(f) I think that humans should eat meat, that is nature, (g) There is a relatively limited choice of a vegetarian diet while eating out, (h) I do not have enough right to change my eating habit, (i) My family members/partners/friends/relatives do not want to eat any vegetarian food, and (j) It is uncomfortable (27). A general summary of the representative research about the perceived barriers to following a vegetarian diet is presented in Table 2. Based on the above, we propose the following hypothesis:

H₄: Traditional prejudice and habit, peer pressure, unavailability, limited choice, and unwillingness or inability to change are negatively related to Generation Z tourists’ vegetarian consumption.

In 2017, Radnitz et al. conducted quantitative research in Belgium where 2,436 participants were invited to complete an online questionnaire with multiple-choice questions. The results indicated that the key barriers to not being vegetarian included not being tasty enough, lack of interest and awareness, as well as limited cooking choices (17, 28). Similarly, in 2020, Rosenfeld and Tomiyama found that not being tasty enough, inadequately

nutritious, inconvenient consumption, high price, and socially stigmatizing were the main barriers to adopting a vegetarian diet (29). A majority of the participants reported that limited plant-based options as the main barrier. More than half of the respondents admitted that the obvious benefits included improvement in personal health by adopting a vegetarian diet, while on the other hand, most family and friend members could not resist the temptation of a meat diet, which may inhibit the adoption of a vegetarian diet (30). Furthermore, as can be seen from Table 2, the principal barrier for vegetarians was unavailability and limited choice, followed by peer pressures, and traditional habits. In other words, limited options together with peer pressure inhibit consumers to adopt vegetarian diets.

Based on the above, we propose the following hypothesis:

H₅: Among all the barriers, unavailability and limited choice, peer pressure as well as traditional habits and prejudice have a stronger negative influence on vegetarian diet consumption.

Previous scholars argued that manual laborers rely more on meat for providing strength and stamina (31). Most rural

populations are mainly engaged in manual labor and, therefore, are more inclined to consume meat. Meat consumption forms a significant portion of rural citizens' daily consumption (32). Second, the existence of a dual economy structure (between the urban and rural) results in the more obvious income and consumption differences, which leads to poor infrastructure and limited vegetarian choices in rural areas (10). Third, according to Hofstede's cultural dimensions, China as an oriental traditional country favoring collectivism (33), and rural citizens may experience more pressure to continue with traditional habits. Based on the above, we propose the following hypothesis:

H₆: The negative influence of traditional prejudice and habit and unavailability and limited choice are higher for tourists in rural areas than those in urban ones.

As a new generation living in an information era, urban Generation Z has convenient access to recent diets and healthcare information through mobile internet, and widespread information helps them to have a deeper understanding and are, therefore, prone to accept vegetarianism (34). In addition, due to the profound influence of foreign vegetarian culture, the urban area has a longer history of vegetarian consumption than rural areas (35). Therefore, urban youth are prone to accept vegetarianism easily. While on the other hand, previous scholars have argued that rural populations, mainly consisting of manual laborers and other working-class members, are especially prone to perceive the consumption of meat as a key component of maintaining strength (31, 36). Thus, we propose the following hypothesis:

H₇: Urban tourists (vs. rural ones) have a higher proclivity toward vegetarian consumption.

Materials and methods

To identify Generation Z tourists' perception toward a vegetarian diet, especially their attitude, motivation, driving factors, and barriers to accepting a vegetarian diet, the research adopted mixed research methods (including both qualitative and quantitatively methods) where the quantitative findings from the questionnaire were cross-checked against the qualitative findings from the focus groups enhancing the validity of the research (37).

Questionnaire design and survey implementation

A questionnaire was adapted from previous studies by Lea and Worsley, Clarys et al., and Hawkins et al. (25, 38, 39). The questionnaire was organized into three parts. The first part addressed 24 perceived benefits of following a vegetarian

diet and the second part had 26 perceived barriers. A five-point Likert scale ranging from 1 to 5 (1 = "strongly disagree" and 5 = "strongly agree"; Cronbach's $\alpha = 0.89$) was used. The third part contained four closed questions and one open-ended question about demographics, such as native place, sex, age, and education major, as well as questions about participants' current diets. Multiple-choice questions were also included in this part to figure out the most important perceived motivations and barriers.

Most of the questions were designed to measure the variables within the hypotheses. These questions were presented as statements and participants were asked to express their attitude toward these statements by using a Likert scale. The 5-point Likert scale is considered suitable for this investigation as it allows the researcher to measure participants' opinions and attitudes toward the statements made (40).

A pilot study was administered for increasing the feasibility and readability of the survey. The pilot questionnaire was compiled with broad open-ended discussion prompts (40). The author, however, did not follow this framework or guidelines rigidly. The discussion was conducted freely so that ideas could emerge and be adequately probed. The results of the pilot study were used to make improvements to the original questions.

The target population for this study was a convenience sample composed of 212 undergraduate and graduate students from Chongqing Three Gorges University who claimed to be vegetarians. The underlying reason for selecting tourism-related students was that most of them had made more than four trips in the past, and they had an intensive perception of motivations and barriers to vegetarianism during their travels. In addition, as a part of the university's Professional Talent Cultivation Plan, all tourism-related students are required to participate in a tour guide internship program conducted each year at different tourist attractions across the country. As instructors of this program, the authors had ample chances to contact these Generation Z and request their participation in the study and collect primary data during their internship.

As to the data collection procedure, the researchers first delivered the survey information on social media like Weibo and WeChat, the requirement, instructions, and procedures of this survey were also sent out simultaneously inviting Generation Z who claimed to be vegetarian. Secondly, the researchers also contacted the class monitor of each internship class and asked them to forward the survey link to their classmates and contemporaries. After identifying qualified participants, the class monitors provided the researchers with a list of potential participants. Thirdly the researchers contacted the potential participants and invited those qualifying among them to participate in the survey. Respondents from different provinces were invited for ensuring representativeness and universality. Fourthly, after obtaining oral approval from the respondents, the researchers briefed them about the questionnaire survey. Lastly, the respondents completed the questionnaire, and the primary

data was collected on the spot. A total of 212 respondents took part in the questionnaire survey and among them, 90 were from rural regions and 122 were from urban regions. Urban respondents were those who were permanent residents or lived in urban areas in the past, and rural respondents were those who were living in rural areas. The whole survey was completed in May 2022.

Data analysis

All the collected data were arranged in a form, in which each question was marked with a certain number, and then they were classified into different categories.

SPSS 2016 was used to interpret the quantitative data because its functions are sufficient for the analysis of this study. Tables with mean value analysis and analysis of variance (ANOVA) are useful and effective tools to identify the important benefits and barriers to adopting a vegetarian diet. To test hypotheses 1 to 4, this research conducted mean value comparison and standard deviation to describe participants' perceived benefits and barriers. This research adopted the arithmetic "mean" to calculate the average in the five groups of perceived benefits and four groups of perceived barriers.

For testing hypothesis 5, ANOVA was conducted for comparing the results between rural and urban respondents. Through ANOVA and content analysis between rural and urban respondents, the researchers were able to determine key findings that informed the conclusion.

Therefore, all the questions were analyzed through SPSS mean analysis. In addition, transcribing was necessary because it allowed the researchers to analyze participants' answers and identify the main themes that emerged during discussions.

Results

Sample description

The survey respondents included 90 rural participants and 122 urban participants, aged between 18 to 27, who claimed that they have always been vegetarians. This sample is consistent with the Chinese urban-rural dual structure where living standard in cities is higher than that in rural areas. There were 212 participants in total, and among them, two questionnaires were completed by flexitarians who did not meet the requirement of the study and were therefore excluded from the data analysis. Another two questionnaires were completed by vegetarians who were aged more than 27 and did not meet the age requirements of the study and thus excluded from the study. Two other questionnaires had more than 30% of the questions left blank, and were discarded. Finally, 206 questionnaires were qualified

TABLE 3 Demographic profile.

Demographic Types/Ranges factors		Number of respondents	Percentage of respondents
Locality	Rural	90	
	Urban	116	
Gender	Female	169	82.00%
	Male	37	18.00%
Age	18	76	36.90%
	19	38	18.40%
	20	47	22.80%
	21+	45	21.80%
Major	Tourism management	61	29.60%
	Hotel management	32	15.50%
	Business management	62	30.10%
	Tour guide	31	15.00%
	Others	20	9.70%

and collected for further analysis. Table 3 below summarizes the respondents' demographic profile in detail.

Results and analysis

Quantitative data comparison

Table 4 presents the comparison of perceived benefits between rural and urban vegetarians. Both sides agreed that personal healthcare, personal taste and choice, environmental protection and resource conservation, and ethical consideration positively motivated participants' vegetarian consumption. However, the score of personal interest was >3.0 , signifying that its effect is relatively weak. Furthermore, data indicated that urban tourists gave higher scores to the benefits of adopting a vegetarian diet, and they thought that it was good for their personal health, and vegetarian consumption could prevent diseases, improve their digestion, and provide them with plenty of food choices, and most importantly, being vegetarian was quite beneficial for environmental protection and resource conservation, and it would promote the welfare of animals. The scores of urban Generation Z were somewhat higher than that of their rural counterparts and it reflects the overall higher acceptance of vegetarianism in urban areas than that of rural regions.

On perceived motivations from urban participants, the motivation with the highest mean score was "I would contribute to animal welfare/rights" (4.68), followed by "I would contribute to the environment" (4.56), and "I would eat a greater variety of plant foods" (4.43). In contrast, the highest mean score

TABLE 4 Comparison of perceived benefits between rural and urban respondents.

Personal healthcare issue	Rural		Urban	
	Mean	SD	Mean	SD
Vegetarian diets/meals help prevent disease in general	2.63	1.258	3.86	1.213
It would help me stay healthy	3.30	0.295	3.88	1.013
It would help me control my weight	3.58	1.186	3.13	1.092
It would help me improve my digestion	3.55	1.053	3.56	0.938
I would be more fit	3.42	1.205	3.62	1.127
I would have a better quality of life	3.06	1.279	3.92	1.122
I would be more content with myself	3.06	1.165	4.13	1.016
Overall	3.23		3.73	
Personal taste and choice				
It would decrease my saturated fat intake	3.97	1.005	3.41	1.151
I would eat more fiber	4.43	0.079	3.82	0.949
I would eat a more “natural” diet	3.40	1.305	3.83	1.195
I would eat lots of vitamins and minerals	3.63	1.131	3.98	0.961
I would eat a greater variety of plant foods	3.42	1.234	4.43	0.901
I would have plenty of energy	3.02	1.161	3.53	1.041
My meals will be tasty	2.78	1.224	4.06	1.025
I would have a lower risk of getting food poisoning	2.90	1.201	3.41	1.162
Overall	3.44		3.81	
Environmental protection and resource conservation				
I would contribute to environmental protection	3.76	1.215	4.56	0.981
I would contribute to resource conservation	3.59		4.35	
Overall	3.67		4.46	
Personal interest				
I would save money	2.55	1.301	2.71	2.191
I would save time	2.90	1.201	1.16	0.994
I would have fewer food storage problems	2.76	1.171	2.26	1.053
I would appear more “trendy” to my friends	2.29	1.209	2.03	1.179
Overall	2.63		2.04	
Ethical consideration				
I would promote animal welfare/rights	3.85	1.232	4.68	0.866
It would increase the efficiency of food production	3.29	1.311	4.06	1.067
It would help decrease hunger in the Third World	2.93	1.336	3.41	1.332
Overall	3.36		4.05	

1, strongly disagree; 2, disagree; 3, neutral; 4, agree; 5, strongly agree.

from rural respondents was “I would eat more fiber” (4.43), followed by “It would decrease my saturated fat intake” (3.97), and “I would contribute to animal welfare/rights” (3.95). The results show that urban vegetarians put more emphasis on environmental issues and ethical considerations, while on the other hand, rural vegetarians emphasized more on taste and diet diversity.

In addition, the multiple-choice questions on tourists’ motivation for following a vegetarian diet indicated that four main factors motivated Generation Z to adopt a vegetarian diet. Of the 206 respondents, 186 (90.3%)

selected ethical considerations, i.e., animal welfare and food conservation. About 86.4% of the respondents selected environmental and resource-related motivations, and 58.7% of the respondents chose personal taste and choice, which encompassed aspects related to fiber/vitamins and minerals intake, and tasty cuisine. A further 53.4% mentioned health-related motivation, i.e., motives related to staying healthy, controlling weight, and improving digestion. Interestingly, only 22% of the respondents chose personal interest-related motivation, i.e., save money, save time, and solve food storage problems. Other motivations including religious

TABLE 5 Comparison of perceived barriers between rural and urban respondents.

	Rural		Urban	
	Mean	SD	Mean	SD
Traditional perceptions and habit				
I like eating meat	3.80	1.119	2.11	1.309
It would be (is) too expensive	3.10	1.258	2.08	1.053
There is not enough iron in vegetarian diets	3.10	1.201	1.86	1.105
There is not enough protein in vegetarian diets	3.13	1.310	1.67	1.075
There is not enough B12 in vegetarian diets	3.09	1.263	2.68	1.360
I would be (or am) worried about my health	3.15	1.176	1.73	1.000
I think humans are meant to eat meat	3.06	1.341	1.45	1.007
It is inconvenient	2.74	1.313	2.01	1.208
Vegetarian diets/meals are not filling enough	2.99	1.402	1.47	0.974
Vegetarian diets/meals are boring	2.52	1.318	1.36	0.883
I wouldn't get enough energy from vegetarian foods	2.95	1.302	1.49	0.957
Overall	3.06		1.81	
Peer pressure				
My friends eat meat	4.06	1.165	2.40	1.332
My family eats meat	4.15	1.105	2.70	1.429
My family/spouse/partner won't eat vegetarian meals	2.40	1.296	1.95	1.210
People would (or do) think I'm a wimp or not "macho" enough	2.24	1.219	1.43	0.937
I don't want people to stereotype me negatively (e.g., that I must be strange)	2.06	1.165	1.83	1.234
Overall	2.98		2.06	
Unavailability and limited choice				
Vegetarian options are not available where I grocery shop	2.34	1.343	1.81	1.051
There is too limited a choice when I eat out	3.40	1.341	2.47	1.258
I need more information about vegetarian diets	3.35	1.429	1.93	1.239
Overall	3.03		2.07	
Unwilling or inability to change				
Someone else decides most of the food I eat	2.40	1.383	1.46	0.965
It takes too long to prepare vegetarian food	2.07	2.070	1.93	1.174
I don't want to eat strange or unusual foods	2.45	1.309	1.43	0.891
I don't have enough willpower	3.01	1.393	1.98	1.144
I don't know what to eat instead of meat	2.41	1.224	1.48	0.975
I lack the cooking skills to change my diet that much	2.58	2.580	1.53	0.983
I don't want to change my eating habits or routine	2.80	1.347	1.76	1.225
Overall	2.53		1.65	

1, strongly disagree; 2, disagree; 3, neutral; 4, agree; 5, strongly agree.

beliefs or consuming trends were cited by just 3.9% of the total respondents.

Table 5 presents the comparison of perceived barriers between rural and urban vegetarian consumers. In contrast to the perceived benefits, the results for perceived barriers showed that rural respondents gave higher scores to the barriers to adopting a vegetarian diet, indicating that rural vegetarians faced a higher degree of barriers to adopting a vegetarian diet. The data from Tables 4, 5 together indicate that urbanites have a longer history of vegetarianism than rural residents. Also, urban

tourists have a much deeper understanding of vegetarianism and its consequence.

Further, both urban and rural respondents agreed that traditional prejudice, peer pressure, unavailability of choices, and unwillingness or inability to change make it somewhat uncomfortable or difficult to adopt a vegetarian diet. Among data from urban ones, the highest mean score was for the barrier "My family eats meat" (2.70), followed by "There is not enough B12 in vegetarian diets" (2.68), and lastly "There is too limited a choice when I eat out" (2.47). In contrast, among

rural respondents, the highest mean score was for the barrier “My family eats meat” (4.15), followed by “My friends eat meat” (4.06), and lastly “I like eating meat” (3.80). These data indicate that both types of respondents were greatly influenced by peers, especially friends and family members. Compared with urban tourists, their rural counterparts were mostly affected by friends and family members, which is typical of the deep-rooted family-based ideology and friendly neighborly culture prevalent in rural China (10).

To sum up, the responses to the multiple-choice questions on tourists’ perceived barriers reflected that out of 206 respondents, 128 (62.1%) selected unavailability and limited choice as the most significant barrier. About 53.9% of the respondents considered peer pressure as the second barrier and 52.4% chose traditional prejudice and habit as the third highest barrier to vegetarianism. A further 44.2% mentioned unwillingness or inability to change, and other barriers including cooking skills

TABLE 6 Participants’ comments on other benefits of vegetarianism.

Theme 1: Personal health issue

After consuming vegetarian, I am feeling lighter and stronger at the gym
It’s amazing, I don’t care about “trendy”. Since I am vegetarian my entire life changed.
I can eat more fiber, and change my unhealthy eating habit, this makes me more energetic
Vegetarians are less likely to have cardiovascular problems than meat-eaters

Theme 2: Personal taste and choice

I am living a more conscious lifestyle
I can live a little bit better in this world
Trying out new recipes all the time is awesome!
I learned so much more about nutrition than before.
It is very interesting to find new vegetarian replacement products! For example, for making a vegetarian “cheesecake”, it’s challenging but at the same time lots of fun.
I lost weight and becoming vegetarian makes me unbelievably happy

Theme 3: environmental protection and resource conservation

To me the most important thing about vegetarianism is that it helps with our environment issues.
Consuming vegetarian will reduce greenhouse gas
It will save the world and animals
Being a role model for my children. I do my job to save the planet for my children and grandchildren.

Theme 4: Personal interest

It got me into a better relationship with food in general
Milk causes acne for me
I avoid violence, by not eating animals who are abused in conventional farms, it can save the planet
It’s better for the skin to eat dairy-free
Being a role model/positive influence on others
It helps to clear up my skin
Peace of mind
It is more aligned with my values

Theme 5: Ethical consideration

Just the thought of killing an animal for the pleasure of my taste feels so wrong.
It’s not a trendy lifestyle; we do not need to eat animals to live.
I practice vegetarianism for global social and environmental justice.
I believe animal consumption harms animals harms our environment and harms people (health aspects) as well as the fact that work in meat and dairy “production” is largely done by marginalized and poor communities, affecting their mental and emotional wellbeing as well as air and water pollution.

and resource constraint were selected by just 1.9% of respondents.

Qualitative data comparison

In addition to the survey, open-ended questions were designed to collect participants' subjective information. At the end of each section of the questionnaire, respondents also had the opportunity to provide additional comments. Some of the comments received on other benefits of vegetarianism included factors such as having a clean conscience, being environment-friendly, living healthier, and having a better relationship with local food in general. Table 6 (below) summarizes participants' comments on the benefits of vegetarianism.

Based on content analysis of participants' comments, two interesting findings emerged. First, expressions such as environmental-friendly, resource conservation, and animal

protection are more frequently mentioned; more than 86% of respondents mentioned these factors. More than 30% of the respondents (n=62) confirmed that their vegetarian consumption was mainly for the public interest, rather than personal-related motivation. Second, in 101 (87%) out of 116 comments received from urban respondents, the main focus was ethical consideration, environmental protection, resource conservation, and climate change. This reflected that they were more concerned about external environmental protection and sustainable social development. However, on the other hand, only 62 (68.8%) out of 90 rural respondents focused on ethical consideration and environmental protection, and 10 (11.1%) respondents in rural areas mainly emphasize their nutrition structure improvement, fiber intake, losing weight, and long-term eating habits. This finding reflects rural tourists' emphasis on food and diet diversity.

TABLE 7 Respondents' comments on other barriers to vegetarianism.

Theme 1: Traditional prejudice and habit

It must also be noted that vegetarianism is treated with prejudice in our culture completely - there are vegetarian traditions in many other countries and cultures but modern-day vegetarianism is largely seen as a privileged upper classes' movement which marginalizes people of remote villages.

Vegetables are contaminated with pesticides.

It is very expensive to buy organic vegetarian food

Eating vegetarian cannot meet nutritional requirement for human beings

The concept of balanced diet requires eating not only vegetables but also the meat

Theme 2: Peer pressure

I don't have vegetarian friend at all

I always have to justify myself while I am eating vegetarian

Some of my friends are annoyed of vegetarians

I have a meat-eating boyfriend

The public is ignorant of vegetarianism

Theme 3: Unavailability and limited choice

There are no vegetarian meals in my university

The vegetarian food in school cafeterias or normal supermarkets are often not clearly labeled - this means I often have to read through the ingredients, which is time-consuming and annoying

Limited access to vegetarian groceries

The fact that vegetarian foods are more expensive

There are no plenty of good vegetarian restaurants. The real vegetarian restaurants in my city can only be found at canteen of temples.

It is difficult to purchase the vegetarian ingredients in some rural cities

Theme 4: Unwillingness or inability to change

Lack of time to make my own food

It takes much longer for prepare the vegetarian diet, thus I am unwilling to accept

I still miss the taste of meat

It is difficult to keep being vegetarian

TABLE 8 Perceived benefits sorted by importance.

Items	Score
Environmental protection and resource conservation	4.19
Ethical consideration	3.76
Personal taste and choice	3.69
Personal healthcare issue	3.52
Personal interest	2.43

1, strongly disagree; 2, disagree; 3, neutral; 4, agree; 5, strongly agree.

Table 7 (below) summarizes the respondents' comments on other barriers to vegetarianism.

Traditional prejudice and habits, peer pressure, unavailability, and limited choice in a vegetarian diet were cited by 90% of the respondents as barriers. Of the 206 respondents, 185 (89.8%) mentioned unavailability and limited choice, 111 (53.8%) cited peer pressure, and 108 (52.4%) stated traditional prejudice and habit. However, one urban respondent remarked, "There is no barrier, only excuses." This reflects how some urban Generation Z are actively supporting the vegetarian movement and are confident about this new consumption trend. More than 90% of the respondents insist on adopting a vegetarian diet their whole life after acceptance. In rural areas, however, more than half of the respondents are not so confident about the new trend, as one participant replied: "It seems extreme for many. It would be more attractive for many people to motivate them to reduce the consumption of animal products as a first step." Rural participants are confused by the traditional concept of a balanced diet, and they have a long history of consuming animal products. Therefore, they seem to face greater barriers when choosing vegetarianism. Almost every rural respondent claimed that they may face greater challenges of vegetarian consumption during travel compared with urban ones.

Through content analysis, this study identified high-frequency words used to explain barriers to vegetarianism. This included limited plant-based options, unavailability, high search costs, the temptation of social circle, family members' request, and peer pressure. However, when asked about prospects, 90% of them remained positive about vegetarian consumption, and almost everyone advocated the promotion of vegetarian consumption during travel.

Hypotheses testing

The perceived benefits and barriers were ranked based on mean utilizing descriptive statistics (see Table 8). The top four motivations were mainly related to environmental protection and resource conservation (4.19), ethical consideration (3.76), personal taste and choice (3.69), and personal health

(3.52), and all these benefits contributed to vegetarian consumption positively. Second, the quantitative outcome of Figure 1 illustrates participants' most-frequently articulated motivations as ethical consideration (90.3%), personal taste, and environmental and resource motivation (86.4%). Thirdly, the qualitative analysis demonstrated that 86% of the participants were vegetarian mainly for the public interest, rather than personal-related motivation.

Therefore, based on the above analysis, it can be stated that the external driving factors of environmental protection and ethical consideration are the top priorities for vegetarians. Thus, H₂ can be accepted.

Similarly, as seen from Table 6, the score of "personal interest" is only 2.43, which is below the average score of 3.0 (it represented the neutral). Taken together with the representation in Figure 1, the response rate of personal interest-related motivation is 22.8%, which is much less than the others. Furthermore, the qualitative analysis outcome also proved that personal-related motivation was not compelling. Thus, H₁ cannot be accepted, as for most respondents, personal interest did not contribute to their vegetarianism.

The top-ranking mean scores for perceived barriers to vegetarian consumption are presented in Table 9. The top three barriers were mainly related to unavailability and limited choice (2.49), peer pressure (2.46), and traditional prejudice and habit (2.35). This implied that the lack of availability of plant-based options and peer pressure had a stronger influence on vegetarian diet consumption. The quantitative outcome of Figure 2 also shows that the most frequently mentioned barriers by the respondents were unavailability and limited choice (62.1%), peer pressure (53.9%), and traditional prejudice and habit (52.4%). In addition, the qualitative analysis demonstrated that high-frequency words used by the respondents included limited plant-based options, unavailability, high search costs, the temptation of social circles, and traditional consuming habit.

From the above, it can be determined that the principal barriers were unavailability and limited choice, peer pressure, and traditional prejudice and habit, and they have a stronger negative influence on vegetarian diet consumption. Thus, H₅ was accepted.

Although all these factors were said to pose a negative influence on the respondents' choice of vegetarianism, the scores for these factors were all below 3.0. This indicated that these factors were weak correlations with perceived barriers, and had a relatively limited weak influence on customers' vegetarian consumption. In addition, the qualitative outcome also revealed that 90% of the respondents were positive about the future of vegetarian consumption although some barriers existed. Thus, the negative influence of these barriers was relatively low for the respondents. Therefore, combining the quantitative and qualitative outcomes together, it can be concluded that H₄ was not accepted.

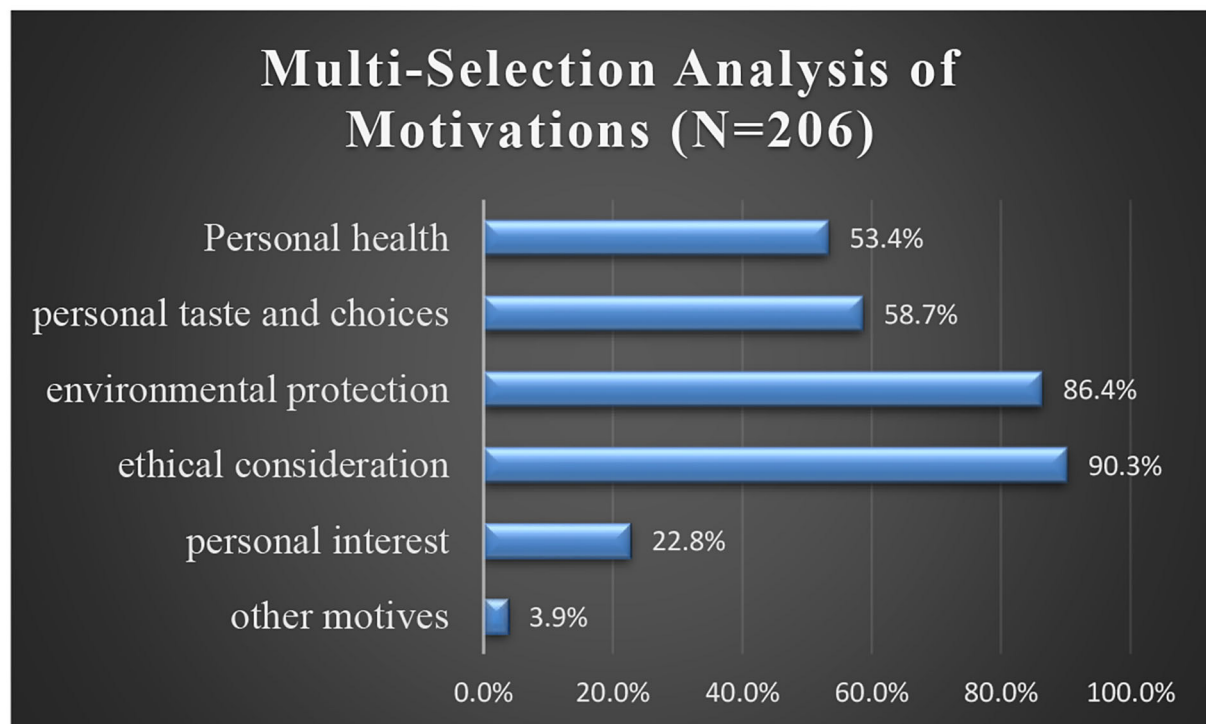


FIGURE 1
Motivations for adopting a vegetarian diet.

The ranking of mean scores for perceived benefits and barriers to vegetarian consumption between rural and urban respondents is listed in Table 10. For the rural respondents, the top three benefits were environmental protection and resource conservation (3.67), personal taste and choice (3.44), and ethical consideration (3.36). This result was somewhat similar to urban respondents whose top three benefits were environmental protection and resource conservation (4.56), ethical consideration (4.05), and personal taste and choice (3.81). Two benefits including environmental protection and resource conservation and ethical consideration were included in both groups, which reflected that both have similar perceptions of motivations regarding vegetarian diets. The subtle difference was in that the average score of urban respondents was higher than their rural counterparts, which indicated that the motivation power in the urban areas was bigger. In addition, the results also demonstrated that urban vegetarians emphasized more on the benefits of environmental protection and ethical consideration, while rural vegetarians emphasized environmental protection and food and taste.

The results of ANOVA (used to test the differences between the two groups) are presented in Table 11. It shows that, though participants' score on benefits was significantly higher for urban tourists ($M = 3.638$, $SD = 0.527$) than rural tourists ($M = 3.266$, $SD = 0.354$, $p < 0.001$), we

TABLE 9 Perceived barriers sorted by importance.

Items	Score
Unavailability and limited choice	2.49
Peer pressure	2.46
Traditional prejudice and habit	2.35
Unwilling or inability to change	2.03

1, strongly disagree; 2, disagree; 3, neutral; 4, agree; 5, strongly agree.

found no significant differences between the urban and rural perception of benefits ($F < F_{crit}$, $p = 0.44142$). These results suggest that there are similar perceptions about the benefits of adopting vegetarian diets in both urban and rural China. Both ethics-related and environmental protection-related motives contributed positively and equally to their perceptions, and they have equal importance among rural and urban respondents. Thus, H_3 was not accepted.

Concerning the comparisons of perceived barriers, the top three barriers to vegetarianism among rural participants were traditional prejudice and habit (3.06), unavailability and limited choice (3.03), and peer pressure (2.98). The orders of these barriers were somewhat different from urban perceived barriers which were unavailability and limited choice (2.07),

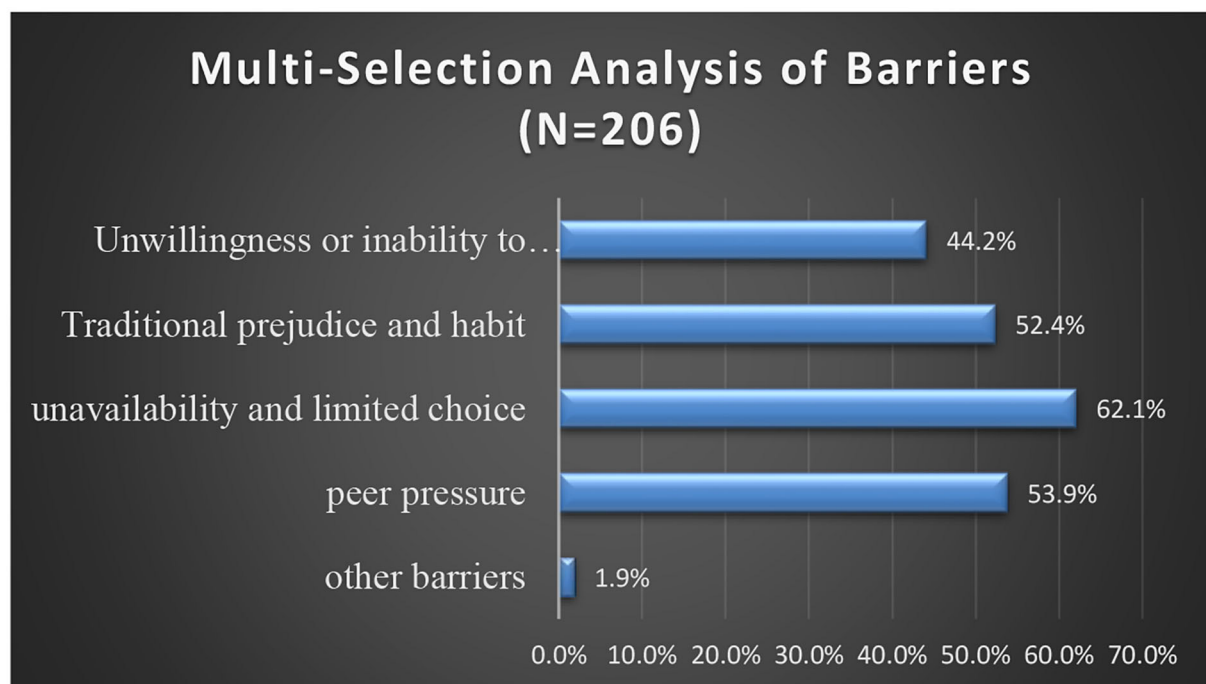


FIGURE 2
Barriers for adopting a vegetarian diet.

TABLE 10 Perceived benefits and barriers to vegetarianism between rural and urban respondents.

Perceived benefits

	Rural	Urban
Personal health issue	3.23	3.73
Personal taste and choice	3.44	3.81
Environmental protection and resource conservation	3.67	4.56
Personal interest	2.63	2.04
Ethical consideration	3.36	4.05

Perceived barriers

	Rural	Urban
Traditional prejudice and habit	3.06	1.81
Peer pressure	2.98	2.06
Unavailability and limited choice	3.03	2.07
Unwillingness or inability to change	2.53	1.65

1, strongly disagree; 2, disagree; 3, neutral; 4, agree; 5, strongly agree.

peer pressure (2.06), and traditional prejudice and habit (1.81). This indicated that although rural and urban respondents have similar perceived barriers, they differ in their levels of

influence. While rural respondents view traditional prejudice and unavailability and limited choice as the top two barriers, urban respondents considered unavailability and limited choice and peer pressure as the top two barriers. In addition, the score of rural respondents was much higher than the urban scores, indicating that the former faced a higher level of barriers and challenges to vegetarianism.

The result of testing the differences in terms of perceived barriers using ANOVA is presented in Table 12. The results show that the participants' score on barriers was significantly higher for rural tourists ($M = 2.900$, $SD = 0.314$) than for urban tourists ($M = 1.898$, $SD = 0.216$, $p < 0.001$). Moreover, we observed significant differences between urban and rural perceptions of barriers ($F > F_{crit}$, $p = 0.00079$). These results mean that rural participants experienced a higher intensity of barriers compared with urban participants concerning vegetarianism. Thus, H_6 was accepted.

Rural vegetarians consider traditional prejudice and habit as the most important barrier, but for urban vegetarians, unavailability and limited choice were accorded priority. The two groups have different understandings and priority sequencing order and these results are also consistent with the conclusions above. The results from comparing the qualitative data indicate that both urban and rural respondents felt peer pressure, but urban respondents worried more about plant-based diet availability, whereas their rural counterparts paid

TABLE 11 One-Way ANOVA of perceived benefits between rural and urban respondents.

Model summary

Group	Count	Sum	Mean	Variance
Method 1	5	16.33	3.266	0.15203
Method 2	5	18.19	3.638	0.90287

ANOVA						
Sources	Sum of squares	df	Mean square	F	P-value	F crit
Between Groups	0.34596	1	0.34596	0.6559105	0.44142	5.31766
Within Groups	4.2196	8	0.52745			
Total	4.56556	9				

TABLE 12 One-way ANOVA of perceived barriers between rural and urban respondents.

Group	Count	Sum	Mean	Variance
Method 1	4	11.60	2.900	0.06193
Method 2	4	7.59	1.898	0.04169

ANOVA						
Sources	Sum of squares	df	Mean square	F	P-value	F crit
Between Groups	2.0100	1	2.01001	38.79397	0.00079	5.98737
Within Groups	0.3109	6	0.05181			
Total	2.3208	7				

1, strongly disagree; 2, disagree; 3, neutral; 4, agree; 5, strongly agree.

much attention to traditional prejudice and historical eating habits. This was the reason behind the huge difference between them in terms of perceived barriers. Rural participants admitted that they might face greater barriers arising from traditional consuming habits, and the change needs great willpower. However, urban respondents had difficulties in searching for plant-based options. Combing the quantitative and qualitative results, the perceived barriers to vegetarianism to both groups were quite different and thus H_6 was accepted.

The two groups had a different understanding and priority sequencing order which is evident from the quantitative data; the motivational scores of urban respondents were generally much higher than the rural respondents, while the scores for barriers were much higher among the rural respondents. In addition, based on the qualitative data comparison, the results indicated that both urban and rural respondents were motivated by environmental and ethical issues, though rural respondents may face greater challenges in pursuing their vegetarian passion. The open-ended interview results indicated that 90% of the respondents were likely to continue on a vegetarian diet their whole life after adopting vegetarianism. However, in rural areas, more than half of the respondents were not so confident about

continuing this new trend. Compared with urban respondents, rural ones had to face greater barriers arising from long-term meat-eating habits as well as peer pressure. Thus, urban tourists had a higher sense of acceptance toward vegetarian consumption. Therefore, H_7 was accepted.

Table 13 provides a summary of the hypotheses testing. In short, H_2 and H_4 are accepted, H_1 and H_3 are partially accepted, and H_5 is rejected.

Discussion, conclusion, and recommendations

Discussions

Perceived benefits

This research showed that the Generation Z tourists' perceived benefits related to vegetarian consumption included improving animal welfare, increasing food taste and choice, protecting the environment, and improving personal health. Personal interests proved to be not positively related to participants' perceived benefits. Environmental protection,

TABLE 13 Summary of hypotheses testing.

Hypotheses	Result
H ₁ : Personal health, personal taste and choices, environmental protection and resource conservation, personal interests, and ethical consideration are positively related with Generation Z tourists' willingness to follow a vegetarian diet.	Partially accepted
H ₂ : In general, of all the benefits, ethical-related and environmental protection-related motives have stronger positive effect on vegetarian consumption willingness.	Accepted
H ₃ : The positive influence of Ethical-related and environmental protection-related motives are stronger for tourists in urban areas than those in rural ones.	Objected
H ₄ : Traditional prejudice and habit, peer pressure, unavailability and limited choice and unwillingness or inability to change are negatively related with Generation Z tourists' vegetarian consumption	Partially accepted
H ₅ : In general, among all the barriers, unavailability and limited choice, and peer pressure as well as traditional habit and prejudice have stronger negative influence on vegetarian diet consumption.	Accepted
H ₆ : The negative influence of traditional prejudice and habit and unavailability and limited choice are higher for tourists in rural areas than those in urban ones.	Accepted
H ₇ : Urban tourists (vs. rural ones) results in higher sense of acceptance toward vegetarian consumption.	Accepted

animal welfare improvement, and personal demand for multiple food choices were considered the most important benefits. Health-related benefits as well as personal interests ranked relatively low.

This result was just somewhat different from the findings of several studies (13, 15, 21) that were conducted in western countries. In their study, personal health benefits topped as the primary motivation, rather than environmental protection or moral considerations. As to the reasons behind it, firstly, as an oriental and traditional country favoring collectivism (23, 41), the Chinese people are wired to place collective concern as their first priority. Environmental consciousness among the public became a widespread concern since the proposition of "Lucid waters and lush mountains are invaluable assets" in 2005. Therefore, as post-2005 college students, it is understandable that they place environmental protection and ethical consideration in the first place while taking a trip. Second, as Glick-Bauer and Yeh stated, the concept of animal rights protection spread from 2013 onwards, and this particular demography pays much importance to the concept and has been influenced by it deeply (42).

The findings of this study are also similar to the findings of several other studies (14, 16–18) most of which stated that ethical factors were the top motivational factors. With increasing incidents of animal cruelty being reported on the internet and social media, people were getting more and more concerned about animal protection and sustainable development in society (43–45). Thus ethical benefits have also emerged as a top priority (46–48) for people embracing vegetarianism. The results of this research are also similar to the finding of Jansen et al. (19) who reported that people placed importance on ethical consideration and environmental protection first and lastly on personal health.

Perceived barriers

The main perceived barriers to adopting a vegetarian diet, ranked in the order of importance as expressed by the respondents are: unavailability and limited choice (2.49), peer pressure (2.46), traditional prejudice and habit (2.35), and lastly, unwillingness or inability to change (2.03). The lack of information about plant-based diets and limited choices was viewed as the strongest barrier. Vegetarians often face a dilemma of relatively few plant-based diet options when compared with others who eat meat. In fact, because of its small market share in the food industry, the number of vegetarian restaurants is relatively less. Together with high search costs and inconvenience, unavailability becomes the main concern for vegetarians. This finding is consistent with previous research (17, 26, 28, 29) that found that while eating out, the choices for vegetarian food were too limited and lacked the availability of plant-based options.

The influence of peers is also consistent with the findings of recent studies (27, 30) which indicate that family/spouse/partner's meat-eating habits inhibit an individual's vegetarian consumption most. This research supplements Radnitz's research that found family members, friends, and partners influencing vegetarian consumption and their importance of influence were ranked as family members first, friends second, and partners ranked third (17, 49).

Traditional prejudice and habit were also proven to have a negative influence on people's vegetarian choices. Three studies conducted in western countries including the US, Australia, and South Africa had similar results. In Lea and Worsley's study, the main barrier to vegetarianism was satisfaction with meat eating and not being able to give it up (25). In Wieliczki's study, unwillingness or inability to alter their current dietary patterns was among the top three barriers to vegetarian

consumption (27). This finding is consistent with the work of Radnitz et al., which stated that “perception that humans are ‘meant’ to eat meat” and “I think humans are meant to eat meat” among to barriers to vegetarianism. Therefore, people’s enjoyment of eating meat and their unwillingness to change their daily diet is also considered the main barriers (17).

The results of this current research are proven to be consistent with previous research conducted by Lea and Worsley (25), Wieliczki (27), and Radnitz et al. (17), especially the finding that although the vegetarian movement has been ongoing for a long time, significant barriers hindering people to adopt vegetarianism still exist and cannot be eliminated completely (50–52).

Perceived benefits and barriers between rural and urban respondents

As to the perceived motivation for vegetarianism among rural and urban post-millennials, this research found that both groups were motivated by environmental and ethical consciousness which played an equally important role in their decision to become vegetarian. However, subtle differences between the two groups exist; compared with rural vegetarians, urban ones had a better positive understanding of being vegetarian. The reasons may be rooted in the fact that vegetarian consumption started earlier and spread wider in urban regions than in rural areas. This result is consistent with the research by Liu, which noted that urban areas have become the leading force in the ‘vegetarian revolution’, and it also found that “since 2016, most urban young adults, in general, became increasingly aware of the benefits of plant-based nutrition in China” (53).

As to their perceived barriers, this research concluded that traditional prejudice, peer pressure, resource unavailability, and unwillingness or inability to change, all pose negative influences on young people’s decision to adopt a vegetarian diet. The biggest difference is that urban vegetarians consider unavailability and limited choice as their foremost barrier, while rural ones view traditional prejudice and habit as their top barrier. This finding, however, is not in line with the research by Memon et al. (32) and He et al. (36). Both quantitative and qualitative results demonstrated rural participants perceive facing greater barriers from traditional consuming habits as well as limited choices, and the change needs great willpower. Under the pressure of long-term meat-consumption habits, together with limited vegetarian diet options, rural vegetarians find it more difficult to follow a vegetarian diet during their travels. Furthermore, compared with urban participants, the rural vegetarians gave a higher appraisal score of perceived barriers to adopting a vegetarian diet. It can be concluded that rural consumers face much more barriers while adopting a vegetarian diet,

and this finding may enrich regional comparison literature on vegetarian consumption.

Conclusions

This study aimed to explore Generation Z tourists’ perception of vegetarianism, including their perception of benefits and barriers. A self-administrated questionnaire was administered for collecting feedback from 206 participants. Of them, 110 participants were from urban China, and 96 participants were from rural China. All of them were vegetarians aged 18 to 27. Data analysis revealed that people choose a vegetarian diet mainly for environmental protection, animal welfare, food and taste, and personal health. Data comparison found that both rural and urban vegetarians put more emphasis on the benefits of environmental protection and ethical consideration, and the subtle difference between them is that rural vegetarians also emphasized food and taste. The reason is rooted in the fact that urban societies have a longer history of vegetarianism and young people are getting more and more concerned about environmental and ethical issues. The participants’ perceived barriers, listed in the order of their priority are unavailability and limited choice, peer pressure, traditional prejudice, and unwillingness or inability to change. The former two were viewed as the strongest barriers to vegetarianism in general. The difference between them is that urban vegetarians consider unavailability and limited choice as their top-most barrier, while rural vegetarians view traditional prejudice as the main barrier. Due to the pressure of traditional dietary habits and peer influence, rural tourists face much more challenges when adopting a vegetarian diet. And compared with urban tourists, rural ones have a lower sense of acceptance toward vegetarian consumption.

Theoretical contributions

This research contributes to the literature in three aspects. First, although previous studies have discussed consumers’ perceptions of motivation and barriers to vegetarianism consumption, most of them were conducted in western countries. Our research investigated these factors in the Chinese context, adding to the relatively few studies in the literature. Our study extends the understanding of vegetarianism in China. Secondly, recent research has investigated micro-level aspects of benefits and barriers to vegetarian consumption in different regions, and our study goes further to make a comparison and contrast analysis of vegetarians from urban and rural areas. Thirdly, in addition to investigating their motivation and barriers, our work also goes further to establish that rural vegetarians face greater challenges during their travel.

Practical implications

Vegetarian consumption during travel has become a primary concern for vegetarian tourists and deserves additional efforts from both tourist operators and the tourism administration department. As to the business practitioners, the categories of vegetarian diet should be increased and a variety of options should be put forward for vegetarian tourists, besides green production, green packaging, as well as green marketing, should also be adopted for meeting these tourists' demand for environmental protection and resource conservation. Third, reasonable planning schemes should be planned to ensure enough availability of vegetarian providers.

Urban regions have long been viewed as the leading force of vegetarianism in China, and rural regions, with a large population of postmillennial consumers, have gradually realized and accepted the importance of plant-based diets.

As for the tourism administration department, additional efforts should be made to alleviate the most commonly perceived barriers to vegetarianism, i.e., vegetarian counseling and education (53), vegetarian exhibitions, vegetarian lectures, and so on (54–56). Public health departments should also adopt some measures to provide enough information about vegetarian diets and address the public's concerns about them (54, 57). Gradually, the benefits of vegetarian consumption will be understood by generation Z consumers both in urban and rural areas. This would ensure that a nutrition-balanced diet has a bright future in China.

Future research

Few researchers have investigated micro-level aspects of benefits and barriers to vegetarian consumption in different regions, and this present study focuses on perception differences in vegetarian consumption among Generation Z tourists. While on the other hand, this research also has some limitations and needs to be improved in the following aspects: (a) data should be collected from a larger sample of the population. It is suggested to examine their perceived differences in a sample of a broader age range, not just limited to millennials. In fact, due to work pressure and worrisome health conditions, more and more middle-aged populations are turning to veganism. Thus, to have a detailed investigation of their motivations for a change in their diet is also necessary. (b) Future research should also examine the relationship between consumers' perception and their demographic factors such as work status, living conditions, and income, which may have a greater influence on people's perception of vegetarianism. Thus, it is necessary to conduct studies to enrich the theoretical and empirical research on this subject in the future. (c) cross-culture and cross-country perceptual differences in vegetarian consumption is a subject worthy of study. Implications can be drawn

for developing effective interventions for healthy and pro-environment dietary patterns.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

Conceptualization and validation: GC and NR. Methodology and project administration: GC. Software, investigation, and visualization: WT. Formal analysis, resources, and supervision: BY. Data curation: NR. Writing—original draft preparation: GC. Writing—review and editing and funding acquisition: JZ. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Nutrition and its footprints: Using environmental indicators to assess the nexus between sustainability and food

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Current food systems are associated with the unsustainable use of natural resources; therefore, rethinking current models is urgent and is part of a global agenda to reach sustainable development. Sustainable diets encompass health, society, economy, culture as well as the environment, in addition to considering all the stages that make up the food production chain. This study aimed to perform a review on the importance of using environmental footprints (EnF) as a way of assessing the environmental impacts of food systems. The most used EnF to assess impacts related to the food system was the carbon footprint, followed by the water footprint, and the land use footprint. These EnF usually measured the impacts mainly of the current diet and theoretical diets. Animal-source foods were the ones that most contribute to the environmental impact, with incentives to reduce consumption. However, changing dietary patterns should not be restricted to changing behavior only, but should also involve all stakeholders in the functioning of food systems. We conclude that EnF are excellent tools to evaluate and guide the adoption of more sustainable diets, and can be applied in different contexts of food systems, such as food consumption analysis, menu analysis, food waste, and inclusion of EnF information on food labels.

KEYWORDS

sustainable development, environmental indicators, water footprint, carbon footprint, ecological footprint, food systems

1. Introduction

For a long time, nutrition science has been seen as predominantly biological science, comprehending physiological, biological, genomics, and medical aspects and geared toward the interaction between foods and the human body, aiming at preventing and maintaining the health of individuals and populations (Beauman et al., 2021).

According to the Giessen Declaration, the world where we live today is very different from the world in which the concept of nutrition as science was created. The conventional concept of nutrition as a biological science can be adapted and expanded to also include social and environmental aspects. Hence, nutrition science starts being defined as the study of food systems, foods and drinks, their nutrients and other constituents, and their interactions within and among all relevant biological, social, and environmental systems (Beauman et al., 2021).

Food systems are characterized by a complex relation of elements and activities that involve the production, transformation, distribution, and preparation of foods for consumption. Such food systems are key for the health and nutrition of people, influence environmental wellbeing, and promote social justice [Ericksen, 2008; High Level Panel of Experts on Food Security and Nutrition (HLPE), 2014; Organização Pan-Americana da Saúde, 2017]. In 2014, at the Second International Conference on Nutrition promoted by the World Health Organization (WHO), it was discussed that there is a great challenge of current food systems to promote adequate, safe, diversified, and healthy eating to all due to unsustainable patterns of production and consumption that lead to the scarcity of resources and environmental degradation (Food Agriculture Organization of United Nations World Health Organization, 2015).

The currently prevailing food systems, associated with current ways of life and production, have caused harm to the environment, climate change, and excessive use of natural resources, exceeding the biocapacity of the planet, in addition to direct negative impacts on the economy and society. In face of this scenario, the United Nations (UN) released in 2015 the Sustainable Development Goals (SDG) to be reached by 2030 (United Nations, 2015). Among the 17 goals listed, goals 2, 6, 12, and 13 have a direct relation with sustainable food systems since they seek, respectively, to end hunger, achieve food security and improve nutrition and sustainable agriculture, ensure the availability of water and sanitation for all, promote responsible consumption and production, and foster urgent actions against global climate change.

The production of food for humans and animals is one of the activities that most cause climate change, particularly by using natural resources such as water, soil, and energy. Arable land for agriculture and livestock causes significant emissions of greenhouse gases (GHG), and the use of agricultural pesticides contributes to impoverishing the soil and contaminating rivers and water, in addition to reducing biodiversity (Vermeulen et al., 2012; Aleksandrowicz et al., 2016; Campbell et al., 2017). Rethinking the models of food production and consumption is part of a worldwide agenda that seeks to transform the agroindustry model. Considering the principles of sustainability (environmental, economic, and social), the evaluation of impacts on the environment is one

of the ways of incentivizing more sustainable production and consumption.

Environmental indicators are instruments used to assess, compare, and control the impacts on the environment, being a way of keeping a tally of the environmental costs involved in the various steps of processing a product. One example of indicators employed to measure environmental impact at a global scale is environmental footprints, which can be used throughout the food production chain, using the Life Cycle Assessment (LCA) methodology (Garzillo et al., 2019).

The analysis of environmental footprints is also associated with the concept of healthy and sustainable diets. According to the Food and Agriculture Organization of the United Nations (FAO), sustainable diets are dietary patterns that are capable of promoting all dimensions of health and wellbeing of individuals, which have a low environmental impact, and are accessible to all, safe, and culturally acceptable (Food Agriculture Organization of the United World Health Organization, 2019).

Several studies (Vanham and Bidoglio, 2013; Rose et al., 2019; Auclair and Burgos, 2021; da Silva et al., 2021; Vanham et al., 2021) have shown the environmental impacts of diets, from the standpoint of environmental footprints, and also point to the need for changes in dietary patterns and, consequently, food systems, given the impact not only on the environment but also on other dimensions of sustainability.

Furthermore, some dietary guidelines from some countries have already started to discuss the relationship between diets and sustainability. The Dietary Guideline for the Brazilian Population is internationally renowned and is, possibly, one of the first ones to fully incorporate the need for sustainability in the dimension of food supply, expanding the discussion to all three components of sustainability (environmental, economic, and social). Also, the guideline states in one of its five principles that healthy diets derive from environmentally and socially sustainable food systems. Other countries such as Australia, Sweden, Qatar, the Netherlands, Nordic Countries, and some countries of the UK (Brasil Ministério da Saúde, 2014; Monteiro et al., 2015; da Silva Oliveira and Silva-Amparo, 2018; Ahmed et al., 2019) also discuss sustainability in their dietary guidelines. This review is considered essential for the academic community and society as there is still the need to explore content and include factors to assess nutrition from a sustainable perspective. In this sense, this review aims to summarize the applicability of environmental footprints in the context of food consumption analysis and its relationship with nutrition, highlighting the relevance and need for a transformation in the current production model toward more sustainable food systems in a global approach. In this sense, this review seeks to answer the following question: “How is the concept and applicability of environmental footprints inserted in the food system, considering socioeconomic, cultural, environmental, and health dimensions?”.

2. Materials and methods

2.1. Search strategy

The information contained in this study comes from an extensive review of the literature on the relationship between environmental footprints and human nutrition. Therefore, this review was carried out in a non-systematic way from February 2021 to December 2021. Google Scholar, PubMed, and ScienceDirect databases were used to identify relevant studies according to the development of the review and complemented with a manual search in the reference lists of selected studies. Books, reports, and official documents were also included. Search terms were the following Health Sciences Descriptors: “environmental footprint,” “sustainable diet,” and “food consumption.” The inclusion criteria were the relevance of the bibliographic material, regardless of the year or place of publication, and articles or documents written in English, Spanish, or Portuguese. Conference abstracts, thesis, preprint, and review articles were excluded. The selection of articles, official documents, books, and reports cover the period from 2000 to 2021. Any disagreement was resolved through discussion between the authors.

2.2. Study selection

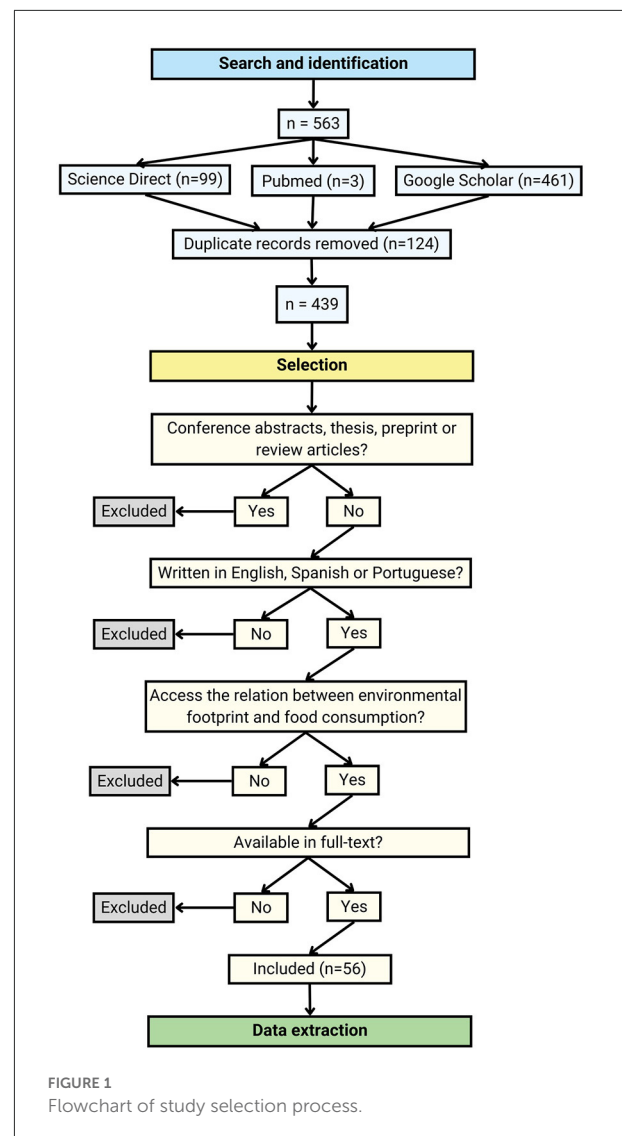
Authors reviewed all studies that met the following criteria: (1) Access relation between environmental footprint and food consumption; (2) Available in full-text.

2.3. Data extraction

The following information was extracted from each selected study: Author, year of publication, location, aim, environmental footprints analyzed, food and/or diet data source, and main findings. The methodology used for this study is better described in Figure 1.

3. Background: Concepts, concerns, and advances in the relationship between nutrition and sustainability

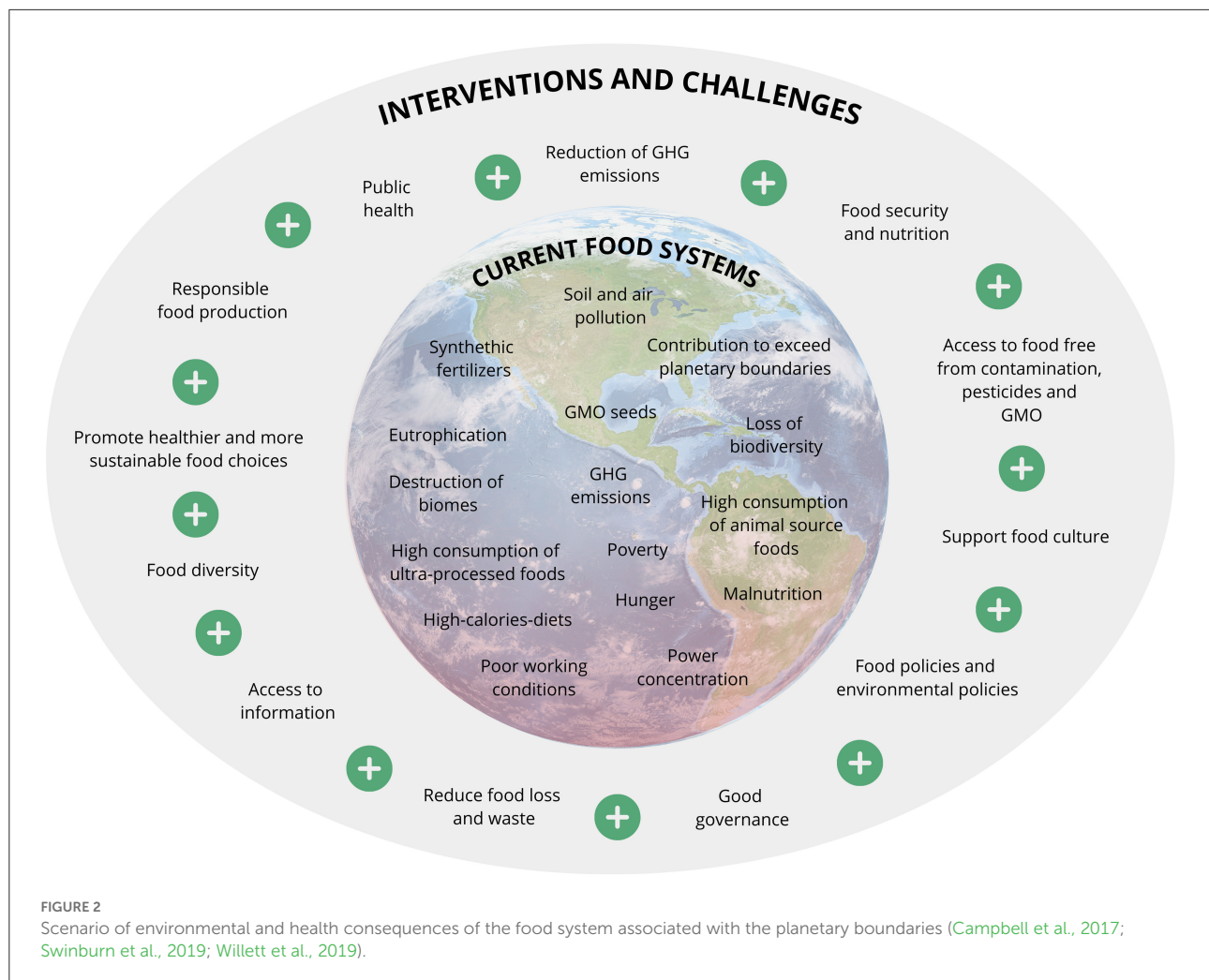
Before presenting the results of the study, it is worthwhile to give an overview of how food production and diets have impacted planet earth over the years, as well as introduce the environmental footprints.



3.1. Food systems and environmental impacts

The current food systems have caused several impacts on the environment. Food production contributed to up to 34% of the total GHG emissions in 2015, of which 71% of this amount came from agriculture. Food production is also associated with deforestation, soil degradation, and considerable loss of biodiversity on the planet (Jägerskog and Jøneh Clausen, 2012; Vermeulen et al., 2012; Crippa et al., 2021).

Current dietary trends, combined with the forecast of population growth of around 10 billion in 2050, may exacerbate the risks to people and the planet. The effects of food production threaten the stability of the Earth's system *via* emissions of GHG, pollution with nitrogen and phosphorus, loss of biodiversity, and water and land use. Strong trends indicate that food



production is one of the greatest drivers of environmental change on the planet (Willett et al., 2019).

In 2009, Rockström, along with other scientists, introduced the concept of Planetary Boundaries (PB), which can be defined as the nine processes that regulate the stability and resilience of planet Earth. By identifying those processes, quantitative limits (high risk, increasing risk, and safe) were also proposed within which humanity could develop. Overcoming the limits (safe operating space) would raise the risk of causing changes to the environment, which could be large and irreversible (Rockström et al., 2009a,b).

The nine PB are (1) land-system change; (2) freshwater use; (3) biogeochemical flows—nitrogen and phosphorus cycles; (4) biosphere integrity; (5) climate change; (6) ocean acidification; (7) stratospheric ozone depletion; (8) atmospheric aerosol loading; (9) introduction of novel entities. Steffen et al. (2015) suggest that at least four PBs have been exceeded, which means they are in the uncertainty/risk zone, possibly causing irreparable changes, namely: climate change, land-system change, biogeochemical flows, and biosphere integrity.

Recently, studies have indicated that the planetary boundaries of freshwater use (specifically the green water) and novel entities have exceeded (Persson et al., 2022; Wang-Erlandsson et al., 2022).

According to Campbell et al. (2017), the current agricultural production is associated with destabilizing the Earth system and has been identified as the main driver of two PBs: land-system change and freshwater use, besides also directly contributing to climate change. Figure 2 shows a graphical representation of the problems caused by the food system that are also related to the PB and some actions needed to protect the Earth and humankind. It is possible to understand how current food systems impact dimensions that go beyond the environment, such as promoting increased hunger and malnutrition, and changes in dietary patterns, favoring the consumption of foods with a high amount of calories and high consumption of food of animal origin.

In this context, the broad approach to nutrition is increasingly necessary when we approach the issue of current food system impacts. The concept of “sustainable nutrition”

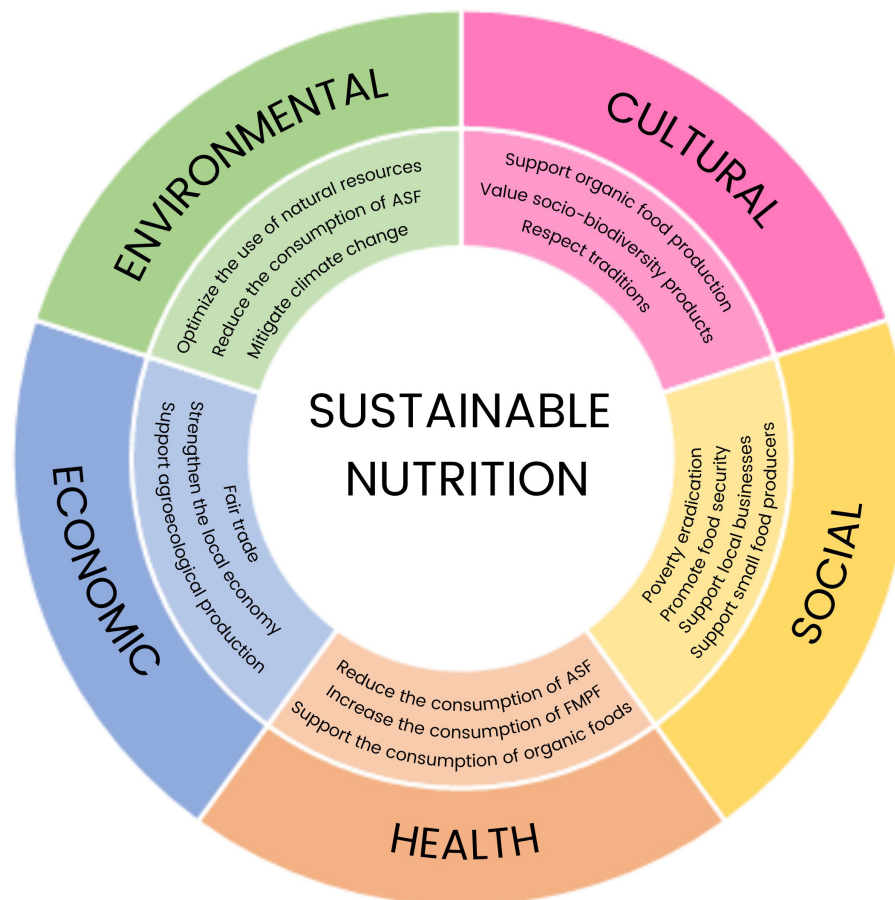


FIGURE 3

Dimensions of Sustainable Nutrition: Symbol of Life. ASF, Animal source foods; FMPF: Fresh or minimally processed foods (von Koerber et al., 2017).

was developed by von Koerber et al. (2017) discusses well how the various dimensions of sustainability should be worked together. Previously, sustainability was defined by three pillars (social, economic, and environmental), the authors, however, include two new pillars to create the concept of “sustainable nutrition” which are health and culture. Health was included since sustainable eating has beneficial effects on health, and culture influences the formation of dietary habits. The authors also enumerated seven principles for individuals to reach sustainable nutrition. Figure 3 illustrates the concept of sustainable nutrition, containing some examples of actions that fit into each of the five dimensions.

This complex relationship between nutrition and food systems was further explored in a recently published report that discusses the Global Syndemic.

The word “syndemic” means a synergy of pandemics, i.e., two or more diseases that coexist and interact and have in common the same social motivators. The Global Syndemic

involves obesity, malnutrition, and climate change pandemics (Swinburn et al., 2019).

According to the report, one of the greatest drivers of this worldwide issue is food and agriculture (Swinburn et al., 2019). The planet currently produces enough food to meet the needs of the global population, however, over one-third of the global population is impacted by malnourishment and nutritional deficiencies. It is estimated that one-third of what is produced is lost and wasted, and how the current food systems are organized today influences this dynamic. Because of globalization and the growing need for commodities to attend to the interests of large food corporations, agriculture production tends to favor the production of basic and energetic foods, not focusing so much on nutritional value.

In this context, the current food system delivers low-quality food, with severe expenses in production, distribution, and consumption, and with a high cost to the environment. As a very important factor for sustainability, diets affect different social, cultural, economic, agricultural, environmental, and

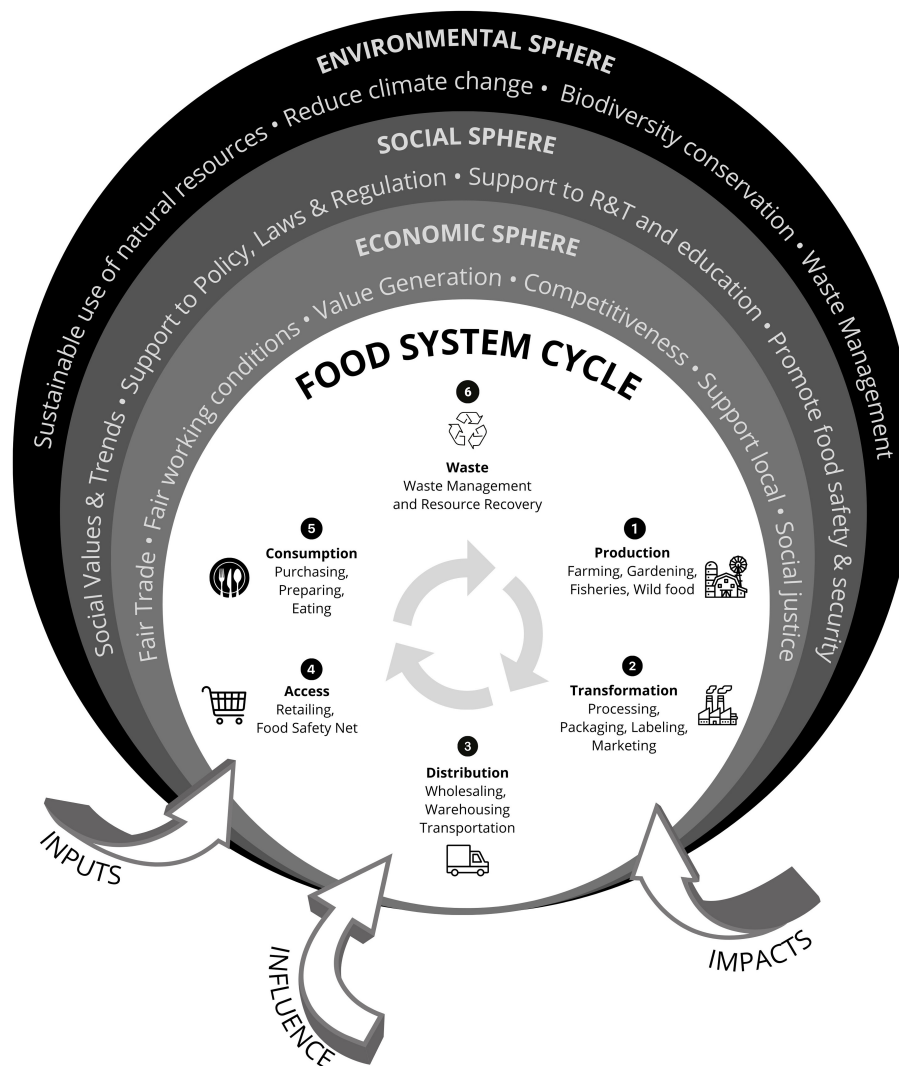


FIGURE 4

Representative scheme of a sustainable food system. R&T, Research & Technology; Inputs, Human Resources (e.g. laborers, managers, professionals) and Natural Resources; Impacts, Outcomes; Influence, Social and Economic Sphere (Harmon and Gerald, 2007; von Koerber et al., 2017; Nguyen, 2018; Bhunnoo and Poppy, 2020).

nutritional factors, which interact with one another (Food Agriculture Organization of the United Nations, 2010). Scientific evidence around the world point to the need to change current food systems toward healthier and more sustainable ones, thinking about the development of more sustainable cities, more resilient healthcare systems, a reduction in food loss and waste, preservation of ecosystems, and reduction in the emission of GHG, among other actions [High Level Panel of Experts on Food Security and Nutrition (HLPE), 2014; Hawkes and Fanzo, 2017; High Level Panel of Experts on Food Security Nutrition HLPE, 2017; IPES-Food, 2017; Food Agriculture Organization of the United World Health Organization, 2019].

In face of this discussion, in Figure 4 we can see a scheme of what a sustainable food system would be like taking into account

the three pillars of sustainability and how each one contributes to this system.

3.2. Environmental indicators: Initial concepts

The use of indicators that measure the environmental impact of products, production processes, and behavioral patterns of society has proven important to warn about the damage caused to the environment. Such indicators assess the potential environmental impact of production processes and help identify points where the consumption of natural resources can be

reduced or where to introduce technologies that reduce or even eliminate the pollution load. They are objective parameters in the choice of products or the adoption of environmentally favorable practices and, in the context of nutrition, can guide the choices of foods and diets (Garzillo et al., 2019).

Some environmental indicators that may be employed in the analysis of food consumption are environmental footprints. According to van Dooren et al. (2018a), 15 different footprint indicators have been identified, of which ten are relevant to the agricultural and food system. After carrying out a literature review, those authors identified five main footprints that are used as instruments to assess nutrition and diets as a whole. The main footprints are ecological footprint, carbon footprint, water footprint, energy footprint, and land footprint. The carbon and land footprints are derived from the ecological footprint. We will discuss below with greater emphasis the carbon, water, and ecological footprints.

3.2.1. Carbon footprint (CF)

There is not a universally accepted definition for CF, and about which gases are included in this estimative. In this sense, for this review we will accept the concept that the CF is “an estimate of the total amount of GHG emitted from a life cycle perspective from the product under study, thus giving an estimate of the contribution to climate change from the product or service provided” (Röös, 2013). The CF is commonly expressed in carbon equivalent (CO₂eq). The emissions for each of the different gases are converted to CO₂eq using the global warming potential factor (GWP), considering the GWP for a time horizon of 100 years, as established by the Intergovernmental Panel on Climate Change (IPCC).

The analysis of CF is considered a measure of climate change impact and makes use of the LCA methodology to assess the potential impact on global warming of different activities or individuals.

The LCA methodology began between the 1960s and 1970s, however, only in the 1990s did it become popular worldwide. According to ISO 14044:2006, the LCA can be defined as a “compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle.” Normally, the LCA is described in six steps, namely: (1) Raw materials extraction; (2) Material processing; (3) Production, Manufacturing, and Assembly; (4) Distribution; (5) Use; (6) End of life (International Standard Organisation (ISO), 2006; Matthew and Defne, 2012).

It is important to also highlight the need to define the limits of the system under study, i.e., isolate it from the natural system. To analyze the production of grains, vegetables, and fruits, for example, the steps of cultivation and harvest must be analyzed. To analyze ready-to-eat foods, the steps of use, consumption, and preparation of those foods at home must be included. And, finally, an analysis of the entire cycle of food must consider

from the beginning until the generation of residues (Pandey and Agrawal, 2014; Röös et al., 2014).

Establishing such boundaries is important so the results can be used in the best way possible, according to the goal. When comparing different agricultural practices, for example, ideally analyses would be used that tally up the emissions up to the gates of the farm. It is also important to point out the difficulties related to the development of such cradle-to-plate studies, for example, since the post-retail steps are controlled by the consumer and those may vary widely, which hinders the calculation (Pandey and Agrawal, 2014; Röös et al., 2014). Figure 5 shows some examples of boundaries that may be used to assess the environmental footprints established for foods.

In that sense, it is common to see a large variation between the values of footprints, even if it is the same product. That variation occurs because, as the analysis takes into account the entire LCA involved in the production of a given food, it may vary depending on the production system (Röös et al., 2014).

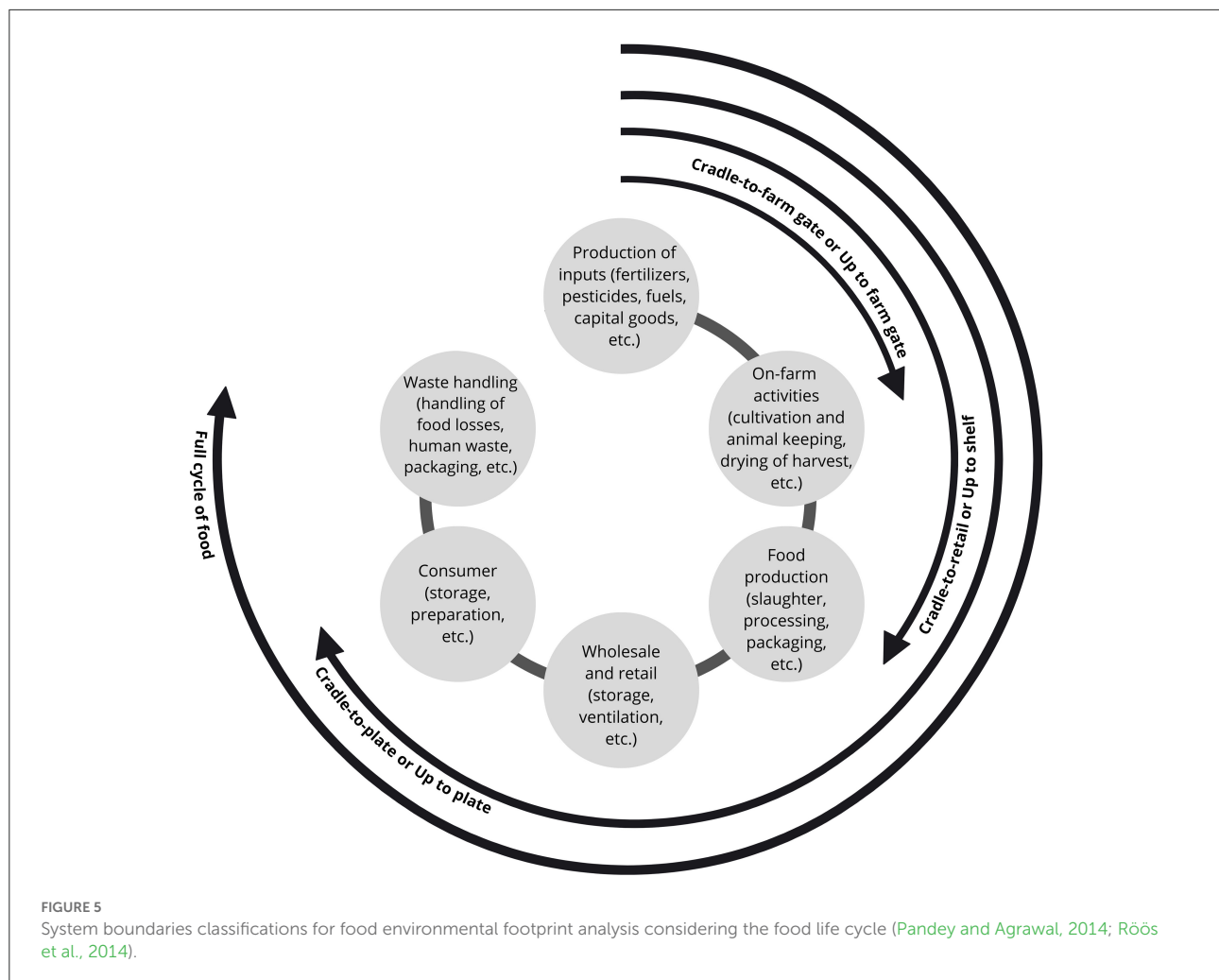
3.2.2. Water footprint (WF)

The WF, developed by Arjen Hoekstra in 2002, is an indicator of the use of freshwater, whether directly or indirectly. The WF considers the entire volume of water used throughout the productive chain, also using LCA methodology. The WF is multi-dimensional and works with several concepts, and is subdivided into three: green water, blue water, and gray water. Blue water refers to the use of surface or subterranean water (such as rivers, lakes, and aquifers), green water refers to the use of rainwater, and the gray footprint is associated with pollution, more specifically with the volume of water needed to assimilate the load of pollutants generated (Hoekstra, 2003, 2008, 2011).

Although the water footprint assesses the consumption and pollution of freshwater, it is not a measure that assesses the severity of the environmental impact. That occurs because analyzing the environmental impact caused by those activities also involves analyzing the vulnerability of the local water system and the number of consumers and polluters, therefore, this interpretation will vary according to each water system (Hoekstra, 2003, 2008, 2011).

The evaluation of the WF may have several focuses, i.e., one can assess the WF of processes, products, individuals, a community, companies, a geographically delimited area, or even of humanity as a whole. What will guide this analysis is the objective, from which the calculation of the footprint will be planned, specifying what will and will not be included in the analysis (Hoekstra, 2003, 2008, 2011).

Thinking about food production and consumption, the WF employed would be those with a focus on products and on a consumer or group of consumers. For the WF of a product, the estimate is done based on the amount of water consumed and the pollution generated in all steps of the productive chain. In the case of foods and agricultural products, WF is normally



expressed as m^3/ton or liters/kg , but it may take other formats. In the case of diet analyses, for example, the values might be expressed in volumes of water/kcal (Hoekstra, 2003, 2008, 2011).

3.2.3. Ecological footprint (EF)

The EF was created as a tool able to assess the demand human activity imposes on the biosphere. More precisely, the EF seeks to measure the biologically productive area of land and water needed to produce all the resources and absorb the residues of an individual, population, or activity. This area analyzed can be defined as biological capacity or biocapacity. Thus, the EF seeks to jointly assess the environmental impacts caused by human beings, impacts that are normally assessed separately, such as GHG emissions (Wackernagel and Rees, 1998; Galli et al., 2012; Garzillo et al., 2019; Global Footprint Network, 2022a).

Biocapacity can be defined as the capacity that ecosystems have of regenerating what people demand from them. The value of biocapacity may change year over year due to human

intervention (Global Footprint Network, 2009). In 2017, the biocapacity of the Earth was estimated at 1.6 gha per person, while the global EF was 2.8 gha per person, i.e., a deficit in biocapacity reserve of -1.2 gha per person. In other words, it is estimated that we would need 1.73 planets to sustain the needs of the human population (Global Footprint Network, 2022a).

Biocapacity is measured in five large types of land, whereas the EF is measured in six. The five types of land or areas analyzed by biocapacity are (1) crops; (2) grazing land; (3) fishing grounds; (4) forest; (5) built-up land. For analysis of the EF, the following lands are considered: (1) crops; (2) grazing products; (3) forest products; (4) seafood; (5) built-up land; (6) carbon footprint (Wackernagel et al., 2019).

Both EF and biocapacity are expressed as global hectares (gha). One global hectare is a biologically productive hectare, with the analysis of the mean worldwide productivity. An analysis of gha also takes into account the type of land, seen as each land has different productivity, such as agricultural land being worth more gha than grazing land. In this way, to convert the calculations and reach the value in gha, one needs

the equivalent factor. Each territory assessed has its own, which represents the global average productivity for each of the types of land assessed, which is divided by the mean global productivity for all types of land. When we analyze the EF of a product, it has been standardized expressing those results as global hectares per year (Global Footprint Network, 2009; Wackernagel et al., 2019). According to the objective of the study and what it intends to analyze, other approaches may be used and other measures may arise.

The ecological footprint, when compared with the water and carbon ones, is the only one capable of providing an ecological benchmark, i.e., biocapacity, which allows establishing clearer targets. It is also worth pointing out that the water and carbon footprints are closely related to estimates based on the analysis of the life cycle of products or processes, whereas the ecological footprint manages to have a broader approach, that seeks to assess the renewable resources available and their use for consumption by goods and services, not focusing so much on production cycles (Becker et al., 2012). However, EF had been criticized in recent years due to lack of transparency and standardization of analyzes. In that respect, in 2009, the standards for EF analysis were published to ensure that the evaluations of footprint are conducted and communicated more precisely and transparently (Global Footprint Network, 2009).

4. Results and discussion

Dietary patterns can be defined as “the quantities, proportions, variety, or combination of different foods, drinks, and nutrients (when available) in diets, and the frequency with which they are habitually consumed” (Alexandria, 2014). Those patterns are changing due to the increase in movement of people to urban centers and cities, demographic changes, increase in the number of meals had away from home, increase in the size of portions and amount consumed, besides the influence of globalization and commerce on the food sector (Fanzo and Davis, 2019).

Due to these changes, an increase has been noticed in the consumption of critical components and some dietary groups such as red meat, dairy, sugar beverages, and processed and ultra-processed foods, which are rich in sodium, sugar, and saturated and trans fats. These current dietary patterns have a direct impact on health, being considered the greatest risk factors for several forms of malnutrition, deaths, and disability-adjusted life-years (DALYs) around the world (Afshin et al., 2019; Swinburn et al., 2019).

That said, changes in the dietary patterns of populations are increasingly discussed with a view to promoting healthier and more sustainable patterns. According to the FAO, healthy and sustainable diets are “dietary patterns that promote all dimensions of individuals’ health and wellbeing;

have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable” (Food Agriculture Organization of the United World Health Organization, 2019). With this in mind, healthier and more sustainable dietary patterns feature lower amounts of animal-source foods, particularly red meat, and processed and ultra-processed products (Swinburn et al., 2019).

The use of environmental indicators such as the WF, CF, and EF may serve as a basis for educational actions and public policies that prioritize the supply of foods that do not negatively impact the environment. According to Lovarelli et al. (2018), one of the greatest environmental impacts caused by activities such as agriculture and food production is related to water consumption. Several studies have also shown the impacts food supply has regarding GHG emissions and other Earth impacts. The consumption of foods at a global level is considered one of the activities that most demand resources, being also considered one of the main drivers of environmental impacts. The food production chain is responsible for 19–29% of all GHG emissions from human activities. Furthermore, 50% of all GHG emissions generated by this food chain come from agricultural activities, related to cattle and emissions of methane gas and nitrous oxide, once again highlighting the impact current dietary patterns have on the environment (Searchinger et al., 2008; Friel et al., 2009; Notarnicola et al., 2017).

According to data provided by the Global Footprint Network, considering the areas analyzed for estimating the EF, the component with the greatest contribution was the carbon footprint with 1.06 gha per person. This same pattern is seen in other countries, which shows the great impact that gas emissions have at both the global and national levels and, as previously mentioned, food production accounts for a considerable percentage of those emissions. The second area that exhibited a greater contribution of EF values was cropland, i.e., the area associated mainly with food production, again showing the impact that food has on the environment and the pressure it exerts on the natural systems of the planet (Global Footprint Network, 2022b).

In face of that context, studies targeting the analysis of the environmental impact of food consumption have been increasingly frequent, especially those associated with the analysis of environmental footprints. For this review, we select articles that analyzed the environmental impacts of food consumption in various dimensions. Figure 6 provides a summary of the selected studies’ characteristics.

As seen in Figure 6, most of the selected studies ($n = 49$) used CF as the main indicator to assess the sustainability of food systems. The other footprints that were also widely used were WF ($n = 27$), land use ($n = 14$), energy use ($n = 12$), and EF ($n = 7$). Some studies used innovative footprints such as the studies by Ridoutt et al. (2020, 2021) and Belgacem et al. (2021). The analysis of the different footprints provides a broader view of the different impacts associated with food systems.

Author	Context	Environmental footprint											Food / Diet							
		GHGE	Water	Ecological	Energy use	Land use	Nitrogen	Phosphorus	Eutrophication potential	Pesticide toxicity	Cropland scarcity	Cropland biodiversity	Cropland malnutrition	Actual diet	Theoretical diet	Menu	Food waste	Future projections	Food labels	Food purchase
Auclair and Burgos, 2021	Canada																			
Bahn et al. et al., 2019	Middle East and North Africa																			
Battle-Bayer et al., 2020	Spain																			
Belgacem et al., 2021	Europe																			
Biesbroek et al., 2017	Netherlands																			
Biesbroek et al., 2018	Netherlands																			
Bruno et al., 2019	Denmark																			
Cao et al., 2020	China																			
Chapa et al., 2020	USA																			
Chen et al., 2020	Global																			
Esteve-Llorens et al., 2019	Galicia, Spain																			
Esteve-Llorens et al., 2019	Galicia, Spain																			
Esteve-Llorens et al., 2020	Portugal																			
Esteve-Llorens et al., 2021	Spain																			
Esteve-Llorens et al., 2021	Spain																			
Galli et al., 2017	Mediterranean																			
González et al., 2021	Spain																			
González-García et al., 2020	Spain																			
Grasso et al., 2020	Netherlands, UK, Germany, and Spain																			
Grosso et al., 2020	Italy																			
Hadjikakou, 2017	Australia																			
Han et al., 2020	China																			
Hatjiathanassiadou et al., 2018	Brazil																			
Kesse-Guyot et al., 2021	France																			
Lacour et al., 2018	France																			
Laurentis et al., 2017	England																			
Leach et al., 2016	NA																			
Long et al., 2021	China																			
Matzembacher et al., 2020	Brazil																			
Mehlig et al., 2020	Sweden																			
Mogensen et al., 2020	Denmark																			
Naja et al., 2018	Lebanon																			
Naja et al., 2020	Lebanon																			
Rabès et al., 2020	France																			
Ridoutt et al., 2020	Australia																			
Ridoutt et al., 2021	Australia																			
Rose et al., 2019	USA																			
Rosi et al., 2017	Italy																			
Rossi et al., 2021	Italy																			
Sáez-Almendros et al., 2013	Spain																			
Scheelbeek et al., 2020	UK																			
Seconda et al., 2018	France																			
Silva et al., 2021	Brazil																			
Sjörs et al., 2016	Sweden																			
Song et al., 2015	China																			
Strasbourg and Jahno, 2015	Brazil																			
Tang and Sobko et al., 2019	China																			
Travassos et al., 2020	Brazil																			
Üçtuğ et al., 2021	Turkey																			
Vale et al., 2021	Brazil																			
Van de Kamp and Temme, 2018	Netherlands																			
van de Kamp et al., 2018	Netherlands																			
van Dooren et al., 2018	Netherlands																			
Vanham et al., 2021	Mediterranean																			
Veeramani et al., 2017	Canada																			
Wang et al., 2020	China																			
Total		49	27	7	12	14	5	2	1	1	1	1	1	41	17	6	6	1	1	3

FIGURE 6

Summary of the characteristics of the selected studies ($n = 56$). GHGE, Greenhouse gas emissions.

Ridoutt et al. (2021), for example, highlighted that a dietary shift toward recommended diets could increase the pesticide toxicity footprint compared to the current average diet in the Australian population. This would contradict dietary recommendations to eat a variety of fruits of different types and colors, once those foods make a large contribution to the dietary pesticide toxicity footprint. In this sense, only changing dietary habits is not enough when we are talking about sustainability. In this case, changing how food is being produced, such as reducing pesticide use, is also very important.

Other studies reinforce this discussion about the importance of not only focusing on changing population behavior but also modifying food systems since they are capable of influencing consumer preferences (Sáez-Almendros et al., 2013; Naja et al.,

2018, 2020; Esteve-Llorens et al., 2019a,b; Auclair and Burgos, 2021; Belgacem et al., 2021). In this way, the offer of healthier, culturally acceptable, accessible, and sufficient food options, as highlighted in some studies, is in line with what is proposed by FAO (Food Agriculture Organization of the United World Health Organization, 2019).

About the methodologies used by the selected studies to access food, food consumption, and diets, most evaluated current food consumption ($n = 41$). The studies that used the current diet evaluated it directly, but also through the identification of dietary patterns (Veeramani et al., 2017; Naja et al., 2018), and division of the population into groups according to footprint values (Rose et al., 2019; Auclair and Burgos, 2021). A relationship between these values and other

information such as sociodemographic factors, food report behaviors, nutrient consumption, and diet quality was also observed (Rose et al., 2019; Auclair and Burgos, 2021).

Another widely used methodology was the theoretical diets ($n = 17$), which in many cases were used in addition to assessing food consumption, scenarios, or standards to compare the environmental impacts. Some theoretical diets used were the Mediterranean diet, the EAT-Lancet reference diet, and different dietary patterns such as vegan and vegetarian (Sáez-Almendros et al., 2013; van de Kamp and Temme, 2018; Bruno et al., 2019; Esteve-Llorens et al., 2019a,b, 2020; Tang and Sobko, 2019; Batlle-Bayer et al., 2020; Grosso et al., 2020; Wang et al., 2020; Belgacem et al., 2021; Ridoutt et al., 2021; Vanham et al., 2021). This analysis is interesting because it allows comparability between different types of dietary patterns and allows us to understand which foods are impacting the most and where it is possible to improve.

In the study by Sáez-Almendros et al. (2013), analyzed the adherence of the Spanish population to the Mediterranean pattern. A greater adherence showed a reduction in all footprints (GHG emissions, agricultural land use, energy consumption, and water consumption), which would also result in a reduction in the consumption of animal-based products and an increase in plant-based products. The authors also point out that in the context of Spain, the adoption of this dietary pattern is in line with the local culture and carries benefits to the health of individuals.

Other methodologies such as menu analysis ($n = 5$), food waste ($n = 6$), and food purchase ($n = 3$) were observed in more than one article. Menu analysis is a different way of assessing food consumption and it is an interesting analysis to be performed, given that more and more people are eating out. The five studies that evaluated menus analyzed school, university, or institutional menus (Strasburg and Jahno, 2015; de Laurentiis et al., 2017; van de Kamp and Temme, 2018; Hatjiathanassiadou et al., 2019; Rossi et al., 2021), and a study evaluated food waste in 6 restaurants with different service categories (Matzembacher et al., 2020). Food waste was a methodology that was often associated with others, as in studies of Song et al. (2015), Veeramani et al. (2017), Mogensen et al. (2020), and Wang et al. (2020) who used food waste along with food consumption analysis, to estimate environmental footprints. However, it can also be used separately (Chen et al., 2020; Matzembacher et al., 2020).

Food Purchase analysis is also a way to access the environmental impacts of food consumption. Three studies (Hadjikakou, 2017; da Silva et al., 2021; Esteve-Llorens et al., 2021a) clearly indicated that they used this information to estimate environmental footprints. In the study by da Silva et al. (2021), the authors highlight the influence of ultra-processed foods on the values of WF, CF, and EF in the diet of Brazilians over the years. The same was observed in the study performed by Hadjikakou (2017), Ridoutt et al. (2020), and

van Dooren et al. (2018b). The profile of ultra-processed products directly impacts environmental footprints values, needing to consider the proportion of meat products in the ultra-processed foods (da Silva et al., 2021; Garzillo et al., 2022). We also emphasize that current footprint assessments, which make use of the LCA methodology, often do not consider industrial processes and the wide variety of components that are added to food, as well as the impacts related to the packaging, which are discarded and are sources of environmental impacts. In addition to the environmental impacts, the excessive use of food additives and components present in packaging can also pose a risk to human health. Thus, these foods may be having their environmental impacts underestimated, which may be greater than expected, a doubly negative impact (Seferidi et al., 2020).

Some studies (Song et al., 2015; Batlle-Bayer et al., 2020; Cao et al., 2020; Esteve-Llorens et al., 2020, 2021a; Vanham et al., 2021) used purchase and/or food supply information as a proxy to access the current diet. This is a very interesting way to be applied in different contexts, especially when there are no studies that seek to analyze food consumption more precisely, using instruments such as a food frequency questionnaire and a 24-h dietary recall, for example.

Finally, two other approaches used were food labels and future projections. Leach et al. (2016) worked with food labels, presenting four examples of environmental impact food label designs. According to the authors, information on environmental footprints on labels will enhance a consumer's ability to make informed purchasing decisions based on the environmental impact of products. It is an interesting approach to disseminate information already explored in the literature, making them reach the population. In the study by Han et al. (2020) future projections were made for the CF, WF, and EF of Chinese food systems by 2100. The authors demonstrated that the footprints would peak between 2030 and 2035 and that they would decline by 2100 due to population aging. However, it should be noted that this increase can be modified depending on the public policies adopted.

It is also important to highlight the need to expand studies that assess the impacts of food around the world. As observed in Table 1, most studies are focused on Europe. Five of the six economies contributing the most to total global GHG emissions from the food system are from outside Europe, namely China, Indonesia, the USA, Brazil, and India. India and China are the most populous countries in the world, followed by Indonesia (Roser and Rodés-Guirao, 2019; Crippa et al., 2021).

4.1. The role of animal-source foods in environmental footprint values

A common discussion found among almost all selected studies was the emphasis given to the impacts of animal

TABLE 1 Number of studies per continent.

Continent ^a	Number of studies	% ^b
Asia	12	20
Africa	3	5
Europe	31	53
America	10	17
Oceania	3	5

^aTwo studies were ignored, one due to its global context and the other because it was not possible to identify the context. Two studies were performed in the Mediterranean, which included the African, European and Asian continents. A study was performed considering the African and Asian continents. Therefore, these studies were considered in the count of each continent. ^bThis percentage considers only the study included in this table (n = 54) (see [Supplementary material](#)).

products, especially red meat (Sáez-Almendros et al., 2013; Song et al., 2015; Strasburg and Jahno, 2015; Leach et al., 2016; Sjörs et al., 2016; Biesbroek et al., 2017, 2018; de Laurentiis et al., 2017; Galli et al., 2017; Hadjikakou, 2017; Rosi et al., 2017; Veeramani et al., 2017; Lacour et al., 2018; Naja et al., 2018, 2020; Seconda et al., 2018; van de Kamp and Temme, 2018; van de Kamp et al., 2018; van Dooren et al., 2018b; Bahn et al., 2019; Bruno et al., 2019; Esteve-Llorens et al., 2019a,b, 2020, 2021a,b; Hatjiathanassiadou et al., 2019; Rose et al., 2019; Tang and Sobko, 2019; Batlle-Bayer et al., 2020; Cao et al., 2020; Chapa et al., 2020; Chen et al., 2020; González-García et al., 2020; Grasso et al., 2020; Han et al., 2020; Matzembacher et al., 2020; Mogensen et al., 2020; Rabès et al., 2020; Ridoutt et al., 2020; Scheelbeek et al., 2020; Travassos et al., 2020; Wang et al., 2020; Auclair and Burgos, 2021; Belgacem et al., 2021; da Silva et al., 2021; González et al., 2021; Kesse-Guyot et al., 2021; Long et al., 2021; Mehlig et al., 2021; Rossi et al., 2021; Üçtug et al., 2021; Vale et al., 2021; Vanham et al., 2021), except for Ridoutt et al. (2021) which presented another view of the problem associated with the analysis of the pesticide toxicity footprint. According to the authors, the fruits had the highest pesticide toxicity footprint scores per serving. Ruminant meats such as beef and lamb had lower pesticide footprint than chicken and pork. In this sense, for this analysis, it is difficult to generalize whether plant-based and animal-based foods are better in terms of environmental impacts. This is an interesting result, since it presents a different point of view of the environmental impacts, highlighting the need to also prioritize how plant-based products are being produced.

Regarding the consumption of animal-source foods, some studies have even pointed out how the reduction in the consumption of these products and the increase in the consumption of plant-derived products are positive not only for reducing the environmental impacts of diets but also at a nutritional and health level (Naja et al., 2018, 2020; Auclair and Burgos, 2021; González et al., 2021), since the association between excessive consumption of meat and the development of obesity, chronic non-communicable diseases (NCDs) such

as cardiovascular disease, type 2 diabetes and some types of cancer are already well-known (Micha et al., 2010; Pan et al., 2011; Bouvard et al., 2015; Clonan et al., 2016; Swinburn et al., 2019).

However, this dietary change will not be so simple. It is known that developed countries have a high consumption of red meat, while developing countries, as they develop, increase the consumption of red meat. This is due to the high status associated with meat consumption, Western dietary patterns, and social and cultural factors. It is important to say that eating patterns are relatively conservative and tend to change slowly over the years (Swinburn et al., 2019). In this context, the development of studies that assess the feasibility and acceptability of changing this consumption by individuals is important (van Dooren et al., 2018a; Grasso et al., 2020).

Going beyond individual food choices, we highlight that the involvement of other sectors is essential for changing food systems and achieving sustainability. The change will only be possible through widespread actions at all levels of the food production chain. Actions such as reducing food waste, intensifying and improving food production, encouraging agroecological production, reducing the consumption of animal-source foods, and implementing public policies aimed at producing more sustainable food and protecting the environment are essential (Swinburn et al., 2019; Willett et al., 2019; Jacob, 2021).

Finally, we emphasize that scientific research is a crucial point for the modification of food systems. It is with research that we identify problems, expose evidence and induce change through knowledge (Willett et al., 2019). Environmental footprints play a crucial role since they are very important indicators for accessing the environmental impacts associated with the production and consumption of current foods, being able, for example, to guide better food choices, compare dietary patterns or scenarios to investigate solutions, make projections and investigate the impacts of food waste. The footprints can be used in isolation as well as in combination with other analyzes that access the other dimensions of sustainability, such as social, cultural, and health through the use of information about sociodemographic factors, food behaviors, and association with the development of NCDs. This combined analysis allows the development of studies that manage to cover all dimensions of sustainability, being more assertive and explanatory since food and food systems are influenced by several factors.

We highlight that this review does not intend to do an exhaustive literature review. The main intent was to provide an overview of how environmental footprints have been used in the context of nutrition, sustainability, and food systems. However, this review has some limitations such as a lack of research that use environmental drivers in food studies/food service and food consumption, the variety of data and diversity of studies which makes comparability between studies difficult, the

heterogeneous potential of selected studies, with their different biases and scope of the publication.

5. Conclusions

We highlight that footprints have proven to be a great tool to analyze and guide actions toward more sustainable nutrition. It is also worth highlighting that the association of footprint estimation with other analyzes such as diet quality, acceptability, and degree of food processing has further enriched the discussion, by going beyond environmental impacts and embracing other important points in the area of nutrition and public health.

Animal source foods, especially red meat, have been identified as one of the main foods related to climate change. With the analysis of the footprints, the impact that these foods have becomes even clearer. Ultra-processed products are also foods that significantly impact the environment and deserve to be highlighted.

The environmental impact of food production and consumption must reach consumers given that the footprints of food products provide a way for consumers to know about those indicators and how to use them to benefit the health of the planet.

However, it is also important to discuss the responsibility of companies, to internalize the costs, as well as governments, to guide actions in favor of minimizing the environmental, social, economic, cultural, and health impacts that are related to food consumption and the food system. Thinking about the applicability of the footprints, the implementation of environmental labels in food products and meals could be a strategy to promote information to consumers and ways for governmental action to promote policies.

It is important to point out as well that environmental sustainability cannot be split from other dimensions (social and economic) as all dimensions are interconnected. Disseminating this type of information will increase the capacity of all to improve the environmental performance of the food system and the planet.

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Author contributions

MH, PR, and LS: conceptualization and writing—review and editing. MH and LS: methodology. MH: investigation and writing—original draft preparation. PR and LS: supervision. All authors have read and agreed to the published version of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2022.1078997/full#supplementary-material>

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Projecting wheat demand in China and India for 2030 and 2050: Implications for food security

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Introduction: The combined populations of China and India were 2.78 billion in 2020, representing 36% of the world population (7.75 billion). Wheat is the second most important staple grain in both China and India. In 2019, the aggregate wheat consumption in China was 96.4 million ton and in India it was 82.5 million ton, together it was more than 35% of the world's wheat that year. In China, in 2050, the projected population will be 1294–1515 million, and in India, it is projected to be 14.89–1793 million, under the low and high-fertility rate assumptions. A question arises as to, what will be aggregate demand for wheat in China and India in 2030 and 2050?

Methods: Applying the Vector Error Correction model estimation process in the time series econometric estimation setting, this study projected the per capita and annual aggregate wheat consumptions of China and India during 2019–2050. In the process, this study relies on agricultural data sourced from the Food and Agriculture Organization of the United States (FAO) database (FAOSTAT), as well as the World Bank's World Development Indicators (WDI) data catalog. The presence of unit root in the data series are tested by applying the augmented Dickey-Fuller test; Philips-Perron unit root test; Kwiatkowski-Phillips-Schmidt-Shin test, and Zivot-Andrews Unit Root test allowing for a single break in intercept and/or trend. The test statistics suggest that a natural log transformation and with the first difference of the variables provides stationarity of the data series for both China and India. The Zivot-Andrews Unit Root test, however, suggested that there is a structural break in urban population share and GDP per capita. To tackle the issue, we have included a year dummy and two multiplicative dummies in our model. Furthermore, the Johansen cointegration test suggests that at least one variable in both data series were cointegrated. These tests enable us to apply Vector Error Correction (VEC) model estimation procedure. In estimation the model, the appropriate number of lags of the variables is confirmed by applying the "varsoc" command in Stata 17 software interface. The estimated yearly per capita wheat consumption in 2030 and 2050 from the VEC model, are multiplied by the projected population in 2030 and 2050 to calculate the projected aggregate wheat demand in China and India in 2030 and 2050. After projecting the yearly per capita wheat consumption (KG), we multiply with the projected population to get the expected consumption demand.

Results: This study found that the yearly per capita wheat consumption of China will increase from 65.8 kg in 2019 to 76 kg in 2030, and 95 kg in 2050. In India, the yearly per capita wheat consumption will increase to 74 kg in 2030 and 94 kg in 2050 from 60.4 kg in 2019. Considering the projected population growth rates under low-fertility assumptions, aggregate wheat consumption of China will increase by more than 13% in 2030 and by 28% in 2050. Under the high-fertility rate assumption, however the aggregate wheat consumption of China will increase by 18% in 2030 and nearly 50% in 2050. In the case of India, under both low and high-fertility rate assumptions, aggregate wheat demand in India will increase by 32–38% in 2030 and by 70–104% in 2050 compared to 2019 level of consumption.

Discussions: Our results underline the importance of wheat in both countries, which are the world's top wheat producers and consumers, and suggest the importance of research and development investments to maintain sufficient national wheat grain production levels to meet China and India's domestic demand. This is critical both to ensure the food security of this large segment of the world populace, which also includes 23% of the total population of the world who live on less than US \$1.90/day, as well as to avoid potential grain market destabilization and price hikes that arise in the event of large import demands.

KEYWORDS

aggregate demand, wheat, projection, time series, China, India

1. Introduction

The world population is expected to reach from 8.9 to 10.6 billion by 2050, compared with 7.75 billion in 2020 (1), and an estimated 68% of those people will reside in urban areas, up from 61% in 2020 (1). The average per capita GDP at constant 2015 prices is projected to increase from US \$11,33 in 2022 to US \$13,747 in 2032 (2). The expected changes in demography, increases in per capita GDP, and greater urbanization will have major implications on future demand for foods and major cereals, such as wheat, maize, and rice. Households in countries in the early stages of development tend to consume a high proportion of cereals and coarse grains, which are relatively cheap sources of dietary energy (3, 4). As development progresses, with increases in income and urbanization, households tend to increase their consumption of energy-dense and more expensive foodstuffs, in place of cereals (4–7), a phenomenon described as the “nutrition transition” (5, 8–14). This paper focuses on how projected economic and demographic transitions, followed by nutrition transition, will affect future demand for wheat.

Several studies project global demand changes for major cereals and agricultural commodities, considering mainly demographic shifts. Such projections are highly relevant to target investments for addressing hunger and poverty. Predictions regarding global food demand, for example, foresee increases by 2050 that range from 70% (15) to 110% (16). Ray et al. (17) cautioned that, to meet rising demand, the average annual yield growth rates for major agricultural commodities, including wheat, should be at least 2.4% over 2005 levels. After reviewing 57 global food security projections, Van Dijk et al. (18) concluded that global food demand is expected to increase from 35 to 56% by 2050, over 2010 levels.

All the preceding are global studies, but GDP growth rate, urbanization, and demographic changes are heterogeneous across countries, and cropping and dietary intake patterns are country and region-specific. For example, in 2019, yearly per capita wheat consumption in Tunisia was nearly 198.4 kg, whereas, in Laos, it was only 1.4 kg (19). Country- and commodity-specific case studies can help to elucidate consumption directions for specific commodities, providing focused and important insights to target investments and policies.

This study examines evolving per capita consumption and aggregate demand for wheat in China and India projected to 2030 and 2050. Economic growth in those countries, measured in per capita GDP growth rate, has been among the fastest in the world, at an annual average 1 8.3% for China and 4.2% for India, over 1990–2020

(1). The nominal per capita GDP of China increased from less than US \$318 in 1990 to US \$12,556 and, in India, from US \$303 in 1990 to US \$2,227 in 2020 (1). There are also important demographic changes underway in both countries. In 2021, the respective populations of China and India were 1.41 billion and 1.39 billion (1). Under the low fertility rate assumption, the total population of China is projected to be 1.44 billion in 2030 and 1.29 billion in 2050 whereas, assuming a high fertility rate China's population will be 1.49 billion in 2030 and 1.51 billion in 2050 (20). For India, low fertility rate projections foresee a population of 1.48 billion in 2030 and 1.49 billion in 2050 and, under a high fertility rate assumption, of 1.54 billion in 2030 and 1.79 billion in 2050 (20).

Urbanization has also accelerated in both countries. From a little more than one-quarter of China and India's populace living in cities in 1990 (1), by 2030, it is expected that nearly 71% of China's inhabitants and 40% of those in India will reside in urban areas (21) and, by 2050, four of every five persons in China and more than half of those in India will be city dwellers (21).

The dramatic changes in per capita GDP, population, and urbanization provide a unique opportunity to examine the effects of these factors on the future demand for wheat, a major food crop for both nations. China and India are the top wheat-producing and consuming countries in the world. In 2019, China produced 134.3 million t of wheat from 23.4 million ha, making it the world's number-one wheat producer and the third-highest in wheat area (22). That same year, India allocated 31.4 million ha of land to wheat—the world's largest area—and produced 105.6 million tons (t) of grain, the second-highest output (22). An estimated 36.5 million farms in China and 37.3 million in India grew wheat in 2020 (23), making the crop a major source of livelihood for farm households. An examination of the future of wheat demand can inform effective policies to improve the livelihoods of resource-poor wheat farmers in China and India.

This information can also help target policies to improve the food security and nutrition of the countries' inhabitants, who constitute 36% of world population of which 23% (22.5% in India and 0.5% in China) live on less than US \$1.90/day (24), many of whom rely on wheat for dietary energy intake. In 1961, the yearly per capita total wheat consumption was less than 21 kg in China and 28 kg in India, which contributed to 12% of the per capita daily total calorie intake in China, and in India it was 11.8% (25). As of 2019, yearly per capita wheat consumption in China had increased to 65.8 kg, supplying 576 kcal per capita per day, and representing 17.2% of daily dietary energy, and in India to 60.4 kg, supplying 515 kcal per capita per day or 20% of daily dietary energy (19). In China and

India, wheat is also a major source of protein. In 2019, the daily total protein intake per person in China was 105.1 grams, in which the contribution of wheat was 18.5 grams (17.6%) (19). In India, in the same year, the daily total protein intake per person is 64.9 grams, in which the contribution of wheat was 15.1 grams (23.2%) (19). Finally, despite being the top ranked wheat producing country, China is a net importer of wheat, and India exports sporadically. Thus, projections regarding their future wheat demand have clear significance, both with regards to internal effects and policies, as well as possible impacts on global wheat supplies and prices. In 2019, the countries jointly consumed 179 million t of wheat which was 35.4% of the total wheat (505 million t) consumed globally (19), net imports of wheat grain by China were 9.6 million t worth US \$2.7 billion and India's net wheat export was 928.5 thousand t, worth US \$243 million (26).

There has recently been global concern around ensuring diversified diets to nurture human health and the environment (27). Also, considering the importance of balanced diets to combat malnutrition and non-communicable disease, there is a call to increase investments in non-cereal crops, such as lentils and vegetables (5, 14). Based on those suggestions, if China and India loosen their efforts to produce more wheat and eventually started importing wheat from the global market, it can generate severe havoc on international wheat prices and food security of the wheat import-dependent developing countries.

The next section presents a brief literature review and the conceptual framework. Section 3 includes materials and methods, and Section 4 presents the major findings. Finally, Section 5 presents the conclusion and policy implications.

2. Literature review and the conceptual framework

Since its domestication around 10,000 years ago (28, 29), wheat has been playing a crucial role in ensuring food and nutrition securities in the world (30–32). In 2019, the yearly per capita wheat consumption in the world was around 66 kg, which supplied daily 538 kcal per person or 18% of total calorie intake (2,963 kcal), as well as 19.5% (16.3 grams) of the daily per capita protein (25). The adoption of improved agronomic practices and high-yielding wheat varieties have contributed significantly to increasing productivity in China, India, and worldwide (33–39). Currently, wheat is the most widely cultivated crop in the world, being grown on 219 million ha in 2020 (22). In 2020, global wheat production was worth nearly US \$190 billion (40).

This study projects wheat demand in China and India during 2019–2050 and specifically focuses on 2030 and 2050. In terms of production and consumption, China and India are ranked as the first and second-largest wheat-producing countries respectively. In 2019, the global wheat production was more than 765 million t, of which 66% (505 million t) was used as food, and China and India jointly consumed 35.4% (179 million t) of the total wheat consumed globally in that year (25). Despite being the top wheat-producing countries, China is a net wheat importing country, and India exports sporadically. As the population of these countries is projected to increase by 2050, and as wheat is the second most important staple in China and India, it is imperative to examine the future demand for wheat to formulate investment strategies to ensure the food security of China and India.

There has recently been global concern around warranting varied diets to foster human health and the environment (27). Also, considering the importance of balanced diets to combat malnutrition and non-communicable disease, there is a call to increase investments in noncereal crops, such as lentils and vegetables (5, 14). Now, if China and India started reducing investment in major cereals, and if the demand for major cereals increases due to the increase in population, these countries will rely more on imports to meet their demand. However, if China and India started importing wheat in bulk from the international market, it can generate severe havoc on international wheat prices and food security of the wheat import-dependent developing countries.

Few studies have projected wheat demand in China and India. Rozelle and Huang (41) considered low- and high-income growth trends to conclude that, by 2020, yearly per capita wheat consumption in China lie between 80 and 83 kg. Applying the household model estimation procedure and employing primary data, Carter and Zhong (42) calculated a negative income elasticity for wheat and concluded that, in China, per capita consumption might decline, as later occurred it was 77 kg in 1990 and fell to 64 kg by 2018 (19).

For India, Chand (43), estimated a yearly per capita wheat consumption of 49.8 kg and an aggregate consumption of 67.5 million t in 2020–21. Mittal (44) projected that, in 2026, a yearly per capita wheat consumption of 48.9 kg and an aggregate consumption of 65.9 million t. Kumar et al. (45) forecast a 2021–22 yearly per capita wheat consumption of 47.6 kg and an aggregate consumption of 73.5 million t. Applying the QUAIDS (Quadratic Almost Ideal Demand System) estimation procedure, Ganesh-Kumar et al. (46) estimated a negative (-0.13) expenditure elasticity for wheat and projected the yearly per capita wheat consumption at 49.3 kg by 2026 and an aggregate wheat consumption ranging from 63.3 to 69.4 million t, dependent on income growth rate assumptions. By 2018, India's yearly wheat consumption surpassed projections considerably, with a per capita consumption of 62 kg and an aggregate wheat consumption of 83.5 million t (19). So, demand forecasts have fallen short to date, suggesting the need to revisit this issue using innovative methods and models.

Several studies have documented wheat consumption growth for countries in sub-Saharan Africa and South Asia, because of rising per capita GDP and urbanization (4, 47, 48). In the present study, the long-term influence of the share of the urban population, domestic wheat production, GDP per capita, and wheat imports are considered to estimate future per capita wheat consumption in China and India. We applied the Vector Error Correction (VEC) estimating procedure under the time series estimation setting. Finally, employing the Box-Jenkins methods for forecasting (49), we forecasted yearly per capita wheat consumption in China and India, providing up-to-date estimates through a simple but strong econometric estimation procedure using the most recent datasets.

3. Materials and methods

This study relies on agricultural data sourced from the Food and Agriculture Organization of the United States (FAO) database (FAOSTAT), as well as the World Bank's World Development Indicators (WDI) data catalog. Data on yearly per capita wheat consumption in kg (PC_t), imports (IMP_t), and domestic production (DPR_t), yields, and the wheat area were retrieved from FAO online

datasets (FAOSTAT). Data for the percentage of urban population (UR_t) and per capita GDP in current US\$ (GDP_t) were collected from the World Bank's World Development Indicators (WDI) catalog.

The study's equations of interest are specified below:

$$\begin{aligned}\Delta \ln PC_t &= \sigma + \sum_{i=1}^k \beta_i \Delta \ln PC_{t-i} + \sum_{j=1}^k \alpha_j \Delta \ln \%UR_{t-j} \\ &+ \sum_{l=1}^k \phi_j \Delta \ln GDP_{t-l} + \sum_{m=1}^k \gamma_m \Delta \ln DPR_{t-m} \\ &+ \sum_{n=1}^k \theta_n \Delta \ln IMP_{t-n} + \psi yd82 \\ &+ \sum_{n=1}^k \tau_n (yd82 \times \Delta \ln \%UR_{t-j}) \\ &+ \sum_{n=1}^k \omega_n (yd82 \times \Delta \ln GDP_{t-i}) + \lambda_1 ECT_{t-1} + \mu_{1t} \\\Delta \ln \%UR_t &= \varphi + \sum_{i=1}^k \beta_i \Delta \ln PC_{t-i} + \sum_{j=1}^k \alpha_j \Delta \ln \%UR_{t-j} \\ &+ \sum_{l=1}^k \phi_j \Delta \ln GDP_{t-l} + \sum_{m=1}^k \gamma_m \Delta \ln DPR_{t-m} \\ &+ \sum_{n=1}^k \theta_n \Delta \ln IMP_{t-n} + \psi yd82 \\ &+ \sum_{n=1}^k \tau_n (yd82 \times \Delta \ln \%UR_{t-j}) \\ &+ \sum_{n=1}^k \omega_n (yd82 \times \Delta \ln GDP_{t-i}) + \lambda_2 ECT_{t-1} + \mu_{2t} \\\Delta \ln GDP_t &= \tau + \sum_{i=1}^k \beta_i \Delta \ln PC_{t-i} + \sum_{j=1}^k \alpha_j \Delta \ln \%UR_{t-j} \\ &+ \sum_{l=1}^k \phi_j \Delta \ln GDP_{t-l} + \sum_{m=1}^k \gamma_m \Delta \ln DPR_{t-m} \\ &+ \sum_{n=1}^k \theta_n \Delta \ln IMP_{t-n} + \psi yd82 \\ &+ \sum_{n=1}^k \tau_n (yd82 \times \Delta \ln \%UR_{t-j}) \\ &+ \sum_{n=1}^k \omega_n (yd82 \times \Delta \ln GDP_{t-i}) + \lambda_3 ECT_{t-1} + \mu_{3t} \\\Delta \ln DPR_t &= \tau + \sum_{i=1}^k \beta_i \Delta \ln PC_{t-i} + \sum_{j=1}^k \alpha_j \Delta \ln \%UR_{t-j} \\ &+ \sum_{l=1}^k \phi_j \Delta \ln GDP_{t-l} + \sum_{m=1}^k \gamma_m \Delta \ln DPR_{t-m} \\ &+ \psi yd82 + \sum_{n=1}^k \tau_n (yd82 \times \Delta \ln \%UR_{t-j}) \\ &+ \sum_{n=1}^k \omega_n (yd82 \times \Delta \ln GDP_{t-i}) \\ &+ \lambda_4 ECT_{t-1} + \mu_{4t} \\\Delta \ln IMP_t &= \upsilon + \sum_{i=1}^k \beta_i \Delta \ln PC_{t-i} + \sum_{j=1}^k \alpha_j \Delta \ln \%UR_{t-j} \\ &+ \sum_{l=1}^k \phi_j \Delta \ln GDP_{t-l} + \sum_{m=1}^k \gamma_m \Delta \ln DPR_{t-m} \\ &+ \sum_{n=1}^k \theta_n \Delta \ln IMP_{t-n} + \psi yd82 \\ &+ \sum_{n=1}^k \tau_n (yd82 \times \Delta \ln \%UR_{t-j}) \\ &+ \sum_{n=1}^k \omega_n (yd82 \times \Delta \ln GDP_{t-i}) + \lambda_5 ECT_{t-1} + \mu_{5t} \\ yd82 &= \upsilon + \sum_{i=1}^k \beta_i \Delta \ln PC_{t-i} + \sum_{j=1}^k \alpha_j \Delta \ln \%UR_{t-j} \\ &+ \sum_{l=1}^k \phi_j \Delta \ln GDP_{t-l} + \sum_{m=1}^k \gamma_m \Delta \ln DPR_{t-m} \\ &+ \sum_{n=1}^k \theta_n \Delta \ln IMP_{t-n} \\ &+ \sum_{n=1}^k \tau_n (yd82 \times \Delta \ln \%UR_{t-j}) \\ &+ \sum_{n=1}^k \omega_n (yd82 \times \Delta \ln GDP_{t-i}) \\ &+ \lambda_6 ECT_{t-1} + \mu_{6t} \\ (yd82 \times \Delta \ln \%UR_{t-j}) &= \upsilon + \sum_{i=1}^k \beta_i \Delta \ln PC_{t-i} + \sum_{j=1}^k \alpha_j \Delta \ln \%UR_{t-j} \\ &+ \sum_{l=1}^k \phi_j \Delta \ln GDP_{t-l} + \sum_{m=1}^k \gamma_m \Delta \ln DPR_{t-m} \\ &+ \sum_{n=1}^k \theta_n \Delta \ln IMP_{t-n} + \psi yd82 \\ &+ \sum_{n=1}^k \tau_n (yd82 \times \Delta \ln \%UR_{t-j})\end{aligned}$$

$$\begin{aligned}&+ \sum_{n=1}^k \omega_n (yd82 \times \Delta \ln GDP_{t-i}) + \lambda_7 ECT_{t-1} + \mu_{7t} \\ (yd82 \times \Delta \ln GDP_{t-i}) &= \upsilon + \sum_{i=1}^k \beta_i \Delta \ln PC_{t-i} + \sum_{j=1}^k \alpha_j \Delta \ln \%UR_{t-j} \\ &+ \sum_{l=1}^k \phi_j \Delta \ln GDP_{t-l} + \sum_{m=1}^k \gamma_m \Delta \ln DPR_{t-m} \\ &+ \sum_{n=1}^k \theta_n \Delta \ln IMP_{t-n} + \psi yd82 \\ &+ \sum_{n=1}^k \tau_n (yd82 \times \Delta \ln \%UR_{t-j}) \\ &+ \sum_{n=1}^k \omega_n (yd82 \times \Delta \ln GDP_{t-i}) + \lambda_8 ECT_{t-1} + \mu_{8t}\end{aligned}\quad (1)$$

Where:

$\ln PC$	= Natural log of yearly per capita wheat consumed;
$\ln \%UR_t$	= Natural log of the share of urban population (%);
$\ln GDP_t$	= Natural log of the per capita GDP (US\$);
$\ln DPR_t$	= Natural log of the domestically produced wheat in tons; and
$\ln IMP_t$	= Natural log of wheat imported (tons)
$yd82$	= Year > 1981 dummy (yes=1)
$k-1$	= the lag length is reduced by 1
$\beta_i, \alpha_j, \phi_j, \gamma_m, \theta_n, \psi, \tau, \omega$	= short-run dynamic coefficients of the model's adjustment toward long-term equilibrium
λ_i	= speed of adjustment parameter with a negative sign;
ECT_{t-1}	= the error correction term is the lagged value of the residuals obtained from the cointegration regression of the dependent variables on the regressors. Contains long-term information derived from the long-term cointegration relationship;
μ_{it}	= the residuals (stochastic error term/impulses or innovations or shocks).

Before estimating Equation (1), as parts of estimation process, the presence of unit root in the data series are tested by applying the augmented Dickey-Fuller test. However, as it is argued that the augmented Dickey-Fuller test is outdated, we also have employed, Philips-Perron unit root test; Kwiatkowski-Phillips-Schmidt-Shin test, and Zivot-Andrews Unit Root test allowing for a single break in intercept and/or trend. The results from these tests are included in the [Annexure](#). The test statistics suggest that a natural log transformation and with the first difference of the variables provides stationarity of the data series for both China and India. The Zivot-Andrews Unit Root test, however, suggested that there is a structural break in urban population share and GDP per capita. To handle the issue, we have included a year dummy and two multiplicative dummies in our model. Furthermore, the Johansen cointegration test suggests that at least one variable in both data series were cointegrated. These tests enable us to apply Vector Error Correction (VEC) model estimation procedure. In estimation the model, the appropriate number of lags of the variables is confirmed by applying the "varsoc" command in Stata 17 software interface. Based on the test statistics, we have applied the VEC estimation procedure, which allow us to elucidate the long-term

relationships among the yearly per capita wheat consumption and the variables of interest: the yearly per capita GDP, share of the urban population, and the domestic production of wheat and wheat import.

After estimating the VEC models, we applied the simple dynamic forecasting process, to forecast yearly per capita wheat consumption in China and India. Finally, to estimate the aggregate wheat demand in 2030 and 2050, we used the following process:

$$AWD_t = \hat{PC}_t \times PP_t \quad (2)$$

Where:

AWD_t = Aggregate wheat demand in year t (= 2030 and 2050);

\hat{PC}_t = Estimated yearly per capita wheat consumption (kg);

PP_t = Projected population in year t (= 2030 and 2050).

Using Equation (2), we estimated the aggregate wheat demand of China and India in 2030 and 2050 considering both changes in the per capita wheat consumption and in population.

4. Discussions and major findings

4.1. Descriptive findings

The worldwide trends of land allocation to wheat (million ha), wheat production (million t), yield (t/ha), consumption

TABLE 1 Temporal changes in wheat production and consumption in the world (1961–2020).

Year	1961	1971	1981	1991	2001	2011	2019/2020
Land allocation (million ha)							
No. of countries	94	98	101	103	125	123	124
Area, average	2.17	2.18	2.37	2.18	1.72	1.79	1.77
Total area	204.2	213.9	239.2	224.2	214.6	220.3	219.0
Standard deviation	7.81	7.8	8.09	7.07	4.97	5.19	5.23
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	63	64	59.2	45.9	25.7	29.1	31.4
Production (million t)							
Production, average	2.37	3.55	4.45	5.32	4.71	5.67	6.14
Total production	222.4	347.5	449.6	547.8	588.2	696.9	760.1
Standard deviation	7.6	11.6	14.1	17	15.2	18.4	21.3
Minimum	0	0	0	0	0	0	0
Maximum	62.5	92.8	76.7	96	93.9	117.4	134.3
Yield (t/ha)							
Yield	1.09	1.62	1.88	2.44	2.74	3.16	3.47
Standard deviation	0.92	1.20	1.46	1.86	1.86	1.89	2.10
Minimum	0.22	0.33	0.40	0.20	0.37	0.39	0.40
Maximum	4.12	4.97	6.70	7.86	9.06	9.86	9.93
Consumption (kg/capita/year)							
No. of countries	154	154	154	155	175	175	180
Average consumption	54.9	56.5	65.0	70.8	68.8	65.3	65.9
Standard deviation	52.7	49.8	48.8	48.2	48.6	46.8	45.4
Minimum	0.0	1.6	1.4	0.1	1.6	1.9	1.4
Maximum	226.0	220.3	210.6	221.0	215.4	219.7	198.5
Calorie intake (kcal/capita/day)							
Calorie intake from wheat	415	436	515	569	555	526	538
Standard deviation	397	374	371	373	375	363	359
Minimum	0	11	11	0	13	15	18
Maximum	1,688	1,569	1,589	1,667	1,634	1,645	1,584
Daily total calorie intake (kcal/capita/day)	2,196	2,365	2,501	2,601	2,725	2,869	2,963
Share of wheat (%)	18.9	18.4	20.6	21.9	20.4	18.3	18.2

Source : FAOSTAT (26).

(kg/capita/year) and daily per capita calorie intake from wheat are during 1961–2020 are presented in [Table 1](#). In 1961, at least 94 countries in the world cultivated wheat on at least on 204 million ha of land. The average land allocation per country was nearly 2.2 million ha, and with an average yield of 1.09 t/ha, total wheat production in the world was 222 million t ([Table 1](#)). In the same year, wheat was consumed by at least 154 countries, and the per capita yearly wheat consumption was nearly 55 kg, that supplied 415 kcal energy daily to a person which was nearly 19% of the total calorie intake of a person in 1961 ([Table 1](#)). In 2020, at least 124 countries in the world cultivated wheat on at least on 219 million ha of land. With

TABLE 2 Temporal changes in wheat area (million ha) production (million t), yield (t/ha) and consumption (kg and kcal) in China and India.

Year	China	India
Land allocation to wheat (million ha)		
1961	25.6	12.9
1971	25.6	18.2
1981	28.3	22.3
1991	30.9	24.2
2001	24.7	25.7
2011	24.3	29.1
2020	23.4	31.4
Production (million t)		
1961	14.3	11.0
1971	32.6	23.8
1981	59.6	36.3
1991	96.0	55.1
2001	93.9	69.7
2011	117.4	86.9
2020	134.3	107.6
Yield (t/ha)		
1961	0.56	0.85
1971	1.27	1.31
1981	2.11	1.63
1991	3.11	2.28
2001	3.80	2.71
2011	4.83	2.99
2020	5.74	3.43
Consumption (capita/kg/year)		
1961	20.9	27.9
1971	33.0	36.7
1981	62.6	45.6
1991	77.6	60.3
2001	71.9	62.2
2011	63.0	58.9
2019	65.8	60.4

Source :FAOSTAT (22).

an average yield of 3.47 t/ha, the total wheat production was 760 million t. In 2019, the yearly per capita wheat consumption was nearly 66 kg that supplied 538 kcal of daily dietary energy per person, which was more than 18% of the daily total calorie intake by a person ([Table 1](#)).

In [Table 2](#), the temporal changes in land allocation to wheat, production, yield, and consumption, are presented for China and India. Wheat is the second most preferred staple after rice both in China and India. It shows that, while in China the land allocation to wheat had increased from 25.6 million ha in 1961 to 30.9 million ha in 1991, later it declined to almost the original size, at 23.4 million ha in 2020. In contrast, the land allocation to wheat has continuously increased in India since 1961. However, total wheat production in China and India has increased continuously since 1961, due mainly to rising yields ([Table 2](#)).

Yearly per capita wheat consumption in China follows a pattern similar to that of land allocations to wheat: it increased initially until 1991 and later decreased slightly. In 1961, the yearly per capita wheat consumption in China was nearly 21 kg and increased to more than 77 kg in 1991 and, by 2019, declined to nearly 66 kg ([Table 2](#)). In contrast in India, yearly per capita wheat consumption has increased steadily from 28 kg in 1961 to 60 kg in 2019 ([Table 2](#)).

Furthermore, the importance of wheat in safeguarding the daily dietary energy security in China and India has increased over the years. In 1961, the contribution of wheat to daily dietary energy in China was 176 kcal per capita, which was 12% of the daily total per capita calorie intake in China ([Figure 1](#)). In India, it was 238 kcal, which was <12% of per capita daily calorie intake ([Figure 1](#)). By 2019, the contribution of wheat to the daily calorie intake in China had risen to 17% and, in India, 20% ([Figure 1](#)).

The temporal changes in net wheat trade (exports—imports) in million t, and self-sufficiency trends, which is measured as domestic production / [(domestic production + (import-export))] are presented for China and India during 1961–2020 in [Figure 1](#). Only around year 2000 did both nations begin to export wheat, but only sporadically ([Figure 2](#)). An analysis of wheat self-sufficiency trends, show that despite dramatic increases in wheat yields, both countries can just meet their domestic demand and often rely on imports to satisfy demand spikes ([Figure 2](#)).

The economies of China and India are changing dynamically, due to changes in population, income, and urbanization. Under the United Nations (20) assumption of low fertility, the population in China may increase to 1.44 billion in 2030 and decline to 1.29 billion by 2050 and, under the assumption of high fertility, it could increase to 1.49 billion in 2030 and 1.52 billion in 2050 ([Table 3](#)). At the same time, 80% of China's inhabitants will reside in urban areas by 2050, compared to 61.4% in 2020, and the per capita GDP of China is projected to reach US \$17,325 by 2030, compared to US \$10,500 in 2020 ([Table 3](#)). Under both low and high fertility growth rate assumptions, the population of India is projected to increase by 2030 and 2050, possibly reaching 1.49 billion or 1.79 billion persons by mid-century, depending on the fertility rate assumption used ([Table 3](#)). Furthermore, by 2030 and 2050, more than 40% and 53% of inhabitants respectively will reside in urban areas, compared to 35% in 2020, and the projected GDP per capita will average US \$3,079 by 2030, compared to US \$1,900 in 2020 ([Table 3](#)).

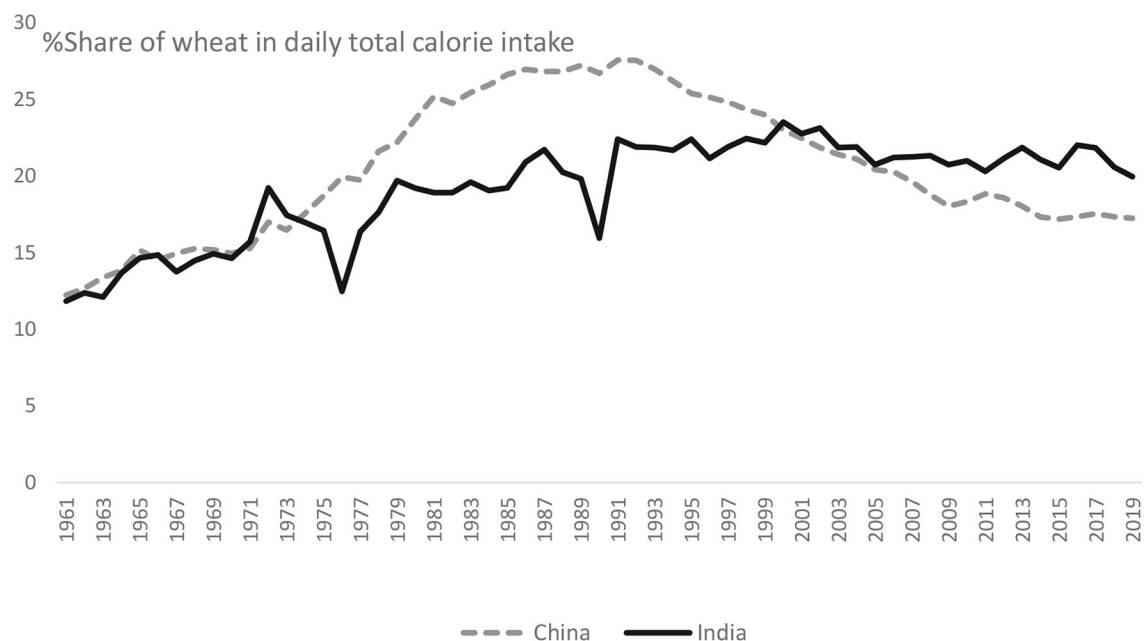


FIGURE 1

Share of wheat in daily total calorie intake in China and India during 1961–2019 [(per capita daily calorie intake from wheat ÷ Per capita daily total calorie intake) × 100]. Source: Authors, based on FAOSTAT (22).

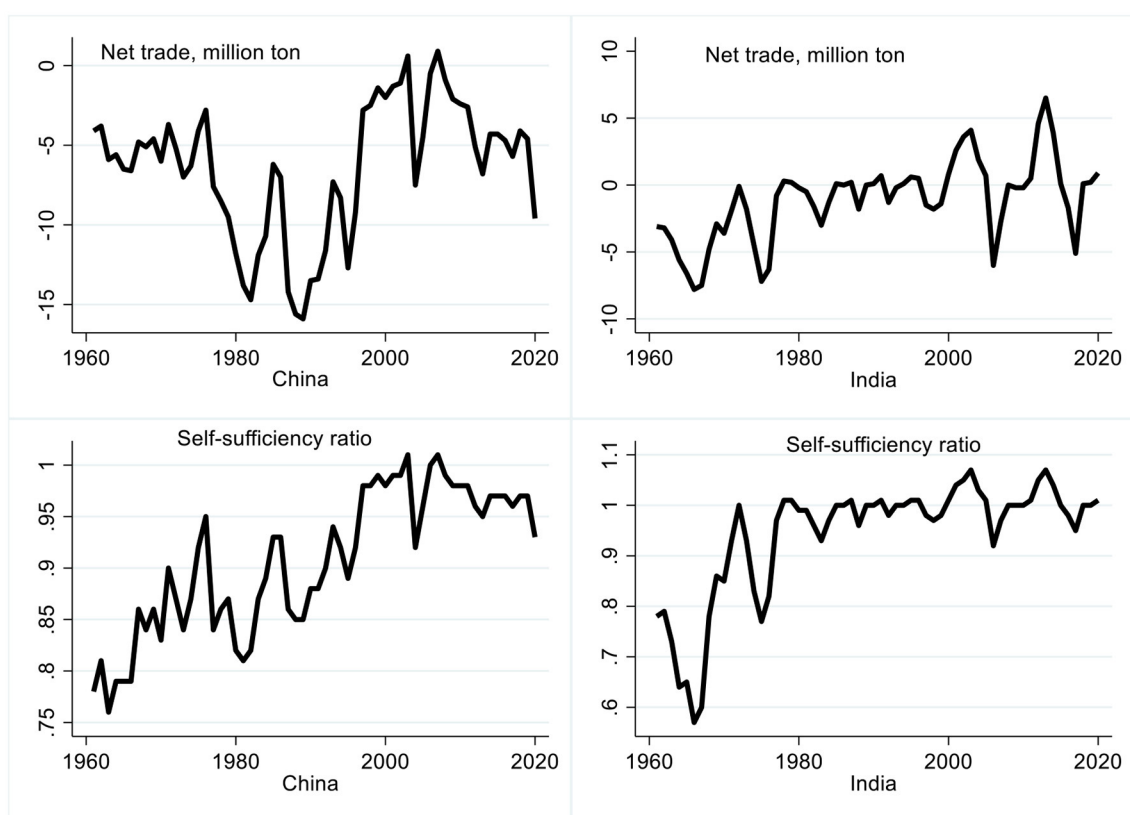


FIGURE 2

Net export (export-import) in million t and self-sufficiency status [domestic production ÷ (domestic production+import-export)] of China and India during 1961–2020. Source: Authors, based on FAOSTAT (22).

TABLE 3 Temporal changes and projection of population (million), the share of the urban population, and GDP per capita (US \$) 1961–2050.

	1961	1971	1981	1991	2001	2011	2020	Projected			
								2030	2030	2050	2050
China											
Population (million)	660	841	994	1,151	1,272	1,344	1,402	1,437 ^a	1,492 ^a	1,294 ^a	1,515 ^a
Urban population (%)	17	17	20	27	37	51	61.4	70.6 ^b		80.0 ^b	
GDP per capita (US\$)	141	238	360	786	1,901	4,961	10,500	17,325 ^c			
India											
Population (million)	460	568	715	891	1,075	1,250	1,380	1,468 ^a	1,540 ^a	1,489 ^a	1,793 ^a
Urban population (%)	18	20	23	26	28	31	35	40.1 ^b		53.0 ^b	
GDP per capita (US\$)	336	394	438	576	852	1,410	1,900	3,079 ^c			
World											
Population (million)	3,072	3,761	4,511	5,368	6,194	7,003	7,753	8,363 ^a	8,734 ^a	8,907 ^a	10,588 ^a
Urban population (%)	34	37	40	43	47	52	56.2	60.4 ^b		68.3 ^b	
GDP per capita (US\$)	3,865	5,340	6,322	7,177	8,223	9,739	10,926	13074 ^c			

Sources: World Bank (1); ^aUnited Nations (20); ^bWorld Bank (21); ^cReal GDP per capita in 2010 price USDA (2).

In the next section, we have econometrically estimated the yearly per capita wheat consumption in China and India in 2030 and 2050, considering long-term relationships among the per capita yearly wheat consumption, the GDP per capita, the share of the urban population, domestic production and import of wheat. Based on the projected wheat consumption, we have calculated the aggregate wheat demand for 2030 and 2050.

4.2. Econometric findings

The long-term relationship between China's yearly per capita wheat consumption and the variables of interest are detailed in Table 4.

The estimated error correction equation (ECT) for China is:

$$\begin{aligned}
 ECT_{t-1} = & \ln PC_{t-1} - +0.03 \Delta \ln IMP_{t-1} - 0.85 \Delta \ln \%UR_{t-1} \\
 & -0.72 \Delta \ln DPR_{t-1} - 0.25 \Delta \ln GDP_{t-1} \\
 & +0.005 (Year > 1981 \text{ dummy}) \\
 & +2.56 (Year > 1981 \text{ dummy} \times \Delta \ln GDP_{t-1}) \\
 & -6.53 (Year > 1981 \text{ dummy} \times \Delta \ln \%UR_{t-1}) + 0.05
 \end{aligned}
 \quad (3)$$

And, setting the yearly per capita wheat consumption (PC) as the target variable, the estimated per capita wheat consumption equation for China is as follows:

$$\begin{aligned}
 \Delta \ln PC_t = & -0.11 - 0.49 \Delta \ln PC_{t-1} - 0.003 \Delta \ln IMP_{t-1} \\
 & + 0.02 \Delta \ln \%UR_{t-1} - 0.07 \Delta \ln DPR_{t-1} \\
 & + 0.18 \Delta \ln GDP_{t-1} - 0.44 (year > 1981 \text{ dummy}) \\
 & + 0.08 (year > 1981 \text{ dummy} \times \Delta \ln GDP_{t-1}) \\
 & - 0.15 (year > 1981 \text{ dummy} \times \Delta \ln \%UR_{t-1}) - 0.0002
 \end{aligned}
 \quad (4)$$

It is important to mention here is that in Equation (3), the sign of the estimated coefficients needs to explain in a reverse way [e.g., (50, 51)]. It shows that, in the long run, with other factors remaining the same, the share of urban population ($p < 0.05$), domestic wheat production ($p < 0.00$) and the share of urban population after 1981 will positively and significantly impact the long run yearly per capita wheat consumption in China. It means, with the increase in domestic wheat production, and increased people in the urban areas, the yearly per capita wheat consumption in China will increase in the long-run. Conversely, while an increase in GDP per capita ($p < 0.00$) will have a positive but insignificant impact on the yearly per capita wheat consumption in China the long-run, the increase in GDP per capita after 1981 will have negative and significant impact on the per capita wheat consumption in China ($p < 0.00$).

For India, the long-term relationship between India's yearly per capita wheat consumption, urban population (%), imports, domestic wheat production, and per capita GDP are presented in Table 5.

The estimated error correction equation (ECT) for India is:

$$\begin{aligned}
 ECT_{t-1} = & \ln PC_{t-1} - 0.03 \Delta \ln IMP_{t-1} - 0.160.3 \Delta \ln \%UR_{t-1} \\
 & - 7.44 \Delta \ln DPR_{t-1} + 56.6 \Delta \ln GDP_{t-1} \\
 & - 1.82 (Year > 1981 \text{ dummy}) \\
 & - 57.4 (Year > 1981 \text{ dummy} \times \Delta \ln GDP_{t-1}) \\
 & + 164.2 (Year > 1981 \text{ dummy} \times \Delta \ln \%UR_{t-1}) \\
 & + 0.02
 \end{aligned}
 \quad (5)$$

And, setting the yearly per capita wheat consumption (PC) as the target variable, the estimated equation for India, is as follows:

$$\begin{aligned}
 \Delta \ln PC_t = & 0.005 - 0.59 \Delta \ln PC_{t-1} + 0.002 \Delta \ln IMP_{t-1} \\
 & + 0.58 \Delta \ln \%UR_{t-1} - 0.14 \Delta \ln DPR_{t-1} - 0.69 \Delta \ln GDP_{t-1}
 \end{aligned}$$

TABLE 4 Estimated functions applying the Vector Error Correction (VEC) model estimation procedure, explaining the relationship between yearly per capita wheat consumption, wheat import, % share of the urban population, domestic wheat production, and GDP per capita in China.

Dependent variables	d.ln(Cons)	d.ln(Imp)	d.ln(%Urb)	d.ln(Pro)	d.ln(GDP)	Year > 1981 dummy (y82)	y82 X ln(GDP)	y82 X ln(%Urb)
ECT _{t-1}	-0.11 (0.11)	0.81 (1.69)	0.21*** (0.04)	0.37 (0.28)	-0.21 (0.14)	0.64* (0.35)	3.62* (2.11)	2.08* (1.07)
D.ln(Cons) _{t-1}	-0.49*** (0.16)	-0.81 (2.51)	-0.0025 (0.06)	-0.19 (0.41)	0.47** (0.20)	-0.70 (0.52)	-4.05 (3.12)	-2.19 (1.58)
D.ln(Imp) _{t-1}	-0.0024 (0.01)	-0.35** (0.15)	-0.0019 (0.00)	0.026 (0.02)	0.0040 (0.01)	0.034 (0.03)	0.20 (0.18)	0.10 (0.09)
D.ln(%Urb) _{t-1}	0.023 (0.25)	1.06 (3.91)	-0.43*** (0.10)	-0.17 (0.64)	0.76** (0.31)	1.99** (0.81)	11.8** (4.87)	6.10** (2.47)
D.ln(Pro) _{t-1}	-0.071 (0.07)	0.19 (1.15)	0.061** (0.03)	-0.26 (0.19)	-0.097 (0.09)	0.73*** (0.24)	4.26*** (1.43)	2.25*** (0.73)
D.ln(GDP) _{t-1}	0.18* (0.11)	-2.03 (1.63)	-0.16*** (0.04)	0.83*** (0.27)	-0.039 (0.13)	-0.027 (0.34)	-0.16 (2.03)	-0.071 (1.03)
Year > 1981 dummy (y82)	-0.44 (0.43)	2.99 (6.64)	0.77*** (0.16)	1.38 (1.08)	-0.76 (0.53)	2.43* (1.38)	7.91 (8.27)	4.85 (4.20)
D.y82 X ln(GDP) _{t-1}	0.080 (0.24)	-4.23 (3.73)	-0.13 (0.09)	-1.47** (0.61)	0.76** (0.30)	-0.26 (0.78)	-1.10 (4.65)	-0.65 (2.36)
D.y82 X ln(%Urb) _{t-1}	-0.15 (0.47)	8.23 (7.24)	0.26 (0.18)	2.89** (1.18)	-1.48** (0.58)	0.48 (1.51)	2.00 (9.02)	1.21 (4.58)
Constant	0.00028 (0.01)	-0.027 (0.10)	-0.0052** (0.00)	-0.014 (0.02)	0.0048 (0.01)	0.00073 (0.02)	0.0087 (0.12)	-0.0012 (0.06)
No. of observations				55				
AIC				-26.06				
HQIC				-24.83				
SBIC				-22.89				
Log likelihood				803.7				
R ²	0.41	0.26	0.74	0.45	0.22	0.27	0.63	0.63

Values in parentheses are standard errors. *Significant at the 10% level. **Significant at the 5% level. ***Significant at the 1% level.

Cons = yearly per capita wheat consumption in kg.

Imp = wheat import in 1,000, ton.

%Urb = % Urban population.

Pro = domestic wheat production in 1,000 tons.

GDP = per capita GDP in nominal US \$.

y82 = Year > 1981 dummy (yes=1).

$$\begin{aligned}
 & -0.86 \text{ (year > 1981 dummy)} \\
 & +0.06 \text{ (year > 1981 dummy} \times \Delta \ln \text{GDP}_{t-1}) \\
 & -0.11 \text{ (year > 1981 dummy} \times \Delta \ln \% \text{UR}_{t-1}) \\
 & -0.001
 \end{aligned}
 \tag{6}$$

From Equation (5), in the long run, with other factors remaining the same, the percentage share of urban population ($p < 0.00$); domestic production ($p < 0.00$), year>1981 dummy ($p < 0.00$) and the GDP per capita after year 1981 will have a positive impact on yearly per capita wheat consumption in the long run, and conversely, the share of urban population after 1981 will have a negative and significant ($p < 0.00$) impact on India's per capita wheat consumption. It is found that import of wheat has no significant impact on wheat consumption in India.

The yearly per capita wheat consumption values in China and India for 2030 and 2050 were forecast using the dynamic forecasting method. Figures 3, 4 present the actual yearly per capita wheat consumption for the period 1961–2018 and the projected

yearly per capita wheat consumption of China and India for the period 2019–2050.

The econometric forecasting shows that, by 2030, the yearly per capita wheat consumption in China will increase to 76 kg and by 2050 it will increase to 95 kg, up from the per capita consumption level of 65.8 kg in 2019 (Table 6). Our findings contradict the findings of OECD/FAO (52), which states that by 2028 China's yearly per capita wheat consumption would amount to 62.6 kg, lower than the country's actual yearly per capita wheat consumption of 65.8 kg.

Considering the United Nations (20) projected population growth rates, by 2030 China will need to produce between 109 and 113 million t, representing 13–18% more wheat than the current total consumption amount of 96.4 million t in 2019 (Table 6). By 2050, depending on the assumption of the fertility rates, the country will need to supply between 123 and 144 million t of grain, which represents +28% to +49% more wheat than the total consumption of 96.4 million t in 2019 (Table 6). China's current average wheat yield is 5.74 t/ha, with 23.3 million ha of land currently allocated for

TABLE 5 Estimated functions applying the Vector Error Correction (VEC) model estimation procedure, explaining the relationship between yearly per capita wheat consumption, wheat import, % share of the urban population, domestic wheat production, and GDP per capita in India.

Dependent variables	d.ln(Cons)	d.ln(Imp)	d.ln(%Urb)	d.ln(Pro)	d.ln(GDP)	Year > 1981 dummy (y82)	y82 X ln(GDP)	y82 X ln(%Urb)
ECT _{t-1}	0.0055 (0.01)	0.39 (0.50)	0.0098*** (0.00)	0.024** (0.01)	−0.0071** (0.00)	0.032** (0.01)	0.20** (0.09)	0.10** (0.04)
D.ln(Cons) _{t-1}	−0.60*** (0.12)	5.02 (4.07)	−0.021 (0.02)	−0.029 (0.09)	0.031 (0.03)	0.013 (0.11)	0.10 (0.69)	0.025 (0.36)
D.ln(Imp) _{t-1}	0.0021 (0.00)	−0.40*** (0.14)	−0.0013** (0.00)	−0.0033 (0.00)	0.00074 (0.00)	0.00099 (0.00)	0.0059 (0.02)	0.0013 (0.01)
D.ln(%Urb) _{t-1}	0.58 (1.46)	16.0 (49.07)	0.28 (0.22)	1.53 (1.03)	−0.66** (0.34)	2.55* (1.37)	15.5* (8.32)	7.99* (4.34)
D.ln(Pro) _{t-1}	−0.14 (0.15)	−5.93 (4.89)	0.047** (0.02)	−0.37*** (0.10)	−0.093*** (0.03)	0.18 (0.14)	1.09 (0.83)	0.59 (0.43)
D.ln(GDP) _{t-1}	−0.69 (0.88)	−40.0 (29.46)	−0.30** (0.13)	0.98 (0.62)	−0.31 (0.20)	−1.30 (0.82)	−8.04 (4.99)	−4.04 (2.61)
Year > 1981 dummy (y82)	−0.86 (2.49)	−65.2 (83.72)	−1.67*** (0.38)	−3.97** (1.75)	1.19** (0.57)	−5.39** (2.33)	−39.1*** (14.19)	−20.1*** (7.41)
D.y82 X ln(GDP) _{t-1}	0.059 (0.85)	−9.48 (28.73)	0.38*** (0.13)	1.12* (0.60)	−0.28 (0.20)	1.31 (0.80)	7.97 (4.87)	4.32* (2.54)
D.y82 X ln(%Urb) _{t-1}	−0.11 (1.65)	17.8 (55.47)	−0.73*** (0.25)	−2.13* (1.16)	0.55 (0.38)	−2.54* (1.54)	−15.4 (9.40)	−8.36* (4.91)
Constant	−0.00059 (0.02)	−0.065 (0.67)	0.00012 (0.00)	−0.0016 (0.01)	0.0013 (0.00)	0.016 (0.02)	0.099 (0.11)	0.051 (0.06)
No. of observations				55				
AIC				−18.6				
HQIC				−17.4				
SBIC				−15.45				
Log likelihood				599.3				
R ²	0.41	0.33	0.58	0.60	0.42	0.17	0.58	0.58

Values in parentheses are standard errors. *Significant at the 10% level. **Significant at the 5% level. ***Significant at the 1% level.

Cons = yearly per capita wheat consumption in kg.

Imp = wheat import in 1,000 ton.

%Urb = % Urban population.

Pro = domestic wheat production in 1,000 tons.

GDP = per capita GDP in nominal US \$.

y82 = Year > 1981 dummy (yes = 1).

wheat production (Table 2). To meet the aggregate wheat demand by 2050, considering the high fertility-rate assumption, China will either need to bring 1.78 million ha of new land under wheat production or increase wheat yields to 6.18 t/ha.

For India, the estimation shows that, by 2030 and 2050, yearly per capita wheat consumption in India will increase to 74 kg and 94 kg respectively, compared to per capita annual consumption of 60.4 kg in 2019 (Table 6). In contrast to our projection, OECD/FAO (52) projected that by 2028, the yearly per capita wheat consumption of India would amount to 60.3 kg.

Our projection shows that by 2030 and based on United Nations population projections, India will need to produce 109–114 million t of wheat, 32–37% more than the 82.5 million t currently consumed, and 140–168 million t by 2050, which is 70–104% more than current consumption (Table 6). These findings support the findings of Gandhi et al. (53) and Nagarajan (47), which predicted an increase in wheat demand in India due to increases in income and

urbanization. India's current average wheat yield is 3.43 t/ha, with 31.4 million ha of land currently allocated for wheat production (Table 2). India will either need to bring extra 9–18 million ha of new land under wheat production or increase wheat yields to 4.46–5.37 t/ha, to meet the projected domestic for 2050.

It is necessary to mention here is that this study relied on a simple prediction process, using only a few years of observations (1961–2018). Future studies should employ more sophisticated and rigorous estimation and prediction process, such as machine learning approach in big datasets in predicting country specific wheat consumption with more model accuracy and prediction power.

4.3. Conclusion and policy implications

The estimation in this study shows that per capita GDP, imports, and domestic production significantly influence yearly per capita

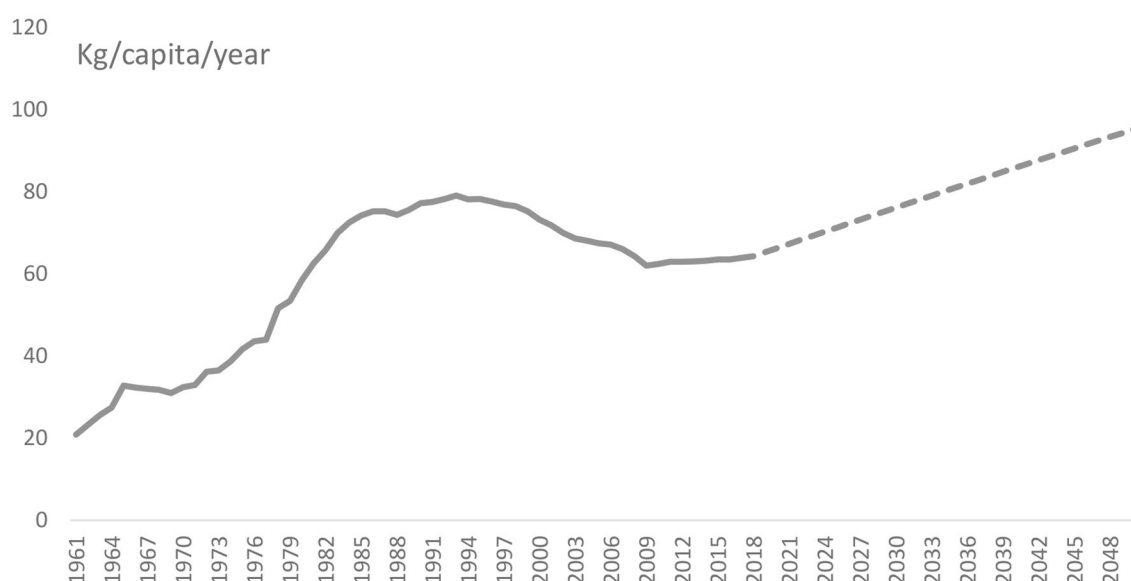


FIGURE 3

Actual (1961–2018) and predicted (2019–2050) yearly per capita wheat consumption in kg in China, [ln (kg/ per capita /year)], based on the Vector Error Correction (VEC) model estimation procedure. Broken line reflects projected consumption. Source: Authors' estimation.

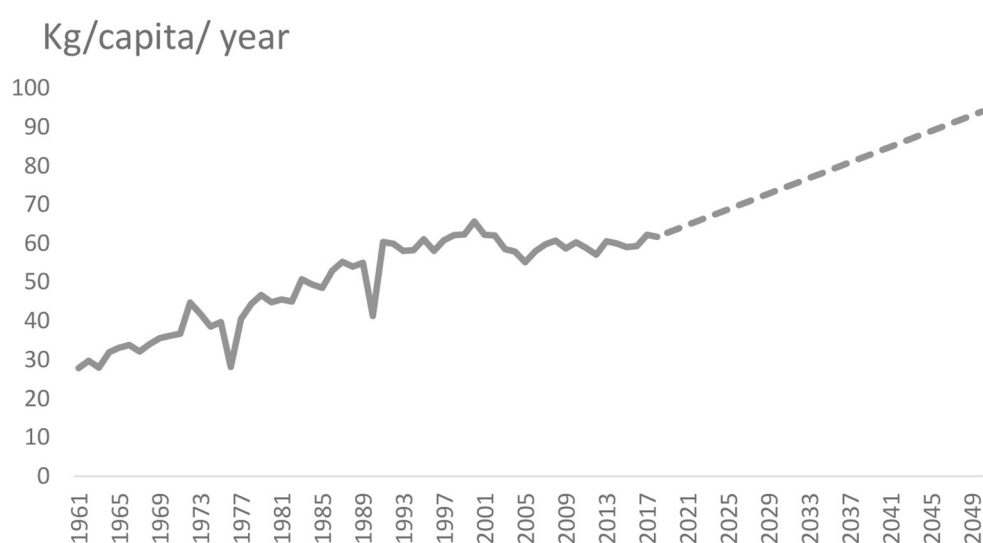


FIGURE 4

Actual and predicted yearly per capita wheat consumption in KG in India, during 1961–2050 [ln(yearly/capita/KG)], based on Vector Error Correction (VEC) model estimation procedure. Broken line reflects projected consumption. Source: Authors' estimation.

wheat consumption in China. Similar to China, domestic production has significant and positive impacts on yearly per capita wheat consumption in India but, in contrast to China, wheat imports have a negative and significant impact on the yearly per capita wheat consumption. Furthermore, in China the percentage share of the urban population ($p < 0.00$) will have a negative impact on the yearly per capita wheat consumption, whereas in India the share of the urban population has no impact.

Currently, 821 million (10.9%) population of the world face hunger (54). By 2050, the world population is expected to increase to between 8.9 billion and 10.6 billion (20) and with it, the number

of hungry people is projected to reach 2 billion, most of whom will hail from the global South. As wheat demand continues to increase in the coming decades, it is imperative to ensure the steady domestic production of wheat in China and India, to help minimize imports by those countries and thereby foster the stability of international wheat markets. This in turn will contribute to stable and affordable wheat grain prices, which will surely benefit the consumers of the wheat importing countries. It will ultimately contribute to ensuring food security and thereby in eliminating global hunger, and in attaining the zero-hunger goal of the United Nations by 2030.

TABLE 6 Wheat consumption projection by considering population dynamics and based on predicted consumption in the sampled countries.

Country	China	India
Kg/capita/year in 2019	65.8	60.4
Total wheat consumed in 2019 (million tons)	96.4	82.5
Predicted consumption (per capita/kg/yearly)		
2030	76 (+15.5)	74.0 (+22.5)
2050	95 (+44.3)	94 (+55.6)
Projected aggregate wheat demand in 2030		
Low fertility rate assumption	109.2 (+13.2)	108.6 (+32.4)
High fertility rate assumption	113.4 (+17.6)	114.0 (+37.4)
Projected aggregate wheat demand in 2050		
Low fertility rate assumption	123.0 (+27.6)	140.0 (+69.7)
High fertility rate assumption	144.0 (+49.4)	168.5 (+104.2)

Source: Authors' estimation.

Values in parenthesis and percentage change compared to the base level of per capita and total wheat consumption in 2019.

Despite tremendous economic progress, during 2019–21, <2.5% of the total population of China and 16.3% of the total population of India were undernourished (55). Given the reality of limited available agricultural land in China and India and based on our findings, investments in research and development relating to cropping systems of wheat and other major cereals are strongly urged. Harnessing genetic gains and enhancing crop yields can significantly contribute to ensuring food security by feeding burgeoning populations in China and India.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: <https://data.cimmyt.org/dataset.xhtml?persistentId=hdl:11529/10548840>.

Author contributions

The idea gap, conceptual framework, data cleaning and analysis, literature review, and first draft were prepared by KM. GK, AF, KS, and SL-R contributed to data acquisition, revising and editing the draft, and supervising the data analysis.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fnut.2022.1077443/full#supplementary-material>

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Sustainable production and distribution practices in Atlantic Canadian short food supply chains: Explorative study

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Introduction: How food is produced, processed, distributed, and consumed significantly impacts the sustainability of food supply chains. Short food supply chains (SFSCs) have been promoted as an alternative approach to offer sustainable solutions. However, empirical studies provide mixed evidence, and the findings greatly vary based on context. This study explores the social, economic, and environmental sustainability practices in Atlantic Canada's SFSCs from the perspective of farm businesses (producers).

Methods: A semi-structured survey was conducted among 64 farmers/producers who participated in Atlantic Canadian SFSCs. Participants were asked what channel they used to sell their products and how far this location is in comparison to the production location if sold to an intermediary, how they believe they could better to improve the sustainability of their production methods, what barriers stood in their way of implementation, and how supply chain supporters could help achieve their sustainability goals.

Results: The findings show that most farm businesses linked to SFSCs have applied ecologically sound production methods such as organic farming, IPM, or other sustainable practices, including regenerative agriculture and no-till farming. Over two-thirds of farm businesses applied sustainable practices such as pasture rotations, green fertilizers, low-carbon couriers, locally sourced inputs, and compostable or recyclable packaging materials. Farm businesses in the Atlantic Provinces highly value the social sustainability of SFSCs, followed by economic and environmental sustainability. Most farm businesses linked to SFSCs were robust to supply- and demand-side shocks, registered a low number of layoffs and fast recovery of operations, and increased their profits during COVID-19 compared to pre-COVID-19 levels. Yet, several barriers remain, the most important ones being high capital costs and longer payback periods. Other barriers include inconsistent inter-provincial trading restrictions, lack of qualified workers and shrinking agricultural land base.

Discussion: SFSCs in Atlantic Canadian SFSCs have implemented several sustainable practices in their production and distribution systems. Most of the farm businesses linked to SFSCs are small, are focused on specific product groups, target small towns or rural areas, and rely on direct-on farm sales to individual customers, and thus can play a crucial role by complementing longer food supply chains. By taking SFSCs in Atlantic Provinces as a case, this study expands our understanding of recent efforts and challenges local producers face to adopt sustainable practices in their production and distribution systems.

KEYWORDS

sustainable production, sustainable distribution, short food supply chains, Atlantic Canada, COVID-19

1. Introduction

How food is produced, processed, distributed, and consumed significantly impacts the sustainability of food supply chains (Govindan, 2018; Wang et al., 2019; Wezel et al., 2020). Indeed, sustainability has gained increasing attention since the end of the Green Revolution as concerns over the sustainability of current food production and distribution systems have reached to new levels (Armanda et al., 2019). Today, the global food system is responsible for 26% of greenhouse gas emissions, of which crop production (human consumption and animal feed) and other stages of the food supply chain (such as food processing, distribution, transport, packaging, and retail) generating about 44% of total food emissions (Poore and Nemecek, 2018; Ritchie and Roser, 2022). Furthermore, the globalization of food production and consumption has significantly increased the carbon footprint of food miles, which is estimated to account for 20% of food emissions (Li et al., 2022).

Short food supply chains (SFSCs) have emerged as sustainable solutions to address the food system's recent and future sustainability concerns, including food sovereignty, which is the ability for citizens to access nutritious, local, and sustainably produced foods to include in their diets (Matacena and Corvo, 2020; Doernberg et al., 2022). Although the definition of SFSCs may vary, they generally describe the distance between where food is grown/produced and consumed or primary production and final consumption (Coelho et al., 2018; Majewski et al., 2020). SFSCs are being popularized as a sustainable alternative (Benos et al., 2022) or complement (Thomé et al., 2021) to conventional, long food supply chains. Indeed, SFSCs can offer solutions for several sustainability challenges in the food system, such as reducing food waste and food miles. Currently, one-third of all food produced is wasted and ends up in landfills, creating 6 to 8% of all carbon and methane emissions (Lipińska et al., 2019; World Wildlife Fund, n.d.); long-distance food distribution accounts for 39% of food waste (Lipińska et al., 2019).

SFSCs are faced with several challenges due to limited production scale, resources and skills. One challenge is for these actors to access funding to invest in new production, processing and distribution technologies that are more sustainable (Jarzebowski et al., 2020). Another barrier is the difficulty of achieving market access. Whether they choose to sell the products themselves, which has initial costs of the location, set up, and proper storage for the foods, or try and sell to grocers who have larger companies that can offer lower prices than a smaller business, they tend to lose money starting off or in the long term (Jarzebowski et al., 2020). Another recent issue SFSCs have faced is the COVID-19 pandemic. This not only affected the demand for food in the service industry but also workers at different stages of the supply chain as they were unable to work because of catching the virus (Weersink et al., 2021). This has prompted interest in understanding the lessons gained during COVID-19 and how future supply chains can use these experiences and adapt and overcome future pandemics. The push for more sustainable supply chains has also resulted in consumers looking to reduce adverse effects on the planet by shopping ecologically sound and socially acceptable food products (Gillespie and Rogers, 2016; Tandon et al., 2020) and increased consumers' desire to purchase local foods (Cappelli and Cini, 2020; Maas et al., 2022).

Against this background, the present study aims to explore social, economic, and environmental sustainability practices in SFSCs and barriers thereof. Although there has been a renewed interest in local foods and SFSCs have been promoted as an alternative approach to

offer sustainable solutions, empirical studies provide mixed evidence, and the findings vary based on context. Therefore, this study seeks to provide insights into current sustainable practices and barriers from the perspective of SFSCs in four Atlantic Canada Provinces (i.e., Nova Scotia, New Brunswick, Newfoundland and Labrador, and Prince Edward Island). More specifically, the objectives of this study are to (1) describe short food supply chains in Atlantic Canada; (2) assess the level of sustainable production and distribution practices within SFSCs in Atlantic Canada; (3) assess the robustness of SFSCs to supply- and demand-side shocks due to COVID-19; and (4) explore opportunities and barriers to implementing sustainable practices in SFSCs. Considering recent changes in demography and dietary habits, local food movement, and sustainability concerns, the findings from this study could inform research gaps in local food systems within Atlantic Canada and beyond. In Canada, about 87% of consumers believe that shopping for food locally is more environmentally friendly and supports the local economy, with 45% trying to buy Canadian brands (Business Development Bank of Canada, n.d.). This has increased the desire of producers to adopt more sustainable practices in all three pillars of sustainability, social, economic, and environmental. Therefore, understanding current sustainable challenges is critical for creating economic incentives for SFSCs and investing in sustainable practices. Specifically in Atlantic Canada, the population is considered leaders in the shop local movement (Business Development Bank of Canada, n.d.). If this trend of supporting local continues, there is great potential for the SFSCs in the region to expand and the creation of more job opportunities for local communities (Business Development Bank of Canada, n.d.).

The remainder of the paper is structured as follows. The next section presents the literature review, followed by the methods section. Section 4 provides the results and discussion, followed by the conclusion section.

2. Literature review

2.1. Sustainable supply chains

The 2030 Agenda for Sustainable Development (United Nations, n.d.) adopted 17 Sustainable Development Goals (SDGs) to meet current needs without compromising future generations' ability to meet their needs. At the heart of these SDGs is sustainability. The first is to have decent work and economic growth such as creating sustainable jobs. Another is having responsible consumption and production by reducing waste and using renewable energy. The last sustainability goal relates to supply chains and their climate action by reducing their carbon footprint (United Nations, n.d.). Pagell and Wu (2009) argue that sustainable supply chains should at least be carbon neutral and not harm social systems but still create a profit that would allow businesses to run continuously. Also, Sisco et al. (2010) defined supply chain sustainability as "the management of environmental, social, and economic impacts, and the encouragement of good governance practices, throughout the lifecycles of goods and services" (p. 7). This definition resonates with the widely used concept called the "triple bottom line approach" that takes environmental, economic, and social dimensions as the minimum threshold for achieving sustainability (Elkington and Rowlands, 1999; Seuring and Müller, 2008).

Sustainable supply chain drivers can be both internal and external. Governmental policies and regulations play a significant role in promoting sustainable business practices (Raut et al., 2019). Also, pressures from society (expectations from consumers and civil society) and industry (competitors) can be important forces in driving sustainable practices in supply chains (Sajjad et al., 2015; Emamisaleh and Rahmani, 2017). For example, Oxfam's global campaign against the disproportionate power imbalance in the global coffee supply chain led to the launch of the Fair-Trade system and other sustainable programs in the coffee industry (Barrientos, 2006; Macdonald, 2007). Also, in 2004, Starbucks launched a sourcing approach called "Coffee and Farmer Equity (C.A.F.E.)" to promote economically, socially, and environmentally coffee growing practices (Starbucks, 2020). Internally, management commitment, operational and economic benefits can drive various sustainable practices (Emamisaleh and Rahmani, 2017; Sajjad et al., 2020). Many global companies have applied Corporate Social Responsibility (C.S.R.) as their business model to apply social and ethical practices (Lindgreen and Swaen, 2010). The blockchain technology is another important initiative aimed at overcoming transparency and traceability issues and enhancing environmental sustainability in the global food supply chains (Friedman and Ormiston, 2022).

2.2. Short food supply chains: Conceptualization and current practices

Malak-Rawlikowska et al. (2019) provide three-proximity criteria to define SFSCs. First, SFSCs must have close geographical proximity from where food is produced to where it will be consumed, and this is measured using food miles (Coelho et al., 2018; Malak-Rawlikowska et al., 2019). The second proximity is organizational, meaning the number of actors within the chain should consist of one or no intermediaries between the initial producer and the end consumer (Chiffolleau et al., 2016). Lastly is social proximity, which is the knowledge and information that is shared by the producer to create a relationship with the end consumer (Marsden et al., 2002). Social proximity focuses on the relationships that are created during the chains and how the consumers feel about the producers, whereas geographical proximity only focuses on the distance the food has gone to reach the end consumer. The later description lacks specifics of the proximities, such as the distance of food miles for geographical proximity, as well as the level of the relationships created between producer and end consumer for social proximity (Marsden et al., 2002; Malak-Rawlikowska et al., 2019). Though other research has suggested that local food or SFSCs can achieve geographical proximity by traveling a few miles within the city or state or even traveling up to 400 miles (Martinez, 2010; Coelho et al., 2018).

SFSCs can take various definitions, including alternative food networks and local food systems. Indeed "Alternative food networks" is an umbrella term to refer to SFSCs, box schemes, which are usually subscription-based, farmers' markets, and community gardens (Kessari et al., 2020). Local food systems, like SFSCs, look at geographical proximity as a determining factor. Typically, their end consumers are farmers' markets, restaurants, and retailers. Local food systems also consider the population of the community for choosing distance; if it is densely populated, the distance to be considered a local food system is much smaller than that of a spread out, less dense

area (Uchanski et al., 2018). In this study, we opted to use SFSCs vis-à-vis alternative food networks as we believe such chains need to be conceptualized as a complement rather than an alternative to longer food supply chains. SFSCs would include sales occurring at farmers' markets, retailers, and restaurants if the food sold comes right from the producer but follows the geographical proximity.

There have been studies attempting to provide empirical evidence about the sustainability of SFSCs. However, the findings are context-specific and diverse. For example, Malak-Rawlikowska et al. (2019) studied the social, economic, and environmental sustainability of SFSCs in Europe in relation to the long food supply chains (LFSCs) or conventional food supply chains. Within economic sustainability, their study found that SFSCs can receive higher prices for their products in comparison to LFSCs. Schmitt et al. (2017) found similar results in European SFSCs in terms of their ability to get higher prices. For environmental sustainability, Malak-Rawlikowska et al. (2019) looked at food miles from production to consumer and the CO₂ that is produced. The study concluded that though some SFSCs create lower levels of CO₂ or food miles, LFSCs, on average, create less of an environmental impact as they can transport and produce larger amounts of food at once. Lastly, for social sustainability, the study looked at labor to production, gender equality, bargaining power, prices, the quantity they can sell, labor hours, and contract ability (Malak-Rawlikowska et al., 2019). For labor to production, due to the smaller batches in SFSCs, more labor is required per product in comparison to LFSCs. As for gender equality in labor, SFSCs tend to have more diverse employment overall. LFSCs typically have better chances of getting contracts and creating more products (Malak-Rawlikowska et al., 2019).

One of the recent projects that documents desired sustainable practices in SFSCs is the Short supply chain Knowledge and Innovation Network (SKIN, n.d.); its Good Practice Repository provides empirical evidence from 24 European countries, the US, and Armenia. The sustainable practices encompass various food sectors such as fresh dairy, fresh meat, fruits, processed dairy, processed meat, processed other, and vegetables (SKIN, n.d.). The main indicators used to measure economic sustainability include profitability, local employment generation, economic uncertainty reduction, training and coaching initiatives, synergies with other sectors, markets/events/initiatives for multiple producers locally, and preservation and valorization of small farms (Vittersø et al., 2019; Jarzebowski et al., 2020; SKIN, n.d.). Environmental sustainability practices can be measured through greenhouse (GHG) emissions, energy use, carbon footprint, ecological soundness of production methods, food miles, and food waste (Malak-Rawlikowska et al., 2019; Vittersø et al., 2019). These studies cite several sustainable practices including Házikó, a catering business in Budapest that uses bicycle delivery to reduce its emissions and use environmentally friendly packaging, and Hello Fresh, a company that helps with reducing food miles and food waste by working closely with producers. With social sustainability, SFSCs are considered very important in creating strong connection between producers and consumers, building trust/sense of community, promoting community education, and recognizing of producers (SKIN, n.d.). Labor to production, gender equality, bargaining power, and other chain performance indicators are considered critical to evaluate the sustainability of SFSCs (Malak-Rawlikowska et al., 2019).

2.3. The COVID-19 effects on food supply chains

When COVID-19 occurred, it had differential effects on SFSCs and LFSCs. Initially, lockdowns caused by the pandemic forced hotels, restaurants, and schools to shut down affecting the distribution of food supplies. This increased sales occurring at grocery stores as at home meals became one of the very few options to get food and due to lockdown measures; this affected farmers' markets and on-farm stand sales (Thilmany et al., 2021; Weersink et al., 2021). The pandemic also required food producers and processors to change how they packaged foods as people wanted some foods in larger quantities. The pandemic also changed what foods people were buying, such as people deciding to bake with the extra time they had. People also started storing foods that can last longer, which resulted in empty shelves for products such as flour and frozen goods (Weersink et al., 2021). During this time, many producers saw a decrease in supply due to a shift in demand.

In Canada, chicken production in May and June of 2020 decreased 6 and 7% respectively, and dairy also decreased around the same time. Another issue that occurred due to COVID-19 was the increase in prices, with beef increasing by around 10%, whereas milk saw consistent pricing due to the supply management system used in Canada (Weersink et al., 2021). During the Pandemic, there were not only issues within the production but also in other parts of the chains. One issue was the difficulty of transporting food to and from the United States due to increased border restrictions (Hobbs, 2020). Also, labor shortages affected food distribution due to the regulations put on travel throughout the pandemic. It also affected processing due to workers being ill or even just having to isolate due to COVID exposures (Hobbs, 2020). Despite the disruptions in global food supply chains due to COVID-19, this may have benefitted SFSCs in some ways. For example, the shift to more online sales during lockdowns created another option for producers in SFSCs to increase sales and expand their reach beyond on-farm sales and customer base (Weersink et al., 2021).

3. Research methods

For this study, a semi-structured survey was conducted to explore the sustainability of current production and distribution systems in Atlantic Canadian SFSCs. The study included farmers/food producers who participated in short food supply chains (i.e., that sell their food products in proximity and/or use one or no intermediaries to sell their products, have a farm business within the four Atlantic Canadian provinces -i.e., Nova Scotia, New Brunswick, Prince Edward Island, and Newfoundland and Labrador- and whose contact information was publicly available). Within public forums, Buy Local New Brunswick (<https://buylocalnb.ca/>), Newfoundland and Labrador Farm Guide (<https://www.gov.nl.ca/farm-guide/farm-directory/all-farms/>), Fresh Products Directory Prince Edward Island PEI (<https://www.princeedwardisland.ca/en/publication/fresh-products-directory-2022>), and Buy Local Nova Scotia (<https://buylocal.novascotia.ca/business-search>) provide the email or phone numbers of food producers in the respective provinces. We found 302 contacts on the provincial forums of local producers, and all of them were contacted (via email or by phone) to participate in the study. Although more than 200 initiated the

online questionnaire, only 64 of them completed the semi-structured questionnaire, with a response rate of 21%.

The questionnaire was distributed to the local producers on the directory boards or personal contacts from each province through email and on Facebook forum. Although more than 200 initiated the online questionnaire, only 64 participants could complete it. Within the survey, most questions were semi-structured, with open-ended questions developed based on the empirical evidence documented in the SKIN's Good Practice Repository (SKIN, n.d.). This was necessary because Europe is considered the leader in sustainable production and consumption practices (Wang et al., 2019). Most questions about the three pillars of sustainability were measured on a 5-point Likert-scale. The questionnaire was hosted on "Opinio" survey tool after Dalhousie University's Research Ethics Board approval.

Participants were asked a variety of questions, such as their education level, what province they operate in, and other demographic information (farm size, main activity, etc.). For characterizing the chains, participants were asked what channel they used to sell their products and how far this location is in comparison to the production location if sold to an intermediary. This was quantitatively analyzed to show the typical length of these chains. Lastly, to understand how they could improve or what support is needed, participants were asked how they believe they could better to improve the sustainability of their production methods, what barriers stood in their way of implementation, and how supply chain supporters could help achieve their sustainability goals.

Data were analyzed both quantitatively (descriptive statistics, factor analysis, and multivariate analysis) and qualitatively. The semi-structured nature of the questions allowed us to gain deeper insights into the current sustainable practices and the potential to enhance the sustainability of current production and distribution systems in SFSCs.

4. Results and discussion

4.1. Description of short food supply chains in Atlantic Canada

Table 1 summarizes the sociodemographic characteristics of the participants in the semi-structured survey from the four Atlantic Provinces. Many participants were between the ages of 46–65 (43%) and 26–45 (33%), and 59% were males. Of the participants, about 78% were owners of the farm business. In addition, many participants (56%) held a "University Degree, Certificate or Diploma" or an "Advanced University Degree" (Graduate) and participants were from New Brunswick (56%). Most of the participants had 1 to 10 employees for their farm business (79%) and a farm income of \$100,000 or more (52%).

Most farm businesses were involved in fruits or vegetables (58%) and sold their products in small towns or rural areas (68%). The farm businesses implemented different farming systems—conventional (31%), organic (23%), Integrated Pest management (IPM) (22%), and other (23%). "Direct on-farm sales" (to individual consumers) was the most commonly used distribution channel (84%), followed by "Direct off-farm" sales at farmers' markets (63%) and delivery to the consumer (58%). Likewise, 59% of the participants reported having sold *via* small retailers (Table 2). The fact that most farm business in Atlantic Canada choose direct on-farm delivery may be attributed its benefits for consumers in terms of the quality and quantity of food

TABLE 1 Sociodemographic characteristics of study participants.

Demographics	Description	%
Age (<i>n</i> = 63)	18–25	4.8
	26–45	33.3
	46–65	42.9
	Above 65	19
Gender (<i>n</i> = 62)	Male	61.3
	Female	38.7
Position (<i>n</i> = 64)	Manager	15.6
	Owner	78.1
	Other	6.3
Education (<i>n</i> = 64)	High School Diploma or Equivalent	15.6
	Registered Apprenticeship or Other Trades Certificate or Diploma	4.7
	College, CEGEP or Other Non-University Certificate or Diploma	23.4
	University Degree, Certificate or Diploma	37.5
	Advanced University Degree (Graduate)	18.8
Location (<i>n</i> = 63)	Nova Scotia	25.4
	New Brunswick	55.6
	Newfoundland and Labrador	12.7
	Prince Edward Island	6.3
	1–10	78.7
# Employees (<i>n</i> = 61)	11–25	11.5
	26–50	8.2
	51–99	1.6
Farm income (<i>n</i> = 62)	<\$35,000	16.1
	Between \$35,000 and \$49,999	8.1
	Between \$50,000 and \$74,999	12.9
	Between \$75,000 and \$99,999	11.3
	Between \$100,000 and \$149,999	8.1
	\$150,000 +	43.5

purchased, as indicated by [Loiseau et al. \(2020\)](#), in the context of France. Studies elsewhere also documented direct-selling, specifically on-farm sales, as a preferred outlet choice for SFSCs (e.g., [Chiffolleau and Dourian, 2020](#); [Jarzowski et al., 2020](#)).

The participants were asked to share the farthest distance their primary product could travel before selling it to a buyer; the median and mean values food could travel were reported at 65 km and mean 83 km, respectively. Apparently, the food miles of SFSCs in Atlantic Provinces are relatively modest but higher than most SFSCs in Europe ([Coley et al., 2009](#); [Vaillant et al., 2017](#)). However, the empirical literature is inconclusive regarding the environmental sustainability of such practices. Some studies indicated that direct-on-farm sales might contribute to increased carbon footprints because it forces buyers to drive to farms and buy smaller quantities ([Coley et al., 2009](#)); this means that LFSCs may have an overall lower food mile and carbon footprint per unit than SFSCs ([Malak-Rawlikowska et al.,](#)

TABLE 2 Summary of production and distribution systems in Atlantic Canada SFSCs.

Variable	Description	%
Main product category (<i>n</i> = 64)	Fruits/vegetables	57.8
	Dairy products	6.3
	Meat	14.1
	Prepared food	4.7
	Other	17.2
Primary production method used (<i>n</i> = 64)	Conventional farming system	31.3
	Organic farming system	23.4
	Integrated pest management	21.9
	Other	23.4
Packaging method used (<i>n</i> = 64)	No packaging	14.1
	Plastic (recyclable)	29.7
	Other recyclable (i.e., glass, cardboard)	43.8
	Non-recyclable material	12.5
Sales outlet/selling location (<i>n</i> = 62)	Urban core	25.8
	Suburban	6.5
	Small town or rural	67.7
Distance traveled to sell products	Kilometers	65 ^a
Distribution channels used (<i>n</i> = 64)	Direct on-farm sales: Pick your own	39.1
	Direct on-farm sales: Sales to Individuals	84.4
	Direct off-farm sales: Internet Deliveries	31.3
	Direct off-farm sales: Delivery to the Consumer	57.8
	Direct off-farm sales: Farmers Markets (fairs)	62.5
	Sales to Small Retail Outlets (one intermediary)	59.4
	Other	31.3
Use of transportation means that requires fuel consumption (<i>n</i> = 64)	Never	2
	Rarely	3
	Sometimes	17
	Often	31
	Always	47
Use of a cooling system that requires fuel consumption (<i>n</i> = 64)	Never	38
	Rarely	20
	Sometimes	14
	Often	20
	Always	8

^aMedian distance.

2019). Also, it should be noted that other factors such as the level of technology used in production and distribution systems may have greater environmental impact than food miles *per se* (Coley et al., 2009; Mundler and Rumpus, 2012).

Regarding packaging material, only 12.5% of the respondents reported using non-recyclable material. The remaining 87.5% either used no packaging (14%), recyclable plastic (30%), or other recyclables such as glasses and cardboard (44%). About 72% of the participants in SFSCs reported that they had never (38%), rarely (20%), or sometimes (14%) used a cooling system that required fuel consumption. About 78% reported having used transportation that required fuel consumption. Most of the farm businesses (69%) used organic farming, IPM, or other farming systems. The overwhelming majority of farm businesses use compostable or recyclable packaging material made of plastic, glass, and cardboard. The use of chemical pesticides, herbicides, and fertilizers is minimal; only 31% of the farm businesses use conventional farming. Some farms use predator insects and culture control to manage pests, pasture rotations, green fertilizers, low-carbon couriers, and locally sourced inputs.

Table 3 summarizes the main source of information and level of trust among participants in SFSCs. Most farm businesses in the study (88%) used social media as the primary method to build their relationships with customer/consumer. However, the overwhelming majority of producers did have no to some influence on the activities of intermediaries or buyers. Likewise, farm-to-farm collaborations are less prevalent. As a result, most farm businesses were either unable to judge or had little or some level of trust in other farm businesses participating in SFSCs. Also, the level of trust between farm businesses and their customers ranges from fair to complete in the Atlantic Provinces SFSCs.

4.2. Analysis of the economic, social, and environmental sustainability of SFSCs

SFSCs in Atlantic Provinces achieved higher social sustainability scores compared to studies elsewhere, such as in Europe (Jarzebski et al., 2020). The strong social factor within SFSCs could serve as an effective marketing tool to receive recognition as a producer and create a trusted relationship between consumers and producers (Schmitt et al., 2017). In addition, farm businesses in the study agree that they supply trusted products that care for consumers' wellbeing and create strong social connections. This finding mirrors that of Maas et al. (2022), who looked at the value of SFSCs from the perspective of Atlantic Canadian consumers. Studies in Europe also provide support about the role of SFSCs in generating local employment (Malak-Rawlikowska et al., 2019; Jarzebski et al., 2020).

Relatively, the economic sustainability dimension received lower scores compared to the social sustainability dimension. In fact, this was reflected in the qualitative responses, which cited economic incentives and longer payback periods as the main obstacles to implementing sustainable production and distribution practices. Yet, compared to the European context, SFSCs in Atlantic Canada provide reasonable economic benefits for the farm businesses. This is perhaps because consumers in the Atlantic region tend to have a higher value of SFSCs as helping the local economy, safe and fresh; as a result, consumers are willing to pay more to encourage farm business

in SFSCs (Maas et al., 2022). According to the farm businesses, SFSCs contribute greatly to generate local employment and link their activities with other local businesses in different sectors. SFSCs in the study are considered as a source of regular and assured payments by establishing long-term relationships with their individual and industrial customers. Farm businesses in Atlantic Canada consider the price received and overall profitability generally "good"; however, the view that SFSCs achieve premium prices (Schmitt et al., 2017; Malak-Rawlikowska et al., 2019) is inconclusive, especially compared to the high capital cost required to implement sustainable practices.

Regarding the environmental dimension, most farm businesses agree that their current production and distribution systems create little to no food waste and are making efforts to reduce greenhouse gas emissions. In fact, over two-thirds of farm businesses applied farming practices that are more sustainable such as organic agriculture, IPM, and other sustainable practices such as regenerative agriculture, hydroponics systems, and Integrated Multi-Trophic Aquaculture (IMTA) (Table 4).

Factor analysis was carried out using the oblique rotation technique and principal components extraction to understand the underlying economic, social, and environmental sustainability factors in SFSCs. All the multi-scale items loaded above 0.5. The Kaiser-Meyer-Olkin (KMO), sampling adequacy, test for the social, economic, and environmental dimensions reported at 0.70, 0.66, and 0.56, respectively, which are all above the minimum acceptable value of 0.5; likewise, Bartlett's Test of sphericity was reported at $p < 0.001$. Both tests confirmed the suitability of the data for factor analysis. Thus, the multi-item scales, measured on a five-point Likert scale, were subjected to factor analysis and reliability tests using Cronbach's alpha. Except for the single construct measuring environmental sustainability ($\alpha = 0.64$), the other four measured a value of 0.69 or above.

As shown in Table 4, there were seven statements measuring the social sustainability dimension; five factors loaded in a single construct (Fac. 1), which relates to "community" related attributes, and the other component (Fac. 2) is attributed to "product authenticity." The highest loaded community-related item is the statement "We work to educate our consumers about the products they are consuming," with a factor loading of 0.772, followed by the statement "We have an equal gender distribution among employees." Both statements loaded high for the construct related to product authenticity (Table 4). Likewise, three statements related to economic sustainability are loaded in one factor (Fac. 1), "sustainable profit" related, and the remaining two statements are loaded to factor 2 (Fac. 2), "local economy" related. For the profit-related construct, the statement "We can sell our products for a premium price" has the highest factor loading (0.892) followed by "We produce a sustainable profit year-round." Both statements related to the "local economy" construct have high factor loadings. The environmental items loaded to a single factor (Fac. 1), and the statements "We work to reduce our overall greenhouse gas emissions" and "We are aware of how much energy and carbon we use during production and delivery" have factor loadings of 0.869 and 0.828.

Next, we carried out a multivariate analysis of variance (MANOVA) to test the effects of the constructs identified in the factor analysis (Table 4) on the choice of distribution channels (sales outlets) by the farm businesses. There was a statistically significant main effect in sales outlet choices based on the economic sustainability constructs "sustainable profit" (Pillai's Trace = 0.227, $F = 2.490$, p

TABLE 3 Information sources and the level of trust in SFSCs.

Variable		%
Methods used to build customer/consumer relationships ($n = 64$)	Social media	87.5
	Farmers markets (for interaction purposes)	57.8
	Smartphones (calling)	14.1
	E-communication (emails)	40.6
	No method used	6.3
To what extent can you influence the activities of intermediates within this chain? ($n = 55$)	I do not influence the activities of other chain participants	51
	I have some influence on the activities of chain participants	42
	I have a significant influence on the activities of chain participants	7
How do you characterize the level of trust among other farmers/producers within this chain? ($n = 63$)	There is little trust among all farmers/producers	6
	I am unable to judge	32
	There is some trust among all farmers/producers	30
	There is a lot of trust among all farmers/producers	17
	Not applicable; no other farmers/producers in the chain	14
How do you characterize the level of trust between farmers/producers and the customers/ consumers? ($n = 64$)	I am unable to judge	9
	Customers do have a fair level of trust in the quality of our products/offering	41
	Customers do have complete confidence in the quality of our products/offering	50

= 0.034) and “local economy” (Pillai’s Trace = 0.336; $F = 4.299$; $p = 0.001$) and the “community” related social sustainability construct (Pillai’s Trace = 0.211, $F = 2.278$, $p = 0.050$). The results show that economic sustainability constructs related to “sustainable profit” ($F = 9.818$; $p = 0.003$) and “local economy” ($F = 18.965$; $p < 0.001$) have a statistically significant effect in choosing “direct on-farm sales to individual consumers” as a primary outlet to sell food products. The “local economy” construct also has a significant main effect ($F = 5.869$; $p = 0.019$) in choosing direct on-farm sales (“pick your own”) as a primary sales outlet by farm businesses in Atlantic Canadian SFSCs. Only one of the social sustainability constructs (“community” related attribute) has a statistically significant main effect ($F = 9.487$; $p = 0.003$) in choosing “farmers markets” as the main off-farm sales outlet by farm businesses in the region. The other social sustainability construct related to “product authenticity” and the environmental construct did not have a statistically significant main effect in any of the on-farm or off-farm sales outlets or selling *via* an intermediary. Overall, the distribution channel decision (direct on-farm sales) appeared to be induced by economic motives. Environmentally, internet sales tends to be a preferred method to reduce food miles and carbon footprint (Majewski et al., 2020); however, direct sales *via* the internet was the lowest used channel in the study context compared to Europe (Malak-Rawlikowska et al., 2019).

Furthermore, study participants were asked to provide the overall attractiveness of SFSCs on a scale of 1 (poor) to 5 (excellent). Accordingly, SFSCs are perceived as “very good” as a source of regular and assured payments and in establishing long-term customer relationships. Likewise, price received and overall profitability of SFSCs are judged “good” by most of the farm businesses in the study context (Figure 1). The findings are generally consistent with the empirical evidence elsewhere (Malak-Rawlikowska et al., 2019; Vittersø et al., 2019; Abebe et al., 2022).

4.3. Robustness of SFSCs to supply- and demand-side shocks

SFSCs’ robustness to supply- and demand-side shocks during COVID-19 was assessed from the perspective of farm businesses in the four Atlantic Provinces. Approximately 63% of the study participants mentioned that COVID-19 affected their operations. However, 79% of them reported that they did not lay off their employees, and only 33% saw a decline in revenue. As of January 2022, about 54% of the farm businesses reported an 80% to a full return of pre-pandemic profit levels. In fact, about 59% had overall profits increased since COVID-19 (Table 5). This is perhaps surprising as farm businesses were affected by labor shortages due to Canada’s border restrictions and strict lockdown measures (Hobbs, 2020). This may be attributed to the closeness of SFSCs to consumers (Cappelli and Cini, 2020) and changes in consumer behaviors toward local foods due to COVID-19 (Benos et al., 2022).

4.4. Opportunities, barriers, and policy options to implement sustainable practices in SFSCs—qualitative analysis

This section explores the intensity and scope of current sustainable practices and the barriers in the context of Atlantic SFSCs using the qualitative information gathered through the semi-structured survey. Many of the farm businesses in the study have implemented multiple sustainable practices in their production and distribution systems, which are largely environmental or social.

TABLE 4 Sustainability of SFSCs (farm businesses' perspectives).

Sustainability dimensions (1 = Strongly Disagree; 5 = Strongly Agree)	Mean	Std. dev.	Factor analysis	
Economic sustainability (<i>n</i> = 64)			Fac. 1 (α = 0.69)	Fac. 2 (α = 0.76)
We generate local employment.	4.42	0.905	−0.016	−0.893
We work with other local businesses in different sectors.	4.28	0.786	0.067	−0.859
We produce a sustainable profit year-round.	3.61	1.002	0.715	−0.227
We have various strategies to reduce economic uncertainties.	3.78	0.863	0.698	−0.249
We can sell our products for a premium price.	3.84	0.996	0.892	0.306
Social sustainability (<i>n</i> = 62)			Fac. 1 (α = 0.77)	Fac. 2 (α = 0.72)
We create a trusted product.	4.78	0.49	0.076	−0.832
We look out for the wellbeing of our consumers when producing our foods.	4.76	0.429	0.661	−0.056
We work to educate our consumers about the products they are consuming.	4.5	0.69	0.772	−0.240
We have strong connections with our consumers.	4.36	0.843	0.662	−0.501
Our local community knows what foods we produce.	4.11	0.893	−0.066	−0.869
We have attended local markets or events to sell or promote our products.	4.09	1.205	0.660	0.015
We have an equal gender distribution among employees.	4.03	1.098	0.702	0.286
Environmental Sustainability (<i>n</i> = 64)			Fac.1 (α = 0.64)	
We create little to no food waste before the products reach consumers.	4.14	0.852	0.571	
We work to reduce our overall greenhouse gas emissions.	4.08	0.931	0.869	
We are aware of how much energy and carbon we use during production and delivery.	3.56	1.067	0.828	

Bold values indicate those statements loaded to the corresponding factor.

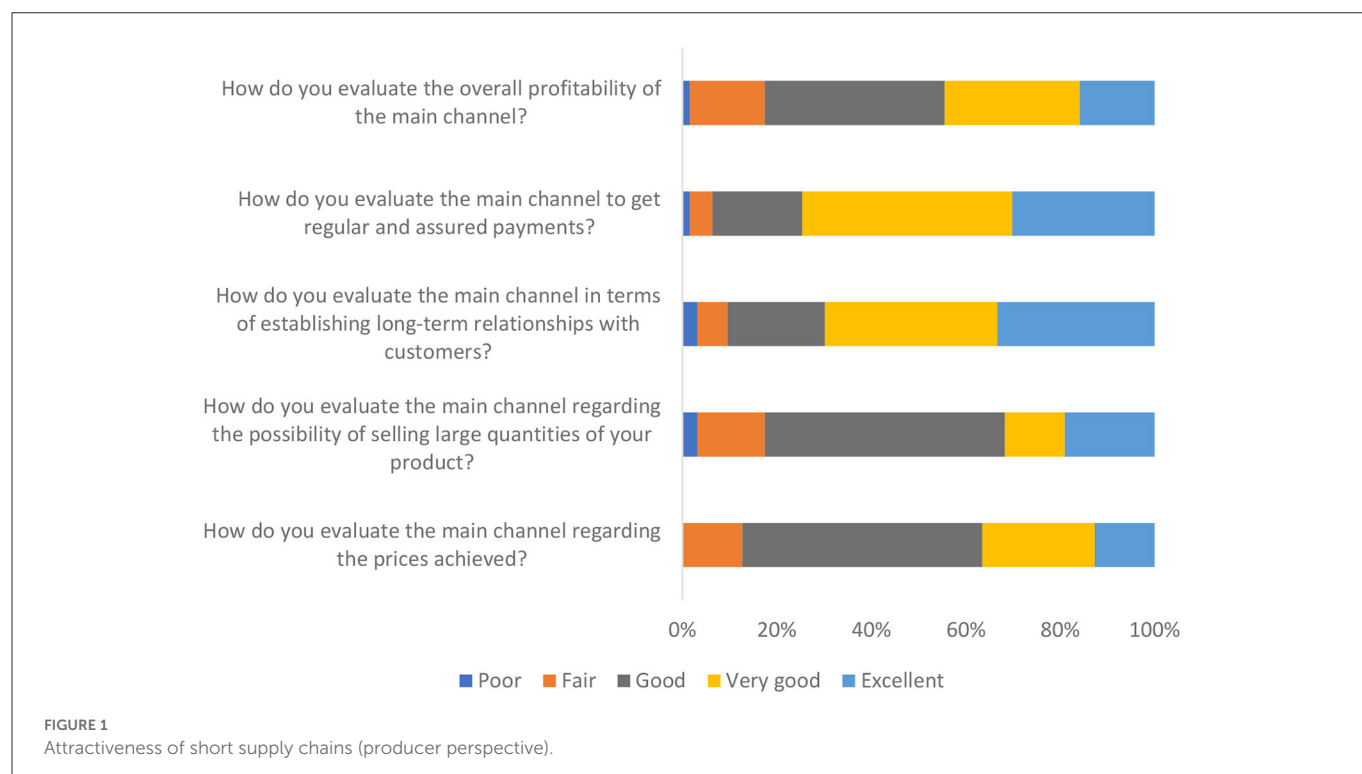


TABLE 5 The effect of COVID-19 on SFSCs.

	Description	%
Have any of your business/farm operations encountered a negative impact during the COVID-19 pandemic that was temporary? (<i>n</i> = 64)	Yes	62.5
	No	37.5
Since the start of the pandemic, have you laid off any of your employees? (<i>n</i> = 63)	Yes	20.6
	No	79.4
Has your overall business/farm revenue declined over the past 20 months of the COVID-19 pandemic compared to 20 months before the pandemic? (<i>n</i> = 64)	Yes	32.8
	No	67.2
If yes to the above question, what percentage of your business/farm revenue returned to the pre COVID-19 level as of January 2022? (<i>n</i> = 26)	Fully returned	23.1
	80–99%	30.8
	50–79%	19.2
	26–49%	3.8
	25% or less	23.1
Has your overall business/farm revenue increased over the past 20 months of COVID-19 compared to 20 months before the pandemic? (<i>n</i> = 63)	Yes	58.7
	No	41.3

However, the findings reveal that achieving economic sustainability in SFSCs remains elusive.

Many farm businesses implemented sustainable production and distribution practices. A farm business manager that used IPM identified “minimum tillage,” reduction of “plant health products,” and “capture carbon” as the primary sustainable practices being implemented (Respondent #33, New Brunswick). Another farm business manager engaged in producing fruits and vegetables using hydroponic systems highlighted some of the current practices: “Sustainability must be prioritized in all aspects of food products to try and reduce the impact of the impending climate disaster(s). Indoor production uses 95% less water, 90% less space (or more), and very little (if any) fossil fuel-burning machinery. We also do not use pesticides, herbicides, or preservatives”. (Respondent #11, Newfoundland and Labrador).

Several farm businesses also adopted better packaging methods, such as compostable materials and a return program for glass materials, reduced energy use and emissions, including a switch from gas-powered tools and vehicles to electric vehicles and power tools, and using energy-efficient appliances or switching to solar or wind energy. For example, the owner of a farm business engaged in organic farming (fruits and vegetables) explained his farm’s practices as follows: “We are willing and have invested in sustainable practices. We have almost eliminated the use of fossil fuels on the farm and would adopt more sustainable packaging if there was a viable/recyclable alternative.” (Respondent #12, Nova Scotia). Likewise, the owner of a farm (fruits and vegetables), using the organic farming system expressed her business commitment to sustainable practices: “I’m buying solar panels this year to offset some of my electricity use. Eventually, I plan to buy an electric vehicle for running errands and delivering produce. I’m also in the process of replacing gas powered

small tools and equipment with electric. I am planting flowering plants to support biodiversity and plan to increase this every year. I am fine-tuning the management of irrigation to reduce water use as much as possible. I am creating a hay field so we can produce our own hay instead of buying off-farm (I also have some livestock). I am trying to minimize tillage as much as possible and experiment with no-till when feasible.” (Respondent #8, New Brunswick).

Table 6 summarizes the qualitative responses regarding current sustainable practices in Atlantic Provinces’ SFSCs. As shown in Table 6, many farm businesses have implemented sustainable practices in their production and distribution systems. This includes a switch from gas (fossil fuel) to electric and solar energy sources for delivery and power tools. Others are using minimum tillage and no-till farming. The overwhelming majority of farm businesses use compostable or recyclable packaging material made of plastic, glass, and cardboard. The use of chemical pesticides, herbicides, and fertilizers is minimal; only 31% of the farm businesses use conventional farming. Some farms use predator insects and culture control to manage pests, pasture rotations, green fertilizers, low-carbon couriers, and locally sourced inputs. Most farm businesses use on-farm sales.

Next, the farm businesses were asked about the barriers to implement sustainable practices in their production and distribution systems. The barriers ranged from high capital costs (most important constraint), access to new technology, regulatory frameworks, and supply chain governance to limited human capital and shrinking farmland bases (Table 7).

A farm business owner described his frustration with access to finance as follows: “We applied for a grant to upgrade our refrigerators, stoves, and freezers to be more energy efficient! It is our aim to attempt to source local pork. We would like to be able to reuse our pickling jars, but we do not have the money for the dish washer required for cleaning the jars.” (Respondent #3, Nova Scotia).

Farm businesses are also struggling due to varying regulations. The owner of a farm business stated her frustration: “The compostable bags and containers that are currently in circulation for these items are not accepted by our waste management in Nova Scotia and therefore are not useful in our system.” (Respondent #26, Nova Scotia). Access to sustainable input sources is another constraint described by the same manager (Respondent #26): “Currently, there are no avenues for larger farms (that require bulk feed delivery) to obtain certified organic feed; this is a major barrier in our system as we would like to begin buying organic feed for our livestock but none of the feed companies will ship organic feed in their trucks. Also, there is nothing currently in place with our waste management to process compostable containers effectively, so they are not allowed in the green bin systems. This makes it useless for us to use these items unless the people buying them put them into their own composting systems or straight into the garbage.”

Another farm business manager engaged in a 95% pesticide-free farming system had to say the following: “We have been working toward more sustainability for 30 years and have been very successful in the running of the farm. However, we are still in a precarious position due to our socioeconomic climate. It is no exaggeration to say that the biggest threat to our existence is irresponsible bureaucracy and politics. We live in a disconnected society with ever-increasing levels of government regulation (interference) that is irresponsible in that they make rules and laws and let us try to find a way to survive. Socialism in Canada is very hypocritical in that it makes socialist rules and expects capitalism and the

TABLE 6 Current sustainable practices in Atlantic Canada SFSCs.

Sustainable practices being implemented	Stage of supply chain applied	Implementation intensity (rank)
Switching from gas (fossil fuel) to electric machinery (electric delivery vehicles, power tools) and solar energy sources	Production, logistics and distribution	1 st
Reduction of packaging waste and use of recyclables and compostable containers	Logistics and distribution	2 nd
Application of natural pest controls, wildflower/native to encourage good predator insects, and culture control of pests.	Production	3 rd
Reliance on locally sourced materials	Processing	3 rd
Minimal use of farm machinery, no-till farming, minimum tillage	Production	3 rd
Green, chelated fertilizers, carbon capture	Production	3 rd
Application of cover crops to reduce soil erosion	Production	3 rd
Use of draft horses, low-carbon courier, and mail services	Logistics and distribution	4 th
Farmland and grazing land rotations	Production	4 th
Waste reduction (make dried ingredients for human and pet consumption out of surplus and cull vegetable products)	Processing	5 th
Reduction of water use through improved irrigation systems	Production	5 th
		5 th
Use of passive thermal heated systems	Production	5 th
Plasticulture	Production	5 th

TABLE 7 Barriers preventing the implementation of sustainable practices.

Barriers to implementing sustainable practices	Constraining factor	Severity (rank)
High cost of implementing sustainable practices	Input supply (financial capital)	1 st
Limited access to technology, including charging stations packaging material, certified organic feed	Input supply (technology)	2 nd
Difficulty in inter-provincial trading—rules, restrictions	Policies and regulatory frameworks	3 rd
Time (long payback period)	Short-term economic motives	4 th
Power imbalance and limited market information	Supply chain governance	4 th
Lack of skilled workers	Input supply (human capital)	5 th
Shrinking farmland base	Input supply (land availability)	5 th

free market to figure out a way to keep going.” (Respondent #20, Nova Scotia).

Perhaps a major challenge within the Atlantic SFSCs is the economic incentives, at least in the short term, in implementing sustainable practices. The owner of a farm business described the sustainability challenges his business faced: “Right now, we are under constant pressure to push the land and employees (and ourselves) harder to generate enough revenue to stay in business. We are very productive, but it is never quite enough. As a result, we sometimes have to use practices that we believe are unsustainable and are caught in a trap where we cannot afford to invest in things like energy-reducing technologies or infrastructure because we

are continually paying those costs and, therefore, must continue to externalize costs in the form of pollution (Respondent #63, New Brunswick). He went on listing the main barriers as follows: “(1) Revenue is limited by prices that are determined by external factors; (2) policies that support cheap food, food is now cheaper as a percentage of income than it has ever been in history; (3) invisible subsidies to transportation of non-local produce in the form of highways and CO2 emissions; (4) invisible externalized social and environmental costs of production, like topsoil loss; and 95) power differentials within the food to retail chain that allow big players to restrict farm revenues and maximize their own profits.” This was also echoed by a farm business manager engaged in fruits and vegetables: “I agree to have sustainable production if it does not negatively impact my income. Society is asking farmers to produce high-quality food and protect the environment without using plant health products at very low prices. I have little sympathy for consumers who are only interested in looking for the lowest price and demanding the highest quality. Farmers can only be suckers for so long. Pay me for quality, and I will apply sustainable production practices.” (Respondent #33, New Brunswick). Another farm engaged in the meat business (certified humane and antibiotic-free) briefly described how economic incentives influence the decision to implement sustainable practices: “I love to use sustainable practices, but there needs to be greater recognition of the additional costs involved.” (Respondent #35, Prince Edward Island). Evidence elsewhere also shows SFSCs struggle to be economically sustainable in the current competitive environment. Due to their economies of scale and scope, large corporations can be able to supply food products at lower prices (Jarzebowski et al., 2020). However, if these companies had to pay for the negative environmental effects, their food prices would increase consumers’ costs by between 12 and 28% (Kalfagianni and Skordili, 2018) and would put SFSCs in a more competitive position, in terms of price.

TABLE 8 Potential policy interventions to promote sustainable practices in Atlantic Canada SFSCs.

Required policy support	Priority index (rank)
Government incentives for sustainable practices (electric vehicles, carbon sequestration, hydroponic, etc.)	1 st
Consistency in (inter-provincial) food inspection regulations	2 nd
Incentives for on-farm innovations and improved systems	2 nd
Easy access to finance	3 rd
Support for local farms (Note Resp #51)	3 rd
Government incentives to promote farming	3 rd
Financial support for small producers	4 th
Investment in research and development	4 th
Payments for set-aside land	5 th
Banning of unsustainable packaging material (non recyclables)	5 th
Market assistance, including co-operative initiatives	5 th

A shrinking farmland base is another concern described by a farm business owner engaged in processed foods by growing own vegetables: “Our farm uses green fertilizers to reduce the use of man-made ones, but we would need another farmland to fully take advantage of green fertilizer and to plant more flowers and plants to encourage beneficial predators and pollinators to prevent spraying of chemicals. We would rely on row covers more often if we had more farm hands.” (Respondent #3, Nova Scotia).

The last part of the qualitative study focused on policy supports and programs farm businesses would like to see introduced or enforced (Table 8). The responses varied from being unsure of the type of policy support to more robust approaches to promote sustainable practices. For example, a farm business owner engaged in processed foods by growing his own vegetables under the conventional farming system stated, “I am unsure of how policies would help us. Some of the food inspection policies tie our hands. We would like to recycle our jam jars, but we are required to have a commercial dishwasher instead of washing the jars in our domestic dishwasher and then baking them in an oven. Financial institutions do not like to support small businesses, especially farms. We went to three institutions to change our banking style to help us with the business and no one wanted to take the risk. I don’t know if policy could help that! In general, government officials move slowly and are not creative. Having said that, Perennia was a help to us when we first started. Small Farm Acceleration program is the only thing that has allowed us to grow!” (Respondent #3, Nova Scotia).

Another farm business engaged in producing fruits and vegetables under indoor vertical hydroponic farming called for a policy refocus toward inter-provincial collaboration: “I am not sure. With disrupted supply chains, this may help make local options more appealing. Maybe this is a time for policymakers to highlight and connect different businesses that can benefit from each other. Perhaps a policy that could help businesses and farms in Atlantic Canada if the four provinces could collaborate on standards. What I mean by this is that if a provincially inspected facility (butcher) can sell its product to all Atlantic provinces and not just the province it is located in. Or

that farmers can sell their produce in Nova Scotia that is grown in New Brunswick, for example.” (Respondent #21, New Brunswick).

Others called for policy incentives to encourage investment in sustainable practices such as electric vehicles (to be used in the production and distribution systems), carbon sequestration, and hydroponic systems; incentives for on-farm innovations and improved systems; easy access to finance; incentives to promote farming (young farmers); financial support for small producers; investment in research and development; payments for set-aside land; banning of unsustainable packaging material (non-recyclables); and market assistance, including co-operative initiatives.

Some of the direct quotes regarding policy interventions include the following:

“Pay farmers who set land aside, uncultivated, to improve biodiversity. Subsidize the cost of organic certification and the cost of transitioning to organic for existing conventional operations. Subsidize the cost of sustainably produced food for low-income folks” (Respondent #8, New Brunswick).

“Every question or problem in agriculture comes down to economics and the unlevel playing field. We all talk about fair-trade coffee and chocolate, but we don’t even have fair-trade food in our own province. We are required to meet ever higher standards for the benefit of our society (mostly food safety, environmental safety and human safety/ decency/ giving wage) but are expected to compete with imported products that meet little or none of these criteria.” (Respondent #20, Nova Scotia).

“From a policy perspective, some of these sustainability practices are very expensive short term, and it needs to be decided if it is a public good to be supported in earnest. Long-term payback on most of the COP practices is there, but we need to engage enough cash flow to support short term.” (Respondent #29, New Brunswick).

“Change food safety policies - too much waste and excessive burdens on small business owners”. (Respondent #44, Nova Scotia).

“Taxing grocery stores who do not allow small production facilities to be part of the distribution of local foods.”

5. Conclusion

How food is produced, processed, distributed, and consumed significantly impacts the sustainability of food supply chains. SFSCs have been promoted as an alternative approach to offer sustainable solutions. However, empirical studies provide mixed evidence, and the findings greatly vary based on context. This study sought to describe SFSCs in Atlantic Canada, assess the level of sustainable production and distribution practices and the robustness of the COVID-19 pandemic, and explore opportunities and barriers to implement sustainable practices in SFSCs.

The findings show that most farm businesses linked to SFSCs in the Atlantic region have applied ecologically sound production methods such as organic farming, IPM, or other sustainable practices, including regenerative agriculture, IMTA, and no-till farming. Such ecologically sound approaches have been cited as essential pathways to transform agri-food systems sustainably (Wezel et al., 2020). In the study context, the median distance food transported was 65 km. Many farm businesses relied on direct-on-farm sales for

both industrial buyers and individual consumers primarily located in small towns or rural areas. Social Media helped farm businesses build trustful relationships with their customers and create strong connections with society. However, the low level of horizontal coordination among farm businesses may prevent them from co-learning and creating economies of scale and scope in their relationship with their customers.

Farm businesses in the Atlantic Provinces show a higher value for the social sustainability of SFSCs, followed by economic and environmental sustainability dimensions. Compared to the European context, SFSCs in Atlantic Canada appeared to offer superior local employment opportunities and economic benefits in the form of regular and assured payments. Environmentally, over two-thirds of farm businesses applied more sustainable practices such as using predator insects and culture control to manage pests, pasture rotations, green fertilizers, low-carbon couriers, and locally sourced inputs. Most farm businesses use compostable or recyclable packaging materials and minimal chemical pesticides, herbicides, and fertilizers.

Consistent with several studies (Hobbs, 2020; Ghosh-Jerath et al., 2022; Maas et al., 2022; Millard et al., 2022), the farm businesses linked to SFSCs in the Atlantic Provinces were robust to supply- and demand-side shocks associated with COVID-19; most of the farm businesses registered low number of layoffs, and fast recovery of operations and increased profits compared to pre-COVID-19 levels. Yet, several barriers remain, the most important ones being high capital costs and longer payback periods. Other barriers include a lack of qualified workers and options to source sustainable materials, such as recyclables and compostable packaging, and a shrinking agricultural land base. Furthermore, inconsistent (inter-) provincial policies remain a challenge for farm businesses in the region.

Finally, as shown in the study, SFSCs in Atlantic Canadian SFSCs have implemented several sustainable practices in their production and distribution systems. Yet, most of the farm businesses linked to SFSCs are small, with a farm income of less than \$150,000 (56.5%), are focused on specific product groups such as fruits and vegetables (58%), target small towns or rural areas (68%), and rely on direct-on farm sales to individual customers (84%). This may suggest that SFSCs can be considered as a complement rather than a replacement for the more efficient (due to economies of scale and scope) longer food supply chains. According to a recent global estimate, SFSCs can serve within a 100-km radius or less and only fulfill the demands of 11–28% of the world population for specific crops (Kinnunen et al., 2020).

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The main limitation of this study was the small number of participants. There were over 200 people who started the survey; however, only 64 were completed it. We believe the semi-qualitative nature of the study would help to overcome the relatively small sample size in the study.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Dalhousie University Ethical Board. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

RB gathered data and authored the first draft. GA guided research design, data collection, and authored the final draft. EY and CH assisted the study design and peer-reviewed the final draft. All authors approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The impact of market-oriented cooperation on food production performance in small-scale farms in rural China

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Introduction: Small-scale farmers in developing countries can significantly contribute to sustainable food production through market-oriented cooperation (MOC). MOC allows farmers to access machinery services and specialized labor, but it also carries economic costs that may impact food production performance in small-scale farms. This study attempts to uncover the association between farmers' MOC participation and food production performance in small-scale farms in rural China, using a sample of 650 rice farmers in Jiangsu province.

Methods: We applied the stochastic frontier analysis to calculate the technical efficiency that indicates the production performance of small-scale farms. The treatment effect model is employed to detect the effect of farmers' MOC participation on technical efficiency, and the multivalued treatment effects model is used to explore the relationship between farmers' intensity of MOC and technical efficiency.

Results: The results show that farmers' MOC participation significantly increases technical efficiency of small-scale farms, with an inverted U-shaped correlation between MOC participation intensity and technical efficiency. A heterogeneity analysis based on production phases reveals that farmers tend to adopt MOC in machinery-driven phases with higher priority than in labor-driven phases. MOC in labor-driven phases, such as seedling and spraying, presents negative effect on technical efficiency.

Discussion: These findings highlight the crucial role of MOC in food production performance in small-scale farms, and provide insights for designing MOC strategies in different production phases in order to facilitate sustainable food production in developing regions. This research addresses the need for solutions to improve food production sustainability under agricultural transformation in developing countries. It also touches on the challenges and opportunities that producers face in adopting new practices and participating in the modern food supply chain.

KEYWORDS

sustainable food production, market-oriented cooperation, efficient resource utilization, small-scale farms, food production performance, treatment effect model

1. Introduction

Market transactions can boost the economic development of rural areas. However, many developing countries have a long history of self-sufficient agricultural production based on small-scale farms. In these countries, agricultural transformation has become increasingly important for securing the sustainable supply of national food and economic growth. It is believed that much potential still exists for the improvement of agricultural production efficiency in developing regions (Henderson and Isaac, 2017). Hence, enhancing efficiency through the market may contribute to the sustainability of food production. In the context of self-sufficient production, small-scale farmers usually choose to increase the input of family labor in agriculture as such labor-intensive cultivation can reduce the explicit labor cost and implicit supervision cost (Ma et al., 2022). Also, existing constraints may hinder farmers' integration

with agricultural markets, such as agricultural credit (Li and Huo, 2021; Rashid, 2021; Chen Z. et al., 2022; Kassouri and Kacou, 2022), production technology (Yang et al., 2020; Mao et al., 2021; Ruzzante et al., 2021), and information communication (Yang et al., 2021; Zheng et al., 2021; Zheng Y. et al., 2022). However, it has been recognized that farmers' participation in the agricultural market can promote a profound transformation of agricultural production, secure the sustainability of food production, and improve the livelihoods of small-scale farmers (Barrett, 2008; Liu et al., 2021).

In this study, market-oriented cooperation (MOC) is defined as the production mode in which farmers seek agricultural machinery services or employ labor according to their needs at different production phases. These are fundamental approaches to alleviate the shortage of agricultural resources in farmer households in developing countries. With about 0.5 billion small-scale farmers in rural areas, China has launched a series of agricultural reform initiatives, such as increasing subsidies for agricultural machinery and promoting agricultural outsourcing services (Lopez et al., 2017; Zhang et al., 2017; Mi et al., 2020). Conventionally, Chinese small-scale farmers cooperate with their relatives or neighbors through social networks in agricultural production. The cooperation is characterized by reciprocity among farmer households, and no explicit exchange of money is involved in the activity. With the enlightenment of market awareness in rural China, the belief is gaining ground that market forces make agricultural cooperation easier. Under the high seasonal requirement for agricultural production, MOC is much more flexible for farmers to seek labor force or other agricultural resources through the market. It can be more effective for realizing agricultural mechanization and reducing sunk costs than farmers' self-purchased machinery (Zhou et al., 2020; Zheng H. et al., 2022). Besides, MOC among farmers is useful to overcome labor shortages caused by migration and aging problems in rural areas. Farmers' cooperation based on the market system has become an essential approach to achieving agricultural modernization in developing regions.

The effect of farmers' MOC on the production performance of farms remains ambiguous. Some argued that MOC exerted a positive effect on agricultural production performance (Liu et al., 2021; Zhang et al., 2021), while others insisted on a negative effect (Qiu and Luo, 2021). Thus, this study attempts to clarify the role of MOC in sustainable food production, using the case of rice production in rural China. Different types of MOC were discussed in existing studies, indicating that agricultural resources can be equipped with market transactions to facilitate farmers (Zhang et al., 2021). For example, agricultural machinery services are mainly considered the key to improving production performance in rural areas (Yang et al., 2013; Takeshima, 2018; Qing et al., 2019; Qian et al., 2022). However, MOCs are not facilitated with complete mechanization in all production phases. The role of labor employment in MOC has not received enough attention. In China, labor employment has also been one of the indispensable ways for small-scale farmers to participate in MOC. Thus, it provides an opportunity to explore the role of MOC in both labor employment and machinery services. In some production phases, small-scale farmers can avoid the sunk costs of self-purchased machinery through MOC (Sheng et al., 2017), but the high cost of agricultural machinery services is likely to drive smallholders out of agriculture (Qiu and Luo, 2021). When farmers can employ laborers in particular production phases through MOC, the tendency of employees to shirk has reinforced the necessity of supervision

in agricultural production (Eswaran and Kotwal, 1986). Despite the fact that agricultural market-oriented services can increase return to scale and agricultural productivity, the opportunism caused by incomplete contracts can still increase the losses and supervision costs of farmers' participation in MOC. These costs caused by the participating market are regarded as transaction costs (Coase, 1937). They may restrict access to markets for smallholders and accelerate poverty (Picazo-Tadeo and Reig-Martínez, 2006). Higher intensity of MOC based on small-scale farms is likely to result in economic inefficiency (Shi et al., 2021). Farmers' high inputs in MOC are not necessarily translated into high outputs as expected. To sum up, although MOC can help farmers with a labor shortage and a low level of mechanization, it makes farmers bear high transaction costs. Thus, the first objective of this study is to uncover the relationship between farmers' participation intensity of MOC and the production performance of small-scale farms. We employed the multivalued treatment effect model to evaluate the effect of farmers' intensity in MOC on the production performance of small-scale farms (Zhou and Ma, 2022). IPWRA and AIPW estimators are used to test the robustness of the estimation results.

To better understand cause and effect between MOC and production performance, the second objective of this study is to analyze the heterogeneous effects of MOC in different production phases. From the perspective of the production phase, rare studies examined the influence of MOC in the entire production process (Sun et al., 2018; Qu et al., 2021). Scholars may get contradictory results from investigating the impact of MOC in different production phases. In certain production phases, farmers can observe the phase progress and quality easily (e.g., plowing), while employees have rough rides to implement opportunistic behavior. However, it is not always the case in different production phases. Evidence suggests that rice yields are not significantly increased with pest control through MOC (Sun et al., 2018). In addition, the machinery harvesting service increases rice farmers' losses (Wu et al., 2017; Qu et al., 2020), showing a negative impact of MOC on production performance. Technical efficiency may be increased due to the high utilization efficiency of inputs, while it may be reduced due to ineffective inputs, such as the supervision costs caused by a moral hazard (Henderson and Isaac, 2017). Previous studies have rarely considered the heterogeneity of MOC in different agricultural production phases. Whether farmers' preferences for MOC are distinct in different production phases? What are the effects of MOC in different production phases on the production performance of small farms? This study attempts to answer the questions based on the case of rice farmers in rural China.

This study may contribute to the existing literature in the following aspects. First, different from prior studies, the MOC covers agricultural mechanization services and labor services in rural markets. It enables us to elaborate on the effects of distinct types of market transactions on the food production performance of small-scale farmers. Second, the possible negative side of MOC has been rarely considered. The increase in costs in MOC may decrease the food production performances of small-scale farms. Farmers' higher participation intensity in MOC requires higher input costs. It can be a barrier to food production performance. This study employs a multivalued treatment effect model (TEM) to analyze the impact of participation intensity in MOC on the production performance of small-scale farmers. Third, we conducted a heterogeneous analysis of the effect of MOC in different production phases. It is conducive to

TABLE 1 Descriptive statistics of input–output indicators of rice farmers.

Variable	Mean	Std. dev.	Min	Max	Unit
Ln (yield)	8.724	1.411	5.485	13.567	Ln (catty)
Ln (land)	1.969	1.195	0.182	6.396	Ln (mu)
Ln (labor)	3.801	1.201	0.000	9.131	Ln (days)
Ln (capital)	7.994	1.706	4.808	13.894	Ln (yuan)
Ln (technology)	6.334	2.026	0.000	11.678	Ln (yuan)

1 catty = 0.5 kg, 1 mu = 1/15 hectare.

understanding farmers' preferences for MOC and its association with food production performances.

The rest of the study is organized as follows. In Section 2, we introduced the estimation strategies of the study. Section 3 presents data and descriptive statistics. The empirical results and discussion are reported in Section 4. We summarized the main conclusions and put forward recommendations in Section 5.

2. Materials and methods

2.1. Data and descriptive statistics

2.1.1. Data source

The data used in this study were obtained from the China Land Economic Survey (CLES) conducted by Nanjing Agricultural University in 2020. The database focuses on the rural land market, agricultural production, ecological environment, and other contents. The sampling method was as follows. First, 26 counties were selected within 13 municipalities in Jiangsu Province by the probability proportionate to size (PPS) sampling method. Second, two sample townships were selected from each county, and one administrative village was selected from each township. Finally, 50 households were sampled within each administrative village. The database contains about 2,600 farmers. Among them, rice farmers were selected as the case of this study because rice is the staple food in China and is grown by almost all sample farmers. After excluding the missing data, the valid sample consisted of 650 rice farmer households.

2.1.2. Variables and descriptive analysis

In the study, we used technical efficiency to represent the production performances of rice farmers. Following the previous studies (Zheng et al., 2021; DeLay et al., 2022; McFadden et al., 2022; Tirkaso and Hailu, 2022), we considered the total rice yield of a farm household as the output indicator and selected four input indicators, including the following components: (1) Capital, (2) Labor, (3) Land, and (4) Technology. Specifically, capital includes the cost of seeds, fertilizers, pesticides, water, electricity, and other expenses. Labor refers to the effort (days) spent by farmers in rice production. Land refers to the land area of rice cultivation of each farmer household. Technology refers to the cost of machinery, including direct use costs and indirect costs of maintenance. The summary of statistics for indicators is given in Table 1. It is important to note that farmers with full MOC in the whole production cycle do not input family labor or self-purchase machinery for rice production. The zero values

of input indicators, such as labor, cannot be directly logarithmic. All zero values need to be replaced with one (Ma et al., 2018).

Table 2 presents the definition and descriptive statistics of the variables in this study. There are two independent variables under question in this study. The first is farmers' binary choices of participation in MOC for rice production. If the household has adopted MOC in any agricultural phase, the value of the participation decision is set to 1, otherwise it is set to 0. The second is farmers' participation intensity, measured by the number of production phases in which farmers used MOC. It is a multi-categorical variable that ranges from 0 to 5 since five production phases (e.g., plowing, seedling, planting, spraying, and harvest) are considered in this study.

To ensure that the treatment effect model is identifiable, the rural industry is considered the instrumental variable. The rural industries in the sample villages include agricultural businesses and other industries, such as the processing industry and rural tourism. These industries provide farmers with off-farm employment. This increases the opportunity cost of rice production for farmer households and may trigger farmers to quit farming (Qiu and Luo, 2021). Consequently, it could influence farmers' willingness to participate in MOC during rice production. Meanwhile, rural industries generally have no significant impact on the technical efficiency of rice farms. The regression results show that rural industry significantly affects farmers' participation decisions in MOC at the 5% level (Coefficient = -0.858^{**} , Prob > chi square = 0.002) but has no significant effect on the technical efficiency of rice farmers (Coefficient = -0.003 , Prob > chi square = 0.000). It indicates that the selected instrumental variable is valid in this study.

We also used the socioeconomic characteristics of farmer households as the control variables. Specifically, we included individual characteristics of household heads (e.g., gender, age, education, health condition, training, off-farm work, and risk preference) and household resources (e.g., family size, income level, subsidies, land slope, land fertility, farm size, and machinery).

2.2. Estimation strategies

2.2.1. The stochastic frontier analysis

As a critical indicator of production performance, technical efficiency and its determinants have been widely discussed. We usually refer to the ratio of observable output to the maximum realizable output given the actual inputs as technical efficiency (Hong et al., 2019; Lawin and Tamini, 2019). Therefore, the utilization efficiency of different MOCs can be reflected by technical efficiency directly (Zheng et al., 2021). The technical efficiency can appropriately reflect the extent to which each observation achieves the feasible production frontier under the given mix of inputs (Bonfiglio et al., 2020; DeLay et al., 2022). Previous studies have shown that either the non-parametric method (data envelope analysis, DEA) (Haq, 2017; Liu et al., 2021; Guth et al., 2022) or the parametric method (stochastic frontier analysis, SFA) can be used to measure technical efficiency (e.g., Sabasi et al., 2019; Zheng et al., 2021; Zhu et al., 2021). In contrast, the SFA model can reduce the deviation caused by random factors (e.g., natural disasters). It is also less sensitive to outliers than the DEA model. Therefore, we employed the SFA model to calculate the technical efficiency of rice farmers.

TABLE 2 Descriptive statistics of variables.

Variables	Definition and measurement	Mean (S.D.)
Dependent variable		
TE	Technical efficiency of rice production	0.855 (0.106)
Independent variables		
Participation decision	1 = if household has adopted MOC in any phase, 0 = otherwise	0.926 (0.262)
Participation intensity	Number of production phases where the household adopted MOC (0, 1, 2, 3, 4, 5)	2.223 (1.222)
Control variables		
Gender	1 = male, 0 = otherwise	0.828 (0.378)
Age	Age of household head in years	60.371 (9.906)
Education	Number of years of schooling	6.802 (3.645)
Health condition	Self-reported health condition (1 = incapacity of work, 2 = poor, 3 = medium, 4 = good, 5 = excellent)	3.918 (1.063)
Training	1 = if farmer has participated in any agricultural training, 0 = otherwise	0.338 (0.474)
Off-farm work	1 = if farmer participated in off-farm work, 0 = otherwise	0.326 (0.469)
Risk preference	Farmer's attitude toward risk (1 = prefer high-risk investment, 2 = prefer medium-risk investment, 3 = prefer less risk investment)	2.697 (0.568)
Family size	Number of laborers (at least 6 months at home in a year) in the family	3.457 (1.705)
Income level	1 = if farmer household has been registered as a low-income family by government, 0 = otherwise	0.080 (0.272)
Subsidies	1 = if household has received government subsidies, 0 = otherwise	0.951 (0.217)
Land slope	1 = Level land, 0 = otherwise	0.923 (0.267)
Land fertility	1 = poor, 2 = medium, 3 = good	2.389 (0.619)
Farm size	Planting area of rice (mu)	22.975 (68.543)
Machinery	1 = if household owns agricultural machinery, 0 = otherwise	0.318 (0.466)
Instrument variable		
Rural industry	1 = if farmer's village has a rural industry, 0 = otherwise	0.169 (0.375)

There are two forms of functions widely used in the SFA model. One is the Cobb-Douglas production function, which requires fewer parameters. But this is subject to the assumption of a constant elasticity of substitution and follows a restriction on constant returns to scale consumption (Huan et al., 2022). Another is the Translog production function which can overcome the constraint of the above assumption. However, it may suffer from a potential multicollinearity problem. In this regard, following Shahbaz et al. (2022), the two production functions have been tested in this study, and the results of the log-likelihood ratio (LR) test show that the Translog production function is more appropriate.

Based on Ubabukoh and Imai (2022), the logarithm expression of the Translog production function is as follows:

$$\ln Y_i = \beta_0 + \beta_1 \ln K_i + \beta_2 \ln L_i + \beta_3 \ln A_i + \beta_4 \ln T_i + \beta_5 (\ln K_i)^2 + \beta_6 (\ln L_i)^2 + \beta_7 (\ln A_i)^2 + \beta_8 (\ln T_i)^2 + \beta_9 \ln(K_i L_i) + \beta_{10} \ln(K_i A_i) + \beta_{11} \ln(K_i T_i) + \beta_{12} \ln(L_i A_i) + \beta_{13} \ln(L_i T_i) + \beta_{14} \ln(A_i T_i) + (v_i - u_i) \quad (1)$$

Where \ln denotes the natural logarithm; the subscript i denotes the i -th rice farmer; β_i is the parameter to be estimated for the input variables and their interaction terms; Y is the output indicator in this study, and it represents the total rice yield of farmer i ; K , L , A , and T are all input indicators; K represents the farmer's capital input; L represents the farmer's labor input; A represents the farmer's land

input; T represents the machinery cost; v_i is a random error; u_i is an inefficiency term; and $u_i \sim ii \, dN^+(\mu, \sigma_u^2)$.

The households' technical efficiency is measured following Lawin and Tamini (2019), given as follows:

$$TE = \frac{E(Y_i | U_i, Q_i)}{E(Y_i | U_i = 0, Q_i)} = \exp(-U_i) \quad (2)$$

Where TE is the technical efficiency of farmer households, Q_i represents the total input of rice production, $E(Y_i | U_i, Q_i)$ represents the expected value of actual output, and $E(Y_i | U_i = 0, Q_i)$ denotes the expected value of the output on the frontier when the technical inefficiency term u_i equals zero.

2.2.2. The treatment effect model for estimating the impact of farmers' MOC on production performance

Farmers' participation decisions in MOC usually depend on observable characteristics (e.g., age, gender, education level, family size, farm size, and health condition) and unobservable characteristics (e.g., farmers' innate abilities). Their decisions usually do not follow the principle of random assignment and may cause self-selection bias among the sample farmers. It is not suitable to use ordinary least squares (OLS) for empirical estimation. Thus, some scholars have employed the propensity score matching

(PSM) method to alleviate the issue (e.g., Yang et al., 2020; Zhang et al., 2020). However, the PSM model can only address the self-selection bias introduced by observable variables. Accounting for both observed and unobserved variables (Cong and Drukker, 2000), this study uses TEM to eliminate the potential endogeneity problem and analyze the effect of MOC on the technical efficiency of farmers.

The estimation of TEM involves two stages. The first stage is referred to as a selection equation. It describes the farmers' participation decision in MOC in rice production. Following the principle of random utility maximization, a farmer adopts the MOC if the random utility obtained through the MOC is greater than that of the farmers' non-participation in MOC. Thus, the discrete selection model can be specified as follows (Ma and Abdulai, 2017):

$$M_i^* = \gamma z_i + \varepsilon_i, M_i = \begin{cases} 1, & \text{if } M_i^* > 0 \\ 0, & \text{if } M_i^* \leq 0 \end{cases} \quad (3)$$

Where M_i^* is the latent variable and M_i is its proxy. If M_i^* is > zero, it means the farmer i participated in MOC, and the M_i value is 1. Otherwise, M_i equals 0. z_i denotes the vector of explanatory variables, and it includes farmers' socioeconomic characteristics that may influence farmers' participation decisions in MOC. γ is a parameter to be estimated. ε_i is a random error term.

The second stage is referred to as an outcome equation. It can be specified as follows:

$$T_i = \alpha X_i + \delta M_i + \varphi_i \quad (4)$$

Where the dependent variable T_i refers to the technical efficiency of rice farmers, α and δ are parameters to be estimated, and φ_i is a random error term. X_i is a vector of control variables that are expected to influence technical efficiency.

Based on Equations (3) and (4), we can figure out the association between MOC and technical efficiency. Further, the average treatment effect (ATE) can be used to accurately calculate the difference in technical efficiency between participants and non-participants in MOC. The formula is given as follows:

$$ATE = E(T_i | M_i = 1) - E(T_i | M_i = 0) \quad (5)$$

Where $E(T_i)$ represents the expected technical efficiency of the two groups.

2.2.3. The multivalued treatment effect model for exploring the effect of farmers' participation intensity of MOC on production performance

We used the multivalued treatment effect (MTE) model to estimate the average treatment effects of farmers' different participation intensities in MOC on the technical efficiency of their rice farms. Following Ma et al. (2021), the random vector $Z_i = (Y_i, T_i, X_i)$ can be observed for each sample farmer household i ($i = 1, 2, \dots, N$). Y_i denotes a vector of the outcome variable technical efficiency, T_i represents a multivalued treatment variable of the

farmers' participation intensity, and X_i is a vector of a farmer's socioeconomic characteristics. $D_{it}(T_i)$ denotes that farmer i received the treatment t , and it can be defined (Ma and Abdulai, 2017) as follows:

$$D_{it}(T_i) = \begin{cases} 1, & \text{if } T_i = t \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

In particular, the outcome variable Y_{it} contains a set of potential outcomes ($Y_{i1}, \dots, Y_{it}, \dots, Y_{ij}$). But only one outcome Y_i can be realized by an individual farmer's household in each period. Following Issahaku and Abdulai (2020), Y_i can be expressed as follows:

$$Y_i = \sum_{t=0}^J D_{it}(T_i) Y_{it} \quad (7)$$

Given that the difference between two potential outcomes is the treatment effect (τ), the treatment effect between two distinct treatment levels (m and k) can be expressed as follows:

$$\tau = E[Y_{im} - Y_{in}], \forall m, n \in J \quad (8)$$

Given the fact that rice farmers can only choose the intensity of participation in MOC during each complete rice production cycle, only Y_{im} or Y_{in} can be observed for an individual farmer's household i . Thus, we cannot identify the treatment effect defined in Equation (8) without further assumptions (Ma et al., 2018; Issahaku and Abdulai, 2020). To eliminate the non-randomness of participation intensity, the MTE model is established on the basis of two assumptions, namely, the conditional independence assumption (CIA) and the overlap assumption (Cattaneo, 2010; Ma et al., 2018).

We controlled for observable pretreatment characteristics as much as possible to meet the CIA assumption. It implies that the farmer's choice of participation intensity can be regarded as a random assignment (Issahaku and Abdulai, 2020). The overlap assumption can be tested by the density plots of the generalized propensity scores (GPS) estimated from the multinomial Logit model (Cattaneo et al., 2013). It ensures that each covariate X_i has a positive probability and satisfies the following conditions:

$$0 < \Pr[T_i = t | X_i = x] \quad (9)$$

Based on the above assumptions, we can guarantee the independence of each farmer at t level from other individuals and calculate the conditional expected potential outcome for each participation intensity. Thus, the conditional expectations under the participation intensities m and n can be specified (Ma et al., 2021) as follows:

$$E[Y_{im} | X_i] = E[Y_i | T_i = m, X_i] = \beta_{0m} + X'_m \beta_{1m} \quad (10)$$

$$E[Y_{in} | X_i] = E[Y_i | T_i = n, X_i] = \beta_{0n} + X'_n \beta_{1n} \quad (11)$$

Then, the augmented inverse probability weighting (AIPW) estimator is used to calculate the average treatment effects, and an inverse probability weighted regression adjustment (IPWRA) estimator is used to check the robustness of the results. The two estimators are doubly robust (Linden et al., 2016), and the average treatment effect can be estimated as follows:

$$\begin{aligned} ATE_{mn} &= \frac{1}{U} (E[Y_{im}|X_i] - E[Y_{in}|X_i]) = \\ &= \frac{1}{U} \left[\sum_{i=1}^U (\beta_{0m} - \beta_{0n}) + \sum_{i=1}^U X'_i (\beta_{1m} - \beta_{1n}) \right] \\ &= (\beta_{0m} - \beta_{0n}) + \frac{1}{U} \sum_{i=1}^U X'_i (\beta_{1m} - \beta_{1n}) \end{aligned} \quad (12)$$

Where U refers to the number of samples with the treatment $T_i = m$ and $T_i = n$. β_{0i} and β_{1i} are vectors of parameters.

3. Results and discussion

3.1. The production performance of rice farmers

In this study, the technical efficiency of rice farmers is estimated only for one period, so the production function contains no time variable t . In this regard, an LR test statistic is required, and it consists of two steps. The first step is to test the applicability of the SFA model (Liu et al., 2020), and the null hypothesis is $H_0: \gamma = 0$. If the null hypothesis is rejected by the test results, it indicates that the SFA model is more applicable than the DEA model. The second step is to verify which production function form is better suited to the model. The null hypothesis of the Cobb–Douglas function (H_0) is that the coefficients of the input variables and their interaction terms are zero. The alternative hypothesis (H_1) represents the Translog function. The more appropriate model can also be identified by comparing the results of the LR tests.

Based on the above hypothesis of the SFA model, the results contribute to revealing the applicability of the models and production function forms. In particular, the coefficient γ in Translog form is equal to 0.947 and is significant at the 1% level. Meanwhile, the result of the LR test is 149.175, which is greater than the critical value of the mixed chi-square distribution at the 1% level, $\chi^2_{1-0.01}(2) = 8.273$. These findings show that the first hypothesis $H_0: \gamma = 0$ is rejected, indicating that the SFA model is more suitable than the DEA model. In terms of the second LR test that cannot be directly observed, we calculated the result by log-likelihood. The log-likelihood in the Translog function is 168.447, and for the Cobb–Douglas function, it is 59.126. The result also rejects the second hypothesis, suggesting that the Translog function is more appropriate than the Cobb–Douglas function ($LR = -2 \times [\ln L(H_0) - \ln L(H_1)] = -2 \times [59.126 - 168.447] = 218.642 > \chi^2_{1-0.01}(2) = 8.273$).

Table 3 shows the estimated technical efficiency of rice farmers based on the Translog function. The technical efficiency of overall samples ranges from 0.273 to 0.979. The average technical efficiency of MOC participants and non-participants is 0.855 and 0.846, respectively, indicating that MOC may play a positive role in improving technical efficiency. The minimum score of technical efficiency among MOC participants (0.273) is not as high as that of non-participants (0.437). It may be attributed to the negative effect of the overuse of MOC in agricultural production by small-scale

TABLE 3 Description of rice farmer's technical efficiency.

	Mean	Std. dev.	Min	Max	Observations
Participants	0.855	0.105	0.273	0.979	602
Non-participants	0.846	0.121	0.437	0.955	48
All	0.855	0.106	0.273	0.979	650

TABLE 4 Estimation results of the treatment effect model.

Variable	Selection equation	Outcome equation
Gender	−0.325 (0.227)	0.032*** (0.012)
Age	−0.010 (0.009)	0.000 (0.000)
Education	−0.003 (0.022)	0.002* (0.001)
Health condition	−0.168** (0.075)	0.002 (0.004)
Training	−0.056 (0.154)	0.011 (0.010)
Off-farm work	0.365** (0.181)	−0.014 (0.010)
Risk preference	0.037 (0.123)	−0.006 (0.008)
Family size	0.048 (0.044)	−0.007*** (0.003)
Low-income households	0.011 (0.273)	−0.023 (0.016)
Subsidies	−0.630 (0.492)	−0.003 (0.020)
Land slope	−0.251 (0.300)	0.022 (0.016)
Land fertility	−0.050 (0.117)	0.021*** (0.007)
Farm size	−0.002* (0.001)	0.000* (0.000)
Farm machinery	−0.259 (0.159)	0.022** (0.010)
Rural industry	−0.435*** (0.147)	–
MOC	–	0.182*** (0.017)
Constant	3.724*** (0.991)	0.586*** (0.055)
ath (ρ)	–	−1.041*** (0.110)
ln (σ)	–	−2.209*** (0.031)
Wald χ^2	–	157.210***
Log-likelihood	–	418.992
LR test of indep. eqns.	–	24.55***
Observations	650	650

The standard deviation is given in parentheses.

***Indicates $p < 0.01$; **indicates $p < 0.05$; *indicates $p < 0.10$.

farmers. Technical efficiency may be decreased by the excessive inputs of MOC in small farms in developing regions. However, the potential heterogeneous effect of MOC on technical efficiency needs to be explored in later sections.

3.2. Determinants of farmers' participation in MOC

The results in Table 4 show that the coefficient of residual correlation $\text{ath}(\rho)$ is significant with a negative sign, suggesting that the selection bias caused by observable and unobservable factors

exists in the sample (Manda et al., 2016; Ma and Abdulai, 2017). The effect of MOC on technical efficiency would be underestimated if the selection bias was not considered. The result of the Wald test also significantly rejects the null hypothesis that the MOC is exogenous (Ma et al., 2018). Therefore, TEM is appropriate to present a more solid estimation of the effect of MOC on the technical efficiency of rice farmers.

The determinants of MOC estimated by the selection equation are listed in the second column of Table 4. The coefficient of farmers' health condition is significant with a negative sign, suggesting that farmers with better health conditions have less participation in MOC. Farmer's poor health conditions would worsen farm labor shortage for agricultural production, and MOC can be adopted as an alternative solution. Similarly, off-farm work also has a significant positive effect on farmers' MOC, indicating that families with off-farm employment are more likely to participate in MOC. This finding is consistent with that of Zheng H. et al. (2022). The income obtained from off-farm work can enable farmers to purchase more services in agriculture. Farm size shows a significant negative impact on farmers adopting MOC. Farmers with larger farms have a lower probability of participating in MOC. The possible explanation is that these farmers are more likely to purchase agricultural machinery and hire long-term laborers rather than adopt MOC (Qiu and Luo, 2021). The coefficient of the rural industry is significant and negative at the 1% level, and the instrument variable is valid.

3.3. The impact of MOC on production performance

The third column of Table 4 presents the influence of factors on the technical efficiency of rice farmers. The results show that MOC has a statistically significant and positive impact on farmers' technical efficiency. It indicates that the adoption of MOC can enable farmers to achieve higher technical efficiency in rice production. The development of agricultural markets can realize the effective allocation of economic resources (e.g., labor and agricultural machinery), especially for small-scale farmers with a shortage of agricultural resources in developing countries.

Regarding the farmers' individual characteristics, gender and education exert a statistically significant and positive influence on technical efficiency. The coefficient of the gender variable implies that male-headed farmers are better at improving technical efficiency than female-headed farmers. Danso-Abbeam et al. (2020) also revealed the impact of gender on technical efficiency in Ghanaian cocoa farms. They attributed these efficiency variances to differences in farmers' resource endowments. The coefficient of the education variable suggests that higher education levels have a positive impact on farmers' technical efficiency. Existing studies have shown that better education can help farmers learn new technologies and exchange information (Ruzzante et al., 2021; Zhu et al., 2021).

With respect to household characteristics, the variable of family size exerts a negative and statistically significant impact on technical efficiency. This finding is in line with Zheng et al. (2021), who attributed this correlation to family composition. The quantity of the labor force is not equal to the size of the family, which may include many non-workers such as the elderly or children.

TABLE 5 Average treatment effects of MOC on technical efficiency.

	Participant	Non-participant	ATE	Percentage
Technical efficiency	0.852 (0.001)	0.846 (0.001)	0.006*** (0.001)	0.709%

The standard deviation is given in parentheses.

***Indicates $p < 0.01$.

Land fertility, farm size, and farm machinery are statistically significant with a positive sign. First, land fertility can improve technical efficiency by increasing output per unit (Al-Amin et al., 2016). Second, a potential pathway for the impact of the land area could be the reduction of inputs and losses per unit area through large-scale production (Liu et al., 2019). Finally, the finding of the land machinery variable is consistent with Shi et al. (2021), who verified that purchasing agricultural machinery is good for the technical efficiency of agricultural production.

3.4. Average treatment effect of MOC

We calculated the average treatment effect (ATE) of MOC based on the estimated results of the selection equation and outcome equation. The ATE represents the difference in technical efficiency between farmers with and without MOC in rice production. The results of ATE are presented in Table 5. The statistically positive and significant coefficient of ATE indicates that farmers' participation in MOC can increase the technical efficiency of their farms. Thus, purchasing production services through the agricultural market is effective to improve the food production performances of small-scale farmers in developing countries (Qiu and Luo, 2021; Chen T. et al., 2022).

Table 6 presents the results of the treatment effects of participation intensity on technical efficiency estimated by the AIPW estimator. For a straightforward interpretation of the coefficient estimates, we also calculated the percentage of change in ATE (Ma et al., 2021).

The results indicate that the adoption of MOC with intensities ranging from 1 to 5 can significantly increase farmers' technical efficiency compared with non-participants. Interestingly, the effect of MOC on technical efficiency does not increase continuously as farmers' participation intensity increases but shows a downward trend after rising initially. In other words, farmers' participation intensity in MOC on technical efficiency presents an inverted U-shaped effect. Technical efficiency peaks when the participation intensity in MOC is 3, indicating farmers who adopt MOC in three production phases have optimal technical efficiency on their farms. However, the declining trend in the effect of MOC on technical efficiency after the peak is much weaker than the upward trend before it. In other words, although the technical efficiency of farmers whose participation intensity is greater than three production phases decreases, it is still higher than that of farmers who adopt MOC only in one or two phases.

The possible insights can be explored with respect to this finding. First, farmers need to adhere to participation in MOC because the results confirm the substantial benefits of technical efficiency associated with MOC. Second, it is necessary for farmers to consider

TABLE 6 ATE results (AIPW estimator).

From 0 to n	ATE estimates		Percentage change in ATE	
	Coefficients	z-value	Coefficients	z-value
From 0 to 1	0.035** (0.017)	2.14	0.044** (0.021)	2.09
From 0 to 2	0.042*** (0.014)	3.10	0.052*** (0.017)	2.98
From 0 to 3	0.056*** (0.013)	4.18	0.069*** (0.017)	3.97
From 0 to 4	0.051*** (0.015)	3.40	0.063*** (0.019)	3.27
From 0 to 5	0.047*** (0.015)	3.11	0.058*** (0.019)	3.01

The standard deviation is given in parentheses.

***Indicates $p < 0.01$; **indicates $p < 0.05$.

TABLE 7 ATE results (IPWRA estimator).

From 0 to n	ATE estimates		Percentage change in ATE	
	Coefficients	z-value	Coefficients	z-value
From 0 to 1	0.036** (0.016)	2.27	0.044** (0.020)	2.23
From 0 to 2	0.044*** (0.013)	3.46	0.054*** (0.016)	3.33
From 0 to 3	0.057*** (0.012)	4.66	0.071*** (0.016)	4.42
From 0 to 4	0.055*** (0.014)	3.91	0.067*** (0.018)	3.75
From 0 to 5	0.049*** (0.013)	3.86	0.061*** (0.016)	3.70

The standard deviation is given in parentheses. ***Indicates $p < 0.01$; **indicates $p < 0.05$.

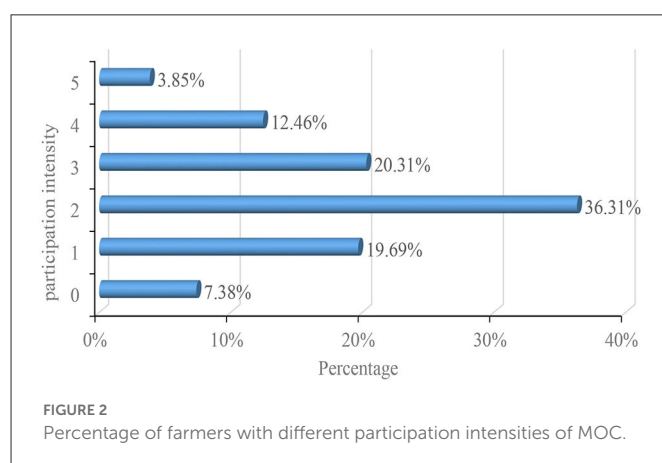
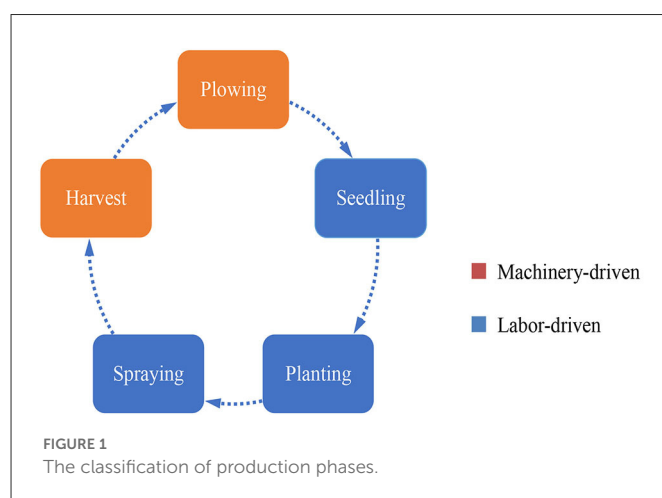
the appropriate participation intensity of MOC in their practices. Excessive costs invested in a small-scale farm may result in allocative inefficiency and diseconomies of scale (Shi et al., 2021), particularly in developing regions.

3.5. Robustness check of the impact of MOC intensity on production performance

Table 7 presents the results of the IPWRA estimator. It shows that farmers who move from 0 to n participation intensity in MOC have positive associations with ATE. The ATE peaked at degree 3 and presents an inverted U-shaped effect. The percentage of change in ATE is similar to the results presented in Table 5. Hence, the estimated results of the previous model are robust. There are no biased estimates caused by the misspecified model (Linden et al., 2016; Ma and Abdulai, 2017).

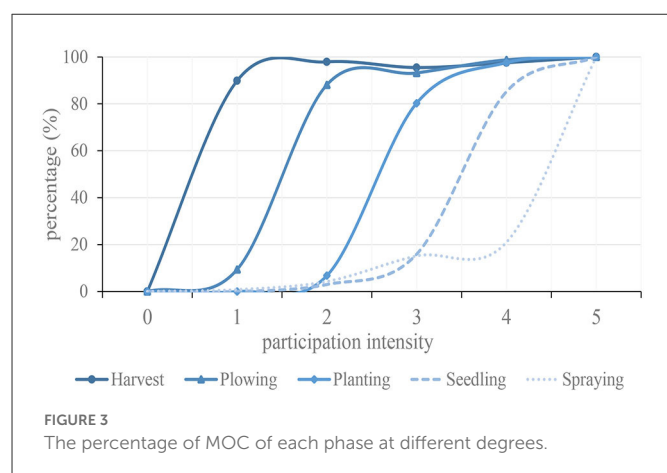
4. Heterogeneous effects in production phases

To better understand the inverted U-shaped effect of participation intensity in MOC on technical efficiency, this study attempts to explain it from two perspectives: the attributes



of different production phases and the resource endowment of farmer households.

It has been noted that farmers' decisions about purchasing services are deeply influenced by the type of each production phase. As highlighted in previous studies (Qiu and Luo, 2021; Qian et al., 2022) the production phases can be divided into "labor-intensive," "capital-intensive," and "technology-intensive" according to their attributes. For simplification, we classified the production phases into "machinery-driven" and "labor-driven" phases based on the difference in demand for labor or machinery in each phase. Figure 1 shows the categories of the five production phases.



Specifically, plowing and harvesting are classified as machinery-driven phases, while seedling, planting, and spraying can be seen as labor-driven phases.

We presented two figures for analyzing the heterogeneous effects. Figure 2 shows the percentages of farmers with different participation intensities in MOC. The percentages of MOC in each phase at different participation intensities are given in Figure 3.

As presented in Tables 6, 7, the value of ATE continued to increase in participation intensity from 0 to 1 and then to 2. This process of changing the intensity of MOC covered nearly 56% of the sample farmers in Figure 2. Meanwhile, corresponding to intensity 2 in Figure 3, 97.9% of farmers in this period adopted MOC for harvesting, and 88.1% of farmers purchased plowing services through the market. The descriptive statistics imply that rice farmers preferred MOC in machinery-driven phases.

The possible explanations can be put forward in this study. First, in terms of production phases, the harvesting and plowing services of the market are characterized by higher mechanization and lower supervision costs (Qing et al., 2019; Qian et al., 2022). Purchasing machinery services can contribute to improving technical efficiency by reducing labor input (Wang et al., 2020). Second, from the perspective of resource endowment of farmer households, MOC is much less expensive than purchasing agricultural machinery and learning how to use it for farmers. Table 8 presents that the proportion of self-owned machinery ranges from 3.846 to 28.462%. The low percentage implies that the majority of farmers have to rely on alternative solutions (e.g., purchasing machinery services or investing more labor effort) in the production phases. The estimation of mean difference analysis also shows that farmers who have purchased agricultural machinery are farmers with larger farms (Qian et al., 2022). Hence, the adoption of MOC in machinery-driven phases can be an economic choice, especially for small-scale farmers who usually cannot afford the machinery.

As shown in Figure 3, the proportion of MOC in the planting phase has increased from 6.780% with intensity 2 to 80.303% with intensity 3. According to the prior results, the technical efficiency is highest when farmers adopt MOC in three production phases. Thus, the MOC in planting plays a crucial role in farmers' improvement of technical efficiency.

Rice farmers prefer MOC in the harvesting and plowing stages than in the planting stage, which is usually labor-driven in rural

China. Labor shortage appears in the planting phase of rice production. The increasing labor costs in rural China and the difficulty in the supervision of pure labor efforts may account for this (Wang et al., 2016). In the same sense, the MOC was introduced later by farmers in labor-driven phases than in machinery-driven phases. However, the role of MOC in increasing technical efficiency cannot be ignored. The increase in technical efficiency in the process of planting can be attributed to three aspects. First, this finding suggests that the marginal effect of labor costs on technical efficiency has not yet exceeded that of the output created by purchased services. Second, the planting service can compensate for the constraint of a labor crunch on agricultural production. Under the high seasonal requirements of the planting phase, the planting service can help farmers complete the work in a short period and mitigate the impact of extreme weather on agriculture (Javed et al., 2020; Ogunleye et al., 2021). Third, the specialized planting team in rural areas enables farmers to avoid frequent searches for individual employees and save transaction costs (e.g., information costs), thus improving the technical efficiency of food production.

Figure 3 also displays the trend of adoption of MOC in the seedling and spraying phases. As labor-driven phases, they present an obviously low rate of MOC until the participation intensity reaches 4. According to the prior results, when farmers used MOC in these phases, the technical efficiency showed a declining trend. The possible reasons are as follows: First, the seedling and spraying services lead to higher supervision costs. The coefficient of the spraying phase in Table 9 is negative, suggesting that the adoption of MOC in the spraying phase would decrease the technical efficiency of rice farmers. Second, among households with 4 or 5 intensities, the input of family labor in agriculture is relatively small. In these farmer households, agriculture may not be the primary source of income. Family members can be engaged in off-farm work when they have adopted MOC in full production phases. The management of their farms becomes more extensive, thus reducing technical efficiency (Xu et al., 2019).

5. Conclusions and policy implications

The MOC is beneficial for small-scale farmers to overcome resource constraints and promote sustainable food production in developing countries. The shortage of agricultural resources in these areas may encourage farmers to develop market transactions. We attempted to assess the impact of MOC on the production performance of rice farmers in China, using the treatment effect model and multivalued treatment effect model based on the 2020 CLES database.

There are three main findings that can be drawn from this study: First, the MOC imposes a positive effect on the technical efficiency of small-scale farms in developing countries such as China. Farmers' participation in MOC can increase the technical efficiency of small-scale farms by 0.709%. Second, the relationship between the intensity of MOC and technical efficiency resembles an inverted U-shaped effect rather than a simple linear relationship. Specifically, when farmers' participation intensity does not exceed critical point 3, technical efficiency increases as the intensity does. Otherwise, technical efficiency decreases if the intensity increases after the critical point. The downward trend in technical efficiency after the peak is considerably weaker than the upward trend before it. Third, the MOC

TABLE 8 Use of agricultural machinery.

	Harvester	Cultivator	Transplanter	Tractor	Truck
Percentage	5.692%	12.769%	5.692%	28.462%	3.846%
Mean (Yes)	140.946	101.456	166.676	55.092	211.888
Mean (No)	17.145	10.349	14.444	8.756	15.679
Difference	123.801***	91.107***	152.231***	46.335***	196.209***

The farm size of small-scale farmers is <50 mu (1 mu = 1/15 ha).

***Indicates $p < 0.01$.

TABLE 9 Impacts of MOC on technical efficiency (each production phase).

	TE (tobit model)				
	Coefficient	Std. err.	Prob > χ^2	Log-likelihood	Control variables
Harvest	0.025*	0.013	0.000	560.460	Added
Plowing	0.005	0.010	0.000	558.777	Added
Planting	0.018**	0.009	0.000	560.957	Added
Seedling	0.012	0.010	0.000	559.342	Added
Spraying	−0.001	0.013	0.000	558.667	Added

**Indicates $p < 0.05$; *indicates $p < 0.10$.

among farmers has a heterogeneous effect in different production phases. Most farmers prefer MOC in machinery-driven phases, which are easier to supervise, than labor-driven phases such as planting. There are distinct impacts of MOC in different production phases on the technical efficiency of small-scale farms. Specifically, the adoption of MOC in harvesting, plowing, or planting has a positive effect on the technical efficiency of their farms, while the adoption of MOC in seedling and spraying presents a negative effect on the technical efficiency of their farms.

Several implications can be considered based on the findings of this study. First, policymakers are suggested to employ various channels to enhance the organization of smallholders, in order to stimulate farmers' willingness to participate in MOC. The high cost may decrease farmers' adoption of MOC. Through rural cooperatives or farmers' social networks, the government can organize farmers to participate intensively in MOC. It can help to reduce production cooperation costs, attract participants to provide production services and achieve the sustainable development of food production. Second, policymakers and stakeholders may take care of the negative effect of MOC on the production performance of small-scale farms. Excessive participation in the MOC of small-scale farmers may reduce technical efficiency in agricultural production. Thus, it affects the sustainability of food production. However, the government can promote land transfer among these farmers, achieve large-scale operation of land resources, and improve the effect of MOC through economies of scale. Third, policymakers can enhance machinery subsidies to promote MOC in machinery-driven production phases, since the use of machinery reduces supervision costs in agriculture. It can guarantee the sustainability of farmers' consumption by reducing their production inputs. In the same sense, the investment in R&D of machinery that is applicable for small-scale farms can be supported, in order to transform the existing labor-based MOCs with advanced machinery.

This study detected the impact of farmers' MOC on their food production performance. However, there are still limitations. First, this study examined the case of rice farmers in China's Jiangsu

Province. The findings should be prudently extended to other crops and other regions with different resource endowments. Second, the cross-sectional data employed in this study only focus on the short-term effects of MOC on agricultural production performance. Further studies should be conducted with a panel dataset and investigate the impact of farmers' MOC in multiple factor markets on sustainable agricultural production.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CZ contributed to the conceptualization, methodology, investigation, data curation, formal analysis, and writing—original draft. YZ contributed to the conceptualization, investigation, formal analysis, project administration, funding acquisition, and writing—review and editing. All authors contributed to the manuscript revision and read and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Do crop diversity and livestock production improve smallholder intra-household dietary diversity, nutrition and sustainable food production? Empirical evidence from Pakistan

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Crop diversification and livestock production is an important strategy to enhance nutrition, sustainable food production, and improve food security, especially at the smallholder household level. However, existing evidences are mixed and there are limited information about the relationship among agriculture crops, household income diversification (HID), and household dietary diversity (HDD) among smallholder farmers in developing country setting like Pakistan. Therefore, this study aims to understand the role of crop diversification (CD) on HDD, nutrition, and sustainable agriculture and food production in the context of smallholder households in Punjab, Pakistan. The study employed ordered probit regression and cross-sectional data from 450 households collected using 24-h recall method. Regression results indicate that crop diversity and intra-household dietary diversity are positively associated across adults, adolescents, and children in all the study districts. Moreover, annual income, key crops grown by the household and family education are also the significant drivers of dietary diversity. Greater travel distance between markets was the most crucial factor in all regions which significantly affect dietary diversity. The overall research findings indicated that crop diversification and livestock production in the selected areas is significantly contributing to improve nutrition and sustainable food production. Therefore this study recommends for promoting crop diversification and livestock production for sustainable agricultural development and improving nutrition in the context of developing countries like Pakistan.

KEYWORDS

crop diversity, food security, sustainable food production, income diversity, Pakistan, livestock production

1. Introduction

Imbalanced diets and a lack of economic access to nutritious food are undoubtedly major reasons for malnutrition (Adjimoti and Kwadzo, 2018; Appiah-Twumasi and Asale, 2022). Almost 75% of the world's populations suffer from various forms of malnutrition, such as obesity, anemia, and stunting in developing countries. According to the United Nations report 2020, ~155 million small children are stunted, nearly 52 million children are wasted,

and nearly 2 billion people are vitamin deficient (Akhtar, 2016; United Nations, 2020). Every year, ~40.2% of children in Pakistan are stunted, and 37.8% of men are anemic (National Nutrition Survey, 2018; Soofi et al., 2022). The prevalence of malnutrition has decreased in Pakistan during the past decade; however, the problem persists, particularly in the rural areas (Asim and Nawaz, 2018; Mahmood et al., 2020; Jamil et al., 2021a). Malnutrition is a pervasive problem affecting people of various ages, genders, socioeconomic standings, and geographic locations. However, it is rampant among the poor in rural areas, where childhood stunting and anemia are more prevalent than in urban areas (Abbas et al., 2020; Usman and Callo-Concha, 2021).

In Pakistan, most people directly attain food from agricultural crops and livestock. In the past few decades, rural areas in Pakistan have begun to experience significant shifts in agricultural practices and revenue streams. Due to limited resources, low income, and subsistence farming, the farm diversification of households has declined (Saqib et al., 2018; Fahad and Wang, 2020). Simultaneously, family members of farming households are quitting the business, expanding the breadth of economic opportunities for rural families in Pakistan (Usman et al., 2016; Drucza and Peveri, 2018; Khan et al., 2020). Currently, 70% of Pakistan's average farm family's income comes from the agriculture sector (Peerzado et al., 2019; Jamil et al., 2021b). At this time, it is unknown how these changes affect family nutrition. In light of ongoing changes, however, it is vital to comprehend these implications so that they can inform efforts to eliminate rural malnutrition in Pakistan.

Previous research has demonstrated the positive relationships between household income, crop diversity, and dietary diversity; this is noteworthy in light of recent variations in crop patterns and sources of income in Pakistani agriculture systems (Munir et al., 2015; Akhtar, 2016). Farm household who cultivate new crop varieties have access to higher household incomes as well as sustainable food production (Sibhatu and Qaim, 2018; Habtemariam et al., 2021). Although it has been demonstrated that rising income increases dietary diversity, very little research has been conducted to investigate the relationship between income diversity (ID) and dietary diversity (DD) among smallholder agriculture farmers in Pakistan (Jones, 2017; Koppmair et al., 2017; Passarelli et al., 2018). It is crucial to comprehend this link since farmers in developing countries rapidly diversify their revenue sources (Davis et al., 2014, 2017; Suberu et al., 2015; Gecho, 2017). Agriculture farmers who cultivate a wider variety of crops provide their families with sustainable food and a higher standard of living (Putra et al., 2020; Iqbal et al., 2021; Yaqoob et al., 2022). Therefore, it is important to understand the relationship among income diversification (ID) and dietary diversity (DD) among smallholder agriculture farmers in developing countries like Pakistan.

This study explored the relationship among crop diversity (CD, HHI, and HDD) among three Pakistani south Punjab districts undergoing distinct livelihood transitions: Layyah, Bhakkar, and Khushab. Consequently, farmers in Layyah and Bhakkar have shifted their focus to producing a wide variety of high-value crops, such as wheat, mung beans, gram, and sugarcane. In contrast, the farmers of Khushab are experts at cultivating wheat and pulses, Pakistan's most important food crops. In addition, these locations offer very low infrastructure compared to the bulk of farming areas in Pakistan, making it difficult for farm

families to diversify their income sources through employment or business ownership. Layyah, Bhakkar, and Khushab are excellent case studies for examining the association among CD, household income diversity (HID), and smallholder farmer household dietary diversity (HDD) because they each represent distinctive livelihood transition pathways for smallholder farmer households in south Punjab, Pakistan, with still-high malnutrition rates. Particularly, we explore the following question: How do crop and household income diversity (CD and HHI) influence the DD of women, men, children, and adolescents among smallholder agricultural farmers in south Punjab districts (Layyah, Bhakkar, and Khushab)? How closely does dietary diversity (DD) at the individual level (male, female, adolescent, and child) associate with the following agricultural and socioeconomic factors?

This study links crop diversification and household income in Pakistani rural communities. In spite of the cross-sectional data, we scrutinize the relationship between CD, HID, and HDD. The main contribution of this study is to understand how crop specialization can increase HID as well as influence HDD. As big as it is, this transformation spreads across Pakistan as rural populations become increasingly connected to markets (Hirani, 2012; Khan et al., 2016; Shahid et al., 2022). Pakistan has one of the highest rates of malnutrition in the world (Doocy et al., 2018). Moreover, no research has been undertaken in south Punjab, Pakistan, correlating CD and HDD. This study's findings have been used to develop strategies and food policy efforts to promote dietary diversity in severely malnourished regions like Pakistan.

In this research, CD was found to be associated with DD in adults (males, females, and adolescents) in both districts (Layyah and Bhakkar) and children in district Khushab. In all districts, dietary diversity scores (DDSs) have positively correlated with family education, crop diversification, and travel distance to markets; however, in Layyah and Bhakkar, cash crops and annual income were the most important determinants. The dwellings of farmers in Layyah, Bhakkar, and Khushab were randomly sampled using a suitable scientific technique (Section Material and methods). Section Results and discussion describes the findings and the principal statistical analyses that elaborate on the regression results and also contains comprehensive information on farming systems in all districts. In Section Discussion, we highlight the fundamental limitations of this approach, along with our key findings and their significance in light of the preceding literature. The primary conclusions and policy implications of increasing food diversity among Pakistani smallholder farmers are in Section Conclusion.

2. Materials and methods

2.1. Study location and sampling methodology

This study based on survey data, we chose three districts in south Punjab, Pakistan (Layyah, Bhakkar, and Khushab) as shown in Figure 1, to compare their crop, farm, and income diversity to that of other states. Using secondary data from the Pakistan census on agricultural output, livestock ownership, economic output, and family education, we were able to find ideal locations along this gradient. Specifically, we based our index on

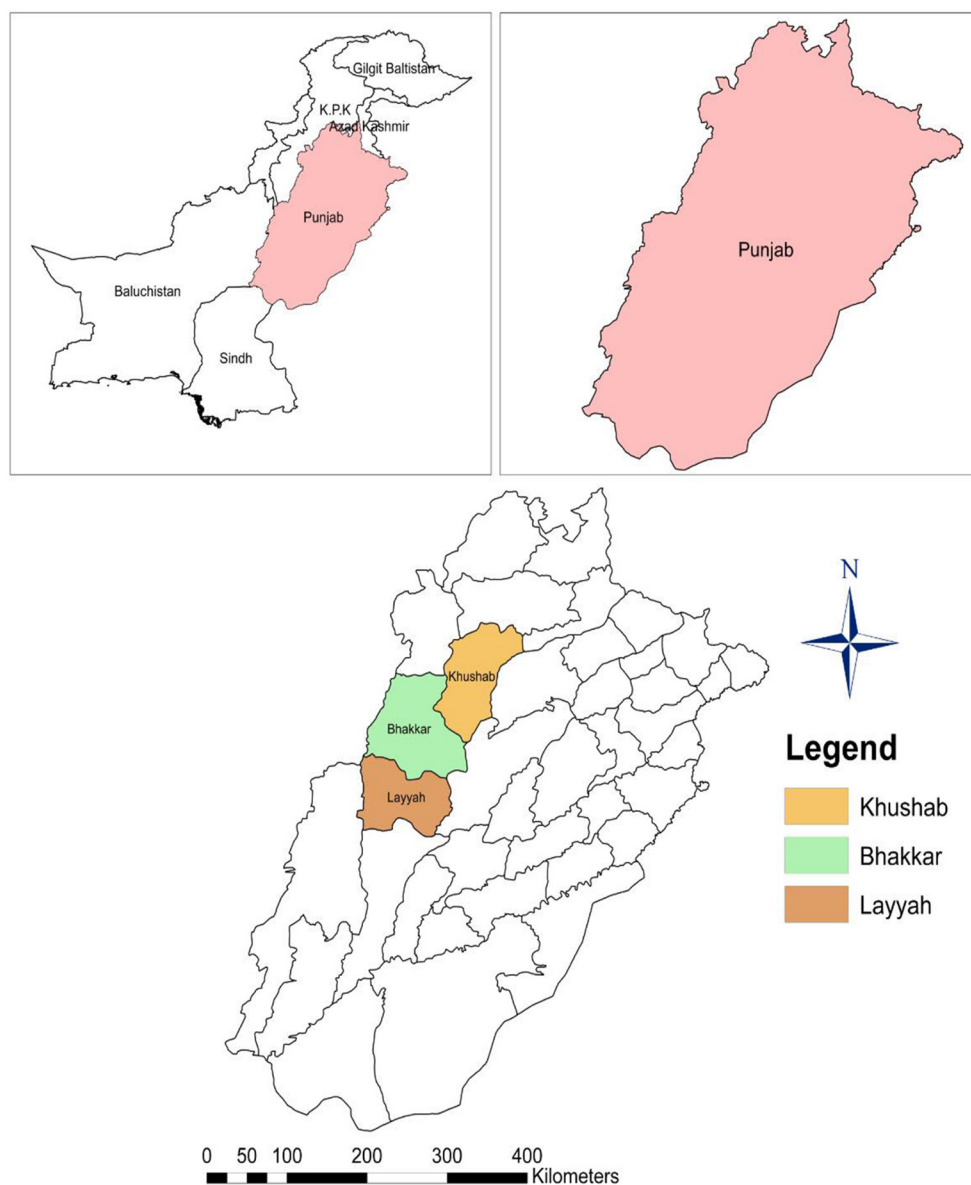


FIGURE 1
A map of Punjab, districts for this study in Pakistan.

Singh and Benbi (2016) and Singh et al. (2020) “Farming Intensity Index.” To measure the degree to which agricultural variety differs from one location to another, we calculated the CDI for each district. The crop diversity (measured by the crop diversity index), farm diversity (measured by per capita of poultry and livestock), agriculture farm income (measured by total agriculture planted crop area as a percentage of total agriculture land), and family education were used to create an index to capture changes in income diversity (e.g., rural literacy).

We followed the same methods to elect union councils in all three of these districts: Layyah, Bhakkar, and Khushab. We chose three groups of villages rather than individual villages within each union council because secondary data at the level of separate villages was unavailable. We chose the villages at random from the union council. Each union council consisted of two or three

adjoining villages. Approximately seven to nine farmer households were randomly selected from each village group using systematic random sampling. Our study included only farms with at least one adult male, one adult female, and one child or adolescent present. We limited our research to agricultural households because we were interested in the correlation between crop diversity and farmers’ food diversity. While some of these farming households depend entirely on agriculture for their income, others have more diverse sources of income. Individuals who do not live in rural areas or often travel to cities for work or study are not treated as well in large conglomerate households as those who live in rural areas. A sample of farm households was randomly selected to conduct research in their homes. One adult male (head of household, >18 years), one adult female (primary food preparer, >18 years), one adolescent (>5 and 18 years), and one child (5 years), regardless

of gender, are randomly selected for each family. Each family's children and adolescents present at home during the survey were randomly selected. Participants included 2,672 people from 450 families from three states.

2.2. Data collection

Each adult male, adult female, adolescent, and child population was assigned a particular survey schedule, which was used to compile the data collected. Five-person teams surveyed each district between April and June 2020. One adult male, one adult female, and one child or adolescent from each family provided information on agricultural output, farm-related activities, sources of income, demographics, and food intake (recall period 24-h). We did not have an exact schedule for visiting the numerous villages; instead, we surveyed a particular settlement whenever farmer household members had free time. The fact that small village markets were not open 7 days a week could have impacted the 24-h recall procedures as shown in Figure 2.

2.3. Metrics constructed

The explanations and calculations of the metrics used in our research are provided below.

2.3.1. Crop diversity index (CDI)

Each farmer household that participated in the survey had their crop diversification index (CDI) determined using the formula (1-H) as the H represents the (HHI) Hirschman-Herfindahl index, which is determined as follows:

$$H = \sum_{i=1}^N S_i^2$$

In the above equation the N represent the total number of crops during the period of 2019–20, the S_i signifies a percentage of the i-th crop area and (1-H), values indicate greater crop diversity (Singh and Benbi, 2016). The crop diversity index (CDI) is determined using whole crops grown throughout year.

2.3.2. Income diversification index (IDI)

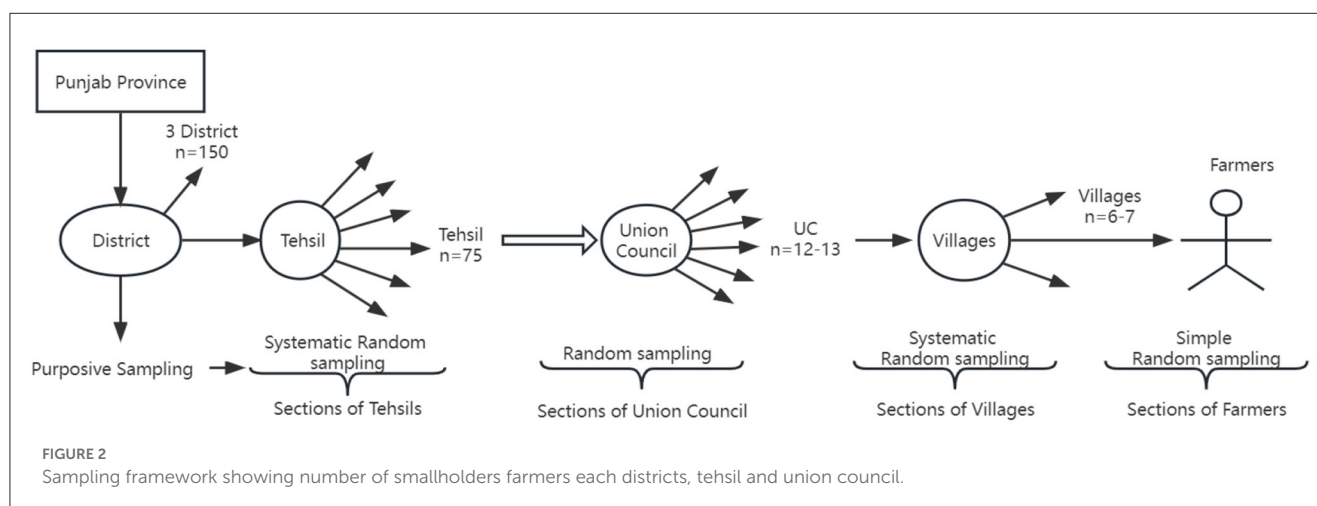
The 1-H formula has used to calculate the Income Diversification Index (IDI), which represents the household income proportion that comes from the sources of agricultural and non-agricultural activities such as non-crop activities, crop production, dairy, poultry, beekeeping, and business. The majority of IDIs were found in the wealthiest communities. We believe it is more accurate to ask farmers what percentage because of their income comes from each source instead of asking for their total revenue. Most farmers do not keep records of their income and spending because their non-farming income. This conclusion is the outcome of extensive fieldwork.

2.3.3. Family education index (FEI)

The family education index (FEI) was determined in this study by aggregating the educational attainment of every adult as well as adolescent dwelling on the farm, then dividing this figure by the total number of adults. We chose the average education of all men, women and adolescents residing in each farmer's household, rather than highest level of education among them because, in our experience, the family's dietary habits are influenced by the food choices made by all of its members, not just the household's head.

2.3.4. Adults and adolescents dietary diversity score

The 10 food groups defined by FAO (2016), as representing the nutritional sufficiency of female diets were employed to assess the dietary diversity DD of men, women, and adolescents (Khan et al., 2019; Baxter et al., 2022). The food groups in the Minimum Dietary Diversity for Women were used to represent males and adolescents that are no validated dietary diversity indicators (MDD-W). This indicator has been used to evaluate the variety of different foods consumed by men, women, girls and adolescent in the selected area. In this study the first food group contains the grains, tubers, roots and plantains, similarly the second food group contains lentils, pulses, peas and beans. The third food group contains the different agriculture crops seeds and nuts. The fourth food group have different dairy and livestock products. The fifth food group



contains the fish, meat and poultry. The six food group has different animal's eggs. The seventh food group contains the different seasonal vegetables as the eighth food groups has seasonal fruits. The ninth and tenth food groups contains the others vegetables and fruits. The respondents are assigned (DDS) ranging from 0 to 10.

2.3.5. Children dietary diversity score

The World Health Organization (WHO) used a slightly different formula to calculate DDS for children compared to adults, considering seven rather than 10 dietary groups (WHO, 2008). The following are the seven classes: Cereals, tubers, and roots are brought in first, followed by legumes and nuts, dairy, meat, fish, and poultry, then eggs, and finally, the remaining fruits and vegetables. The DDS evaluates each child on a continuous scale ranging from 0 to 7. The DDSs could determine a child's consumption of the four World Health Organization-recommended essential nutrients (2008).

2.4. Framework to examine associations

Using regression analysis, association among the crops, income, and socioeconomic characteristics were assessed. Based on review of literatures, the following factors hypothesized to affect the outcome variable and accordingly included as independent variables in the regression analysis.

2.4.1. Crop diversity index (CDI)

The crop diversification index is a vital indicator in this study to examine, as there is an increasing number of farm households in Pakistan (Ahmed et al., 2017). According to Islam et al. (2018) and Singh et al. (2020) crop diversity and DD has significant relationship.

2.4.2. Crop and livestock groups

In this study the crop group also very important. We investigate the different pulses, vegetables, and cash crops that are associated with dietary diversity DD. Previous research has demonstrated an association between the cultivation of cash crops (Asaleye et al., 2020), vegetables (Balali et al., 2020), and pulses (Naik and Nagadevara, 2020). Livestock production in Pakistan is a major industry. Each year, Pakistan exports over 4.5 million tons of quality halal meat to places like the Middle East, Malaysia and Indonesia. Pakistan is the world's fifth largest producer of eggs and the fourth largest producer of milk.

2.4.3. Income diversification index (IDI) and annual per capita income

Many Pakistani agricultural households are transitioning toward more diversified assortment of income sources, which is emphasized (Kanwal et al., 2016; Batool et al., 2017; Iqbal et al., 2021; Habib et al., 2022). Previous research has indicated that more diverse income portfolio effect food security and nutrition at home; therefore, we examined link between IDI and dietary diversity

(Milajerdi et al., 2018; Onah et al., 2022). Previous research (Warren et al., 2015; Larson et al., 2019; Singh et al., 2020; Mehraban and Ickowitz, 2021) have shown a positive correlation between higher income and dietary diversity.

2.4.4. Family education index (FEI)

In our regressions, we use the household education level as a control variable because it has been shown in previous research (Worku et al., 2017; Blackstone and Sanghvi, 2018; Gebrie and Dessie, 2021; Sambo et al., 2022) to be a significant predictor of dietary diversity.

2.4.5. Distance traveled to food markets (Kms)

The distance from agriculture farms to market place also very important in this study. According to previous studies the market access has significant impact on DD (Islam et al., 2018; Gupta et al., 2020; Usman and Callo-Concha, 2021; Usman and Haile, 2022). To do this, we attempted to incorporate market access as a control variable. As a proxy for farmers' access to markets, we examined the average distance farmers traveled to purchase fresh produce.

2.5. Statistical models

Initially, we compiled descriptive statistics for each district and state to determine the range of values for each of our variables across the various research sites. We used a series of regression, and the correlations between dietary diversity, socioeconomic factors, and crop and income diversification have been conducted. All continuous variables were averaged and normalized. As our outcome variables are count and ordered in nature, we have used ordered Probit as main regression and Poisson regression was used as a robustness check to verify all results. Poisson regression results are placed in the [Supplementary Tables](#). All statistical calculations were performed using Stata 14 software including the ordered Probit and Poisson regression model.

An ordered probit model is used when the data are naturally ordered. In other words, it is used when the outcome variable is a discrete variable which takes on values that reflect the natural order of things (i.e., the outcome variable is in some sense ordered). Ordered Probit Model is a model in which the dependent variable takes on only two levels (a binary variable) or three levels. It is like the linear regression model but with replacement of normal or Gaussian distribution with the beta distribution. In an ordered probit model, the linear probability model for the mean depends on the value of the dependent variable. Ordered Probit regression uses a latent variable that must be ordered. The ordered probit model is a multivariate extension of the unconditional or standard probit model. It extends the standard probit model to situations in which the dependent variable is a set of ordered categorical outcomes. The ordered probit model used when the dependent variable is qualitative, the individual categories of which are ordered. Alternately, the dependent variable can be quantitative and book-end category values used to indicate the upper and lower limits of the dependent variable.

We categorize the DD into three categories: 0, 1, DDS4 and 2, where 0 is the lowest category of dietary diversity. The food consumption categories are represented by an ordered variable Y that assumes the discrete ordered values of 0, 1 and 2. The ordered probit model for Y (conditional on explanatory variables X) can be derived from a latent variable model. Assume that the latent variable Y^* is determined by $Y^* = X\beta + \epsilon$, where X is a vector of household's and community characteristics entering the equation and ϵ refers to the error term, which we assume is normally distributed across observations. However, Y^* , the probability to consume from a particular food group, is latent variable and unobserved. Given that we observe Y , the intra-household's dietary diversity status, the observed aspects of a dietary diversity status can be written as (Rammohan et al., 2019):

$$Y = \begin{cases} 0 & \text{if only 2 food groups are consumed} \\ 1 & \text{if 3 food groups are consumed} \\ 2 & \text{if 4 food groups are consumed} \\ 3 & \text{if 5 or more food groups are consumed} \end{cases}$$

and each of these categories is a discrete category of the dependent variable, which can be explained by the same set of explanatory variables including household and community characteristics as well as key explanatory variables including crop and income diversity.

3. Results and discussion

3.1. Results of individual dietary diversity scores

Table 1 compares the results of DDS in all selected areas. According to the findings, the district of Layyah has higher average dietary diversity scores as compared to the districts of Bhakkar and Khushab. According to the results across all districts, we consider the standard cut-offs for dietary diversity, and only one-third of children (men: 50%; women: 55%; adolescents: 57%; children: 43) attained the required minimum score for dietary diversity. The results also indicated that in district Bhakkar, only 43–50% of men, women, adolescents, and children attained minimum dietary diversity scores. In addition, in the district Khushab, 50–57% of men, women, and adolescents and 43% of children meet the dietary diversity scores, while in the Layyah district, 64% of men, women, and adolescents and 38% of the children achieve the required dietary diversity scores, respectively. So due to more crop diversification, the district Layyah achieved a higher DDS as compared to the districts Bhakkar and Khushab.

Table 1 shows that all of the males, females, and teens who were surveyed in the different districts ate grains, white roots and tubers, and plantains. In Layyah, over three-fourths of men, women, and adolescents consumed pulses, beans, peas, and lentils, whereas in other districts, the corresponding percentage was substantially lower. Among farmer households in all districts, dairy products were equally popular. However, 8–10% of the respondents in each district consumed nuts, meat, and eggs. In comparison to the other districts, Bhakkar and Khushab, only 20–24% of Layyah's men, women, and adolescents consumed dark-green leafy vegetables.

TABLE 1 Results of average (DDS), across farmer households in Layyah, Bhakkar, and Khushab (24-h recall) in percentage.

Factor/variables	Layyah	Bhakkar	Khushab	Total
Average dietary diversity score				
Men	10.8	9.8	9.2	9.9
Women	10.6	9.1	9.1	9.6
Adolescents	9.5	9.1	9.2	9.3
Children	4.5	4.4	4.6	4.5
Individuals fulfilling the dietary diversification cut-off (percent)				
Men	64	43	44	50
Women	64	50	50	55
Adolescents	55	54	61	57
Children	38	51	41	43
Food groups: men, consumed %				
FG1: Grains, white roots and tubers, and plantains	284	283	269	278
FG2: Beans, pulses, lentils, and peas	102	90	99	97
FG3: Nuts and seeds	61	17	21	33
FG4: Livestock product (Dairy)	183	177	143	167
FG5: Fish, poultry, and meat	34	25	30	29
FG6: Eggs	11	9	4	8
FG7: Dark green leafy vegetables	171	167	146	161
FG8: Others and vegetables fruits	50	33	43	42
FG9: Other vegetables	99	95	93	96
FG10: Other fruits	87	90	79	85
Food groups: women, consumed %				
FG1: Grains, white roots and tubers, and plantains	241	233	231	235
FG2: Beans, pulses, lentils, and peas	134	117	129	127
FG3: Nuts and seeds	43	13	19	25
FG4: Dairy	194	188	158	180
FG5: Fish, poultry, and meat	26	18	29	24
FG6: Eggs	2	1	3	2
FG7: Dark green leafy vegetables	167	147	129	148
FG8: Other vitamin a-rich fruits and vegetables	48	13	17	26
FG9: Other vegetables	135	117	112	121
FG10: Other fruits	76	70	85	77
Food groups: adolescents, consumed %				
FG1: Grains, white roots and tubers, and plantains	204	208	197	203

(Continued)

TABLE 1 (Continued)

Factor/variables	Layyah	Bhakkar	Khushab	Total
FG2: Beans, pulses, lentils, and peas	67	60	76	68
FG3: Nuts and seeds	30	16	20	22
FG4: Livestock product (Dairy)	195	194	171	187
FG5: Fish, poultry, and meat	43	34	37	38
FG6: Eggs	12	9	15	12
FG7: Dark green leafy vegetables	156	143	129	143
FG8: Other Vitamin A-rich fruits and vegetables	73	67	70	70
FG9: Other vegetables	86	102	108	99
FG10: other fruits	93	85	99	92
Food groups: children, consumed %				
FG1: Grains, white roots, and tubers, and plantains	121	124	134	126
FG2: legumes and nuts	36	63	60	53
FG3: Livestock product (Dairy)	172	160	166	166
FG4: flesh food (fish, poultry, and meat)	11	19	18	16
FG5: Eggs	3	5	2	3
FG6: Other Vitamin A-rich fruits and vegetables	60	32	43	45
FG7: other fruits and vegetables	53	44	40	46

Nearly two-fourths of men, women, and adolescents in Layyah consumed vitamin-A-rich fruits and vegetables. In contrast, in other districts, only one-third of individuals ate this food group. In districts Bhakkar and Khushab, a significantly higher percentage of men, women, and adolescents reported consuming other vegetables than in district Layyah. The fruit consumption proportion was similar in all communities among men, women, and adolescents. Regarding the components of children's diets, 85–90% of children consumed dairy items, grains, roots, and tubers across the districts. Children ate more legumes and nuts in Bhakkar and Khushab than in Layyah district. In district Layyah, ~68% of children's diets included fruits and vegetables, compared to only 50–53% of children in districts Bhakkar and Khushab. However, 2–3 percent of children in all districts consumed flesh and eggs. It is essential to remember that respondent households were randomly selected without stratifying across vegetarian and non-vegetarian families.

3.2. Results of men's dietary diversity

Although income diversity had no association with men's dietary diversity in both Bhakkar and Khushab regions, it

was significantly associated in the Layyah ($p < 0.01$) (Table 2), respondents growing more crops (i.e., with more crop diversity) in a given year had a higher dietary diversity score in all districts ($p < 0.05$), annual income and farming experience were important drivers of men's DDS in Layyah ($p < 0.05$), considering main crop groups, respondent's households. All regressions were run with poisson regression as a robustness check (Table 1). In Layyah, the results remained similar across all variables except the local market in the village, which became insignificant with Poisson regression. In the district Bhakkar, the significance level became smaller for pulses, vegetables, and fruit crops ($p < 0.001$). With Poisson regression in district Bhakkar, the local market in the village became insignificant. In Khushab, the results remained similar across all the variables except farm size, which became negligible with Poisson regression.

3.3. Results of women's dietary diversity

Table 3 represents the results of dietary diversity among women and socioeconomic factors. The finding of the study indicated that higher crop diversity had more relationship with women's dietary diversity in Khushab ($p < 0.001$), whereas not associated with Layyah and Bhakkar women's DDS. Growing cash crops ($p < 0.001$) was associated with higher women's DDS in the Layyah and Bhakkar districts, but there is no association of cash crops with women's DDS in the Khushab district. Farming experience, family size, farm size, and distance travel to food markets ($p < 0.05$) was significantly associated with women's dietary diversity in district Layyah. In contrast, the farming experience was significantly associated with women's DDS in Bhakkar though the significance level was low ($p < 0.10$). Distance from the city and the main road ($p < 0.001$) were significantly associated with women's DDS in district Khushab. These regressions were run with Poisson regression as a robustness check (Table 2), and results remained similar across all variables in district Layyah. In Bhakkar, all the variables were significant with a low level ($p < 0.05$). In Khushab, the variables' results were the same, whereas the farming experience was highly effective ($p < 0.01$).

3.4. Results of adolescents dietary diversity

Table 4 represents the results of dietary diversity among adolescent and socioeconomic factors. The finding of the study indicated the significant ($p < 0.05$) association between the diversity of crops grown in the Khushab district and the variety of the adolescents' diets. The relationship between adolescent DDS and the output of cash crops and pulses was significant ($p < 0.05$) ($p < 0.01$). Adolescents in Khushab who grew their own fruits and vegetables had significant association with dietary diversity score ($p < 0.05$). Adolescents from Bhakkar household with higher annual incomes and those who did travel as far to purchase food in Layyah had higher dietary diversity. In addition, there was no correlation between adolescents' educational achievement and their dietary diversity in either district. Poisson regression was employed to evaluate the stability of the results. Poisson regression showed the

Variables	Layyah marginal effects				Bhakkar marginal effects				Khushab marginal effects			
	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX
Age	0.0241 (0.278)	−0.0076 (0.275)	0.0014 (0.304)	0.0061 (0.276)	0.0096 (0.613)	−0033 (0.613)	0.0006 (0.624)	0.0026 (0.612)	−0.0178 (0.439)	0.0064 (0.434)	−0.0012 (0.460)	−0.0051 (0.432)
Farming experience	0.0382 (0.035)**	−0.0120 (0.028)	0.0023 (0.070)	0.0097 (0.030)	−0.0068 (0.725)	0.0023 (0.725)	−0.0004 (0.731)	−0.0019 (0.724)	0.0122 (0.602)	−0.0044 (0.600)	0.0008 (0.611)	0.0035 (0.599)
Family size	−0.1815 (0.031)**	0.0572 (0.025)	−0.0111 (0.076)	−0.0461 (0.025)	0.0377 (0.628)	−0.0132 (0.628)	0.0026 (0.633)	0.0105 (0.628)	−0.1187 (0.095)*	0.0431 (0.088)	−0.0084 (0.128)	−0.0346 (0.092)
Farm size	−0.0406 (0.037)**	0.0128 (0.032)	−0.0024 (0.088)	−0.0103 (0.032)	−0.0138 (0.636)	0.0048 (0.635)	−0.0009 (0.642)	−0.0038 (0.635)	−0.022 (0.043)**	0.0080 (0.038)	−0.0015 (0.071)	−0.0064 (0.044)
Family Structure 1. Single 2. joint	−0.0717 (0.741)	0.0226 (0.740)	−0.0043 (0.744)	−0.0182 (0.740)	0.0036 (0.987)	−0.0012 (0.987)	0.0002 (0.987)	0.0010 (0.987)	−0.1909 (0.354)	0.0686 (0.351)	−0.0133 (0.368)	−0.0552 (0.354)
Distance from city	−0.0043 (0.902)	0.0013 (0.902)	−0.0002 (0.902)	−0.0011 (0.902)	−0.0835 (0.092)*	0.0292 (0.041)	−0.0059 (0.209)	−0.0233 (0.036)	−0.0256 (0.616)	0.0092 (0.615)	−0.0017 (0.617)	−0.0074 (0.615)
Distance from the main road	−0.0540 (0.510)	0.0170 (0.510)	−0.0033 (0.518)	−0.0137 (0.510)	−0.0219 (0.783)	0.0076 (0.783)	−0.0015 (0.782)	−0.0061 (0.783)	−0.317 (0.002)***	0.1139 (0.001)	−0.0221 (0.016)	−0.0917 (0.001)
Distance from input/output market	−0.0842 (0.004)***	0.0265 (0.002)	−0.0051 (0.011)	−0.0214 (0.004)	0.0472 (0.410)	−0.0165 (0.409)	0.0033 (0.446)	0.0132 (0.404)	0.0500 (0.018)**	−0.0179 (0.031)	0.0035 (0.43)	0.0144 (0.029)
Local market in the village	−0.6813 (0.062)*	0.2149 (0.060)	−0.0416 (0.114)	−0.1732 (0.060)	−4.117 (0.000)***	1.4431 (0.000)	−0.2914 (0.003)	−1.1517 (0.000)	0.3907 (0.063)*	1.443 (0.000)	−0.2914 (0.003)	−1.1517 (0.000)
Drinkable water is available within 60 min walk	0.4860 (0.444)	−0.1533 (0.442)	0.0297 (0.459)	0.1235 (0.442)	−0.1334 (0.795)	0.0467 (0.794)	−0.0094 (0.793)	−0.0373 (0.795)	−0.3583 (0.448)	0.1287 (0.446)	−0.0250 (0.453)	−0.1036 (0.448)
Road to village 1. Yes, 2. No.	0.4438 (0.163)	−0.1400 (0.158)	0.0271 (0.187)	0.1128 (0.162)	0.5312 (0.285)	−0.1862 (0.283)	0.0376 (0.318)	0.1486 (0.282)	−0.425 (0.303)	0.1526 (0.298)	−0.0297 (0.305)	−0.1229 (0.304)
Crop diversity Index	4.9801 (0.043)**	−1.5709 (0.040)	0.3047 (0.063)	1.2661 (0.046)	0.3346 (0.055)**	−2.1173 (0.073)	0.0376 (0.141)	0.0936 (0.41)	−0.5340 (0.049)**	0.2816 (0.009)	−0.0548 (0.024)	−0.2268 (0.019)
Income diversity Index	−2.9442 (0.005***)	0.9287 (0.003)	−0.1801 (0.033)	−0.7485 (0.003)	0.0964 (0.907)	−0.0338 (0.907)	0.0068 (0.908)	0.0269 (0.907)	0.9796 (0.239)	−0.3519 (0.232)	0.0685 (0.253)	0.2834 (0.237)
Family education index	−0.1375 (0.848)	0.0433 (0.848)	−0.0084 (0.849)	−0.0349 (0.848)	1.0206 (0.154)	−0.3577 (0.149)	0.0722 (0.201)	0.2855 (0.149)	0.6723 (0.248)	−0.2415 (0.248)	0.0470 (0.270)	0.1945 (0.252)
Cash crop group	0.0652 (0.036)**	−0.02005 (0.033)	0.0039 (0.078)	0.0165 (0.035)	0.01851 (0.289)	−0.0064 (0.281)	0.0013 (0.306)	0.0051 (0.283)	−0.0162 (0.437)	0.0058 (0.433)	−0.0011 (0.449)	−0.0047 (0.433)
Pulses crop group	−0.0320 (0.529)	0.0101 (0.528)	−0.0019 (0.535)	−0.0081 (0.529)	−0.1108 (0.016)**	0.0388 (0.015)	−0.0078 (0.040)	−0.0310 (0.019)	0.0133 (0.792)	−0.0048 (0.792)	0.0009 (0.789)	0.0038 (0.793)
Vegetables and fruits groups	0.045027 (0.528)	−0.0142 (0.528)	0.0027 (0.543)	0.0114 (0.527)	−0.1400 (0.019)**	0.0490 (0.012)	−0.0099 (0.035)	−0.0391 (0.017)	−0.0675 (0.258)	0.0242 (0.250)	−0.0047 (0.266)	−0.0195 (0.257)
LR chi2 (17) Prob > chi2 Log-likelihood	51.19 0.0000 −134.34725				16.83 0.0000 −145.269				21.50 0.0895 −149.875			

Age calculated in Years, Farming experience in Years, Farm size in Acres, Distance in Km. Significance code: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Variables	Layyah marginal effects				Bhakkar marginal effects				Khushab marginal effects			
	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX
Age	0.0279 (0.221)	−0.0086 (217)	0.0016 (0.258)	0.0069 (0.216)	−0.0380 (0.077)*	0.0138 (0.069)	−0.0026 (0.106)	−0.0111 (0.075)	−0.0070 (0.740)	0.0025 (0.740)	−0.0009 (0.740)	−0.0015 (0.741)
Farming experience	0.036 (0.035)**	−0.0114 (0.030)	0.0021 (0.071)	0.0092 (0.032)	0.0381 (0.063)*	−0.0138 (0.056)	0.0026 (0.098)	0.0111 (0.060)	0.0126 (0.564)	−0.0046 (0.563)	0.0017 (0.565)	0.0028 (0.564)
Family size	−0.212 (0.010)***	0.0656 (0.007)	−0.0125 (0.043)	−0.0531 (0.008)	−0.0020 (0.979)	0.0007 (0.979)	−0.0001 (0.979)	−0.0005 (0.979)	−0.0453 (0.520)	0.0164 (0.518)	−0.0063 (0.516)	−0.0101 (0.523)
Farm size	−0.043 (0.024)**	0.0134 (0.020)	−0.0025 (0.069)	−0.0108 (0.020)	0.0140 (0.604)	−0.0051 (0.604)	0.0009 (0.601)	0.0041 (0.606)	0.0655 (0.766)	−0.0238 (0.766)	0.0092 (0.766)	0.0146 (0.766)
Family structure 1single 2. joint	−0.153 (0.463)	0.0475 (0.461)	−0.0091 (0.475)	−0.0384 (0.461)	0.1348 (0.510)	−0.0491 (0.509)	0.0095 (0.508)	0.0395 (0.513)	0.0428 (0.006)***	−0.015 (0.003)	0.006 (0.007)	0.009 (0.007)
Distance from city	−0.001 (0.967)	0.0005 (0.967)	−0.0001 (0.967)	−0.0004 (0.967)	0.0232 (0.591)	−0.0084 (0.591)	0.0016 (0.591)	0.0068 (0.592)	−0.092 (0.010)***	0.033 (0.008)	−0.012 (0.016)	−0.020 (0.013)
Distance from the main road	−0.073 (0.365)	0.0226 (0.363)	−0.0043 (0.390)	−0.0183 (0.363)	0.1395 (0.057)**	−0.0508 (0.052)	0.0098 (0.087)	0.0409 (0.057)	0.0431 (0.621)	−0.015 (0.620)	0.006 (0.625)	0.009 (0.619)
Distance from input/output market	−0.087 (0.004)***	0.0271 (0.004)	−0.0052 (0.016)	−0.0219 (0.004)	−0.0192 (0.665)	0.0069 (0.665)	−0.0013 (0.665)	−0.0056 (0.665)	0.0667 (0.083)*	−0.024 (0.081)	0.009 (0.092)	0.014 (0.091)
Local market in the village	−0.070 (0.089)*	0.2190 (0.083)	−0.0419 (0.136)	−0.1771 (0.084)	−0.3617 (0.426)	0.1317 (0.424)	−0.0255 (0.437)	−0.1061 (0.425)	0.354 (0.313)	−0.129 (0.309)	0.049 (0.328)	0.079 (0.306)
Drinkable water is available within 60 min walk	0.462 (0.440)	−0.1431 (0.438)	0.0274 (0.453)	0.1157 (0.438)	−0.3142 (0.508)	0.1144 (0.508)	−0.0222 (0.437)	−0.1061 (0.425)	0.0661 (0.910)	−0.024 (0.910)	0.009 (0.910)	0.014 (0.911)
Road to village 1. Yes, 2. No.	0.586 (0.067)*	−0.1816 (0.060)	0.0347 (0.096)	0.1468 (0.065)	0.3309 (0.442)	−0.1205 (0.439)	0.0234 (0.451)	0.0971 (0.441)	0.4356 (0.352)	−0.158 (0.350)	0.061 (0.346)	0.097 (0.359)
Crop diversity index	5.079 (0.108)	−1.5733 (0.101)	0.3011 (0.134)	1.2722 (0.106)	2.6458 (0.520)	−0.9639 (0.520)	0.1872 (0.511)	0.7767 (0.524)	9.047 (0.003)***	−3.291 (0.001)	1.272 (0.003)	2.018 (0.004)
Income diversity Index	−2.321 (0.040)**	0.7189 (0.035)	−0.1376 (0.083)	−0.5813 (0.037)	−1.1455 (0.121)	0.4173 (0.116)	−0.0810 (0.176)	−0.3362 (0.115)	0.3161 (0.668)	−0.115 (0.667)	0.044 (0.668)	0.070 (0.668)
Family education index	0.133 (0.845)	−0.0413 (0.845)	0.0079 (0.846)	0.0334 (0.845)	0.5127 (0.483)	−0.1867 (0.481)	0.0362 (0.504)	0.1505 (0.479)	0.2896 (0.673)	−0.105 (0.672)	0.040 (0.670)	0.064 (0.674)
Cash crop group	0.077 (0.035)**	−0.0241 (0.029)	0.0046 (0.067)	0.0195 (0.033)	0.0466 (0.009)***	−0.0169 (0.006)	0.0033 (0.029)	0.0136 (0.009)	0.0100 (0.565)	−0.0003 (0.564)	0.001 (0.559)	0.002 (0.569)
Pulses crop group	−0.013 (0.803)	0.0040 (0.803)	−0.0007 (0.802)	−0.0033 (0.803)	−0.0451 (0.322)	0.0164 (0.320)	−0.0031 (0.359)	−0.0132 (0.317)	0.0432 (0.404)	−0.015 (0.402)	0.004 (0.400)	0.009 (0.410)
Vegetables and fruits groups	0.065 (0.323)	−0.0202 (0.320)	0.0038 (0.351)	0.0163 (0.319)	−0.0155 (0.769)	0.0056 (0.769)	−0.0010 (0.768)	−0.0045 (0.769)	−0.076 (0.180)	0.027 (0.175)	−0.010 (0.178)	−0.016 (0.187)
LR chi2 (17) Prob>chi2 Log-likelihood	52.97 0.0000 −132.84				21.45 0.2070 −150.1594				21.14 0.2201 −141.2929			

Significance code: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

TABLE 4 Results of dietary diversity among adolescent as assessed by an analysis of agricultural and socioeconomic factors.

Variables	Layyah marginal effects				Bhakkar marginal effects				Khushab marginal effects			
	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX
Age	0.0473 (0.039)**	−0.0160 (0.033)	0.0032 (0.076)	0.0128 (0.036)	0.0027 (0.897)	−0.0008 (0.897)	−0.0000 (0.906)	0.0008 (0.897)	0.0238 (0.265)	−0.0079 (0.259)	0.0003 (0.563)	0.0076 (0.263)
Farming experience	−0.0090 (0.584)	−0.0030 (0.584)	0.0006 (0.588)	0.0024 (0.584)	0.0071 (0.722)	−0.0022 (0.722)	−0.0000 (0.810)	0.0023 (0.722)	−0.0311 (0.168)	0.0104 (0.161)	−0.0004 (0.552)	−0.0099 (0.164)
Family size	0.0063 (0.935)	−0.0021 (0.935)	0.0004 (0.935)	0.0001 (0.935)	−0.0145 (0.863)	0.0046 (0.863)	0.0000 (0.881)	−0.0046 (0.863)	0.1145 (0.105)	−0.0382 (0.104)	0.0017 (0.557)	0.0364 (0.102)
Farm size	0.0363 (0.061)*	−0.0123 (0.055)	0.0025 (0.113)	0.0098 (0.055)	−0.0080 (0.793)	0.0025 (0.792)	0.0000 (0.842)	−0.0026 (0.792)	−0.0282 (0.896)	0.0094 (0.896)	−0.0017 (0.903)	−0.0090 (0.895)
Family Structure 1. single 2. joint	0.1379 (0.508)	−0.0468 (0.506)	0.0095 (0.514)	0.0372 (0.507)	0.0788 (0.709)	−0.0250 (0.709)	−0.0004 (0.807)	0.0254 (0.709)	0.0294 (0.074)*	−0.0098 (0.063)	0.0004 (0.546)	0.0093 (0.063)
Distance from city	−0.0068 (0.857)	0.0023 (0.857)	−0.0004 (0.857)	−0.0018 (0.857)	−0.0096 (0.830)	0.0030 (0.830)	0.0000 (0.858)	−0.0031 (0.830)	−0.0314 (0.448)	0.0105 (0.445)	−0.0004 (0.625)	−0.0100 (0.445)
Distance from the main road	−0.2283 (0.005)***	0.0775 (0.003)	−0.0158 (0.022)	−0.0616 (0.004)	0.1398 (0.090)*	−0.0444 (0.084)	−0.0007 (0.753)	0.0452 (0.084)	−0.0135 (0.879)	0.0045 (0.879)	−0.0002 (0.883)	−0.0043 (0.879)
Distance from input/output market	0.0088 (0.755)	−0.0030 (0.755)	0.0006 (0.755)	0.0023 (0.755)	0.0643 (0.166)	−0.0204 (0.161)	−0.0003 (0.754)	0.0208 (0.160)	0.0494 (0.243)	−0.0165 (0.237)	0.0007 (0.571)	0.0157 (0.238)
Local market in the village	0.8936 (0.037)**	−0.3036 (0.031)	0.0621 (0.067)	0.2415 (0.035)	−0.9510 (0.089)*	0.3021 (0.086)	0.0051 (0.747)	−0.307 (0.082)	−0.0104 (0.980)	0.0035 (0.980)	−0.0001 (0.980)	−0.0033 (0.980)
Drinkable water is available within 60 min walk	1.2734 (0.072)**	−0.4326 (0.064)	0.0621 (0.089)	0.3441 (0.071)	−0.2934 (0.544)	0.0932 (0.543)	0.0015 (0.779)	−0.3073 (0.543)	−0.6616 (0.084)*	0.2209 (0.077)	−0.0102 (0.528)	−0.2106 (0.083)
Road to village 1. Yes, 2. No.	0.5621 (0.060)**	−0.1909 (0.052)	0.039 (0.087)	0.1519 (0.058)	−0.1084 (0.821)	0.0344 (0.821)	0.0005 (0.850)	−0.0350 (0.820)	0.1005 (0.824)	−0.0335 (0.824)	0.0015 (0.830)	0.0320 (0.824)
Crop diversity index	−0.6310 (0.810)	0.2144 (0.810)	−0.0438 (0.810)	−0.1705 (0.810)	−2.774 (0.567)	0.8814 (0.565)	0.0151 (0.782)	−0.8965 (0.566)	5.853 (0.049)**	−1.954 (0.043)	0.0910 (0.60)	1.863 (0.042)
Income diversity index	1.3152 (0.208)	−0.4468 (0.204)	0.0914 (0.229)	0.3554 (0.208)	−1.483 (0.066)**	0.4712 (0.061)	0.0080 (0.749)	−0.4793 (0.059)	0.1888 (0.813)	−0.0630 (0.813)	0.0029 (0.829)	0.0601 (0.812)
Family education index	0.1475 (0.832)	−0.0501 (0.832)	0.0102 (0.833)	0.0398 (0.832)	0.6063 (0.602)	−0.1926 (0.602)	−0.0033 (0.784)	0.1959 (0.601)	0.6269 (0.315)	−0.2093 (0.314)	0.0097 (0.577)	0.1996 (0.317)
Cash crop group	−0.0306 (0.342)	0.0104 (0.339)	−0.0021 (0.363)	−0.0082 (0.339)	−0.0375 (0.034)**	0.0119 (0.029)	0.0002 (0.752)	−0.0121 (0.029)	−0.0094 (0.551)	0.0031 (0.549)	−0.0001 (0.656)	−0.0030 (0.550)
Pulses crop group	−0.0633 (0.227)	0.0215 (0.222)	−0.0044 (0.250)	−0.0171 (0.225)	0.1682 (0.002)***	−0.0534 (0.001)	−0.0009 (0.749)	0.0543 (0.001)	0.0439 (0.394)	−0.0146 (0.391)	0.0006 (0.605)	0.0139 (0.392)
Vegetables and fruits groups	−0.0405 (0.533)	0.0137 (0.532)	−0.0028 (0.540)	−0.0109 (0.532)	0.1050 (0.076)*	−0.0349 (0.069)	0.0030 (0.227)	0.0319 (0.071)	−0.1132 (0.053)**	0.0378 (0.046)	−0.0017 (0.542)	−0.0361 (0.046)
LR chi2 (17) Prob>chi2 Log-likelihood	33.79 0.0089 −141.792				36.36 0.0041 −144.275				29.49 0.0303 −152.7064			

Significance code: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

same results regardless of the variable in Layyah, with the exception of age and farm size, where the significant threshold decreased ($p < 0.10$). With the exception of cash crops ($p < 0.10$) and vegetables and fruits ($p < 0.10$), the level of significance remained constant in Bhakkar. In the Khushab district, each component is of similar importance.

3.5. Results of children dietary diversity

There was a link between the prevalence of child DDS in Layyah and the diversity of crops grown in respondents' households (Table 5). Most developmental delays among adolescents in the Layyah district correlated with the production of cash crops and pulses ($p < 0.01$). Children in the Layyah district who lived further from the city, the central road, and the marketplaces were more likely to have DDS. In neither district is exposure to farming or family education associated with children's DDS rates. Poisson regression was also applied to each of these additional regressions as a robustness test. Despite the higher significant values for crop diversification and cash crops in Layyah, the results were consistent and independent of the variable. In Bhakkar, agricultural diversification and family education are closely connected with child DDS, thereby contributing additional stability. Adolescent DDS testing in the district of Khushab indicated a substantial correlation with agricultural diversification.

3.6. Factor importance

The significance of all agricultural and socioeconomic factors that operate independently of one another and the dietary diversity of men, women, adolescents, and children was evaluated (DDS). The diversity of crops grown in a region impacts the variety of foods available to men and women in a specific location. In every area, the average annual income and the distance to food markets were the most critical factors for male and female DDS. Crop diversification, yearly revenue, and travel time to markets were the three most influential factors affecting men's and women's DDS in all regions. Due to adolescent DDS, agricultural diversification and cash crops were necessary for Layyah and Bhakkar. The correlation between adolescent DDS and annual income was the strongest across all locales. In all aspects, adolescents with DDS were less constrained than their adult counterparts by factors such as distance to food markets and annual income. The significant variable plots for child DDS appear significantly different than those for men, women, and adolescents. Among adults of all ages and adolescents, crop diversity (CD) remained one of the most significant characteristics of DDS. Children in Layyah and Khushab ranked crop diversity as the first and third most important factors in dietary diversity, respectively. Cash crops, pulses, and annual income were the primary causes of district Layyah's child DDS being illuminated. However, in Bhakkar and Khushab, the same factors remained significant, such as the distance to the market, the composition of households, the availability of fresh vegetables, etc.

4. Discussion

To examine the relationship between farmers' income, crop diversification, and the variety of foods they consume, we analyzed primary data from 450 farmer families. We are exploring this relationship to better understand how recent agricultural developments, such as the diversification of farmers' income sources and the increase in crop specialization, have affected the diets of Pakistani farm families. In this study, the association between farmers' diets and their ability to produce many sources of income (as indicated by the crop diversity index, or CDI) was investigated (measured by the income diversity index, or IDI). Our research indicates a high association between crop diversification and dietary diversity among adults (men, women, and adolescents) and children in the Layyah and Bhakkar districts and the Khushab region. Thus, the nutrition of the children of Khushab was determined primarily and secondarily by the variety of available crops. Even though IDI was the second-most crucial factor in explaining variation in child DDS in Layyah and Bhakkar, we could not detect a statistically significant correlation between IDI and individual DDS across districts. Even though our data are cross-sectional and only examine the associations between crop and income diversity and dietary diversity over a single time step, our analysis has important implications for understanding how crop specialization and increased income diversity may affect family food variation. Our data indicate that crop specialization may be connected with a reduction in Pakistan's dietary diversity among farm households.

Consistent with prior studies, we identified a strong positive correlation between CDI and DDS at the district level (Dabo et al., 2013; Singh et al., 2020; Dereje et al., 2021; Derso et al., 2021; Mengistu et al., 2021; Azupogo et al., 2023). There is empirical support for a beneficial link between crop diversity and dietary diversity, which two distinct mechanisms may mediate: (1) by providing a farmer's household with a variety of food groups to consume and (2) by providing a variety of crops that can be sold to the market to generate income that is used to purchase a wider variety of foods from markets (Achterbosch et al., 2014; Hill and Vigneri, 2014; Ntakyio and van den Berg, 2019; Baker et al., 2020; Soukand et al., 2020).

As demonstrated by our research, both routes are involved in the link between crop diversity and individual dietary diversity. This study explored the association between farming various crops to fully comprehend how a higher CDI can improve nutritional diversity through the consumption and income pathway (cash crops, pulses, vegetables, and fruits). The prevalence of DDS is higher among adults, children, and adolescents in Layyah and Khushab, where the pulse population is growing. Farming households consumed more pulses than non-farming households in Bhakkar, where overall consumption was lower than in Layyah and Khushab (Table 1). Considering the potential impact of CDI on dietary diversity through growing income, for example, in Layyah, producing cash crops was related to a more diverse diet for men and adults, whereas Bhakkar and Khushab were associated with a more varied diet for all members of a farming household. Notably, the CDI of cash crop producers was much greater than that of other farmers. Similar results were found in Indonesia, Kenya, Ethiopia,

TABLE 5 Dietary diversity among children as assessed by an analysis of agricultural and socioeconomic factors.

Variables	Layyah marginal effects				Bhakkar marginal effects				Khushab marginal effects			
	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX	Coefficients	Prob (Y = 0/X) dY/dX	Prob (Y = 1/X) dY/dX	Prob (Y = 2/X) dY/dX
Age	−0.0826 (0.005)***	0.0179 (0.002)	−0.0151 (0.005)	−0.0028 (0.030)	0.0303 (0.281)	−0.0080 (0.275)	0.0067 (0.275)	0.0012 (0.341)	0.0236 (0.241)	−0.0088 (0.233)	0.0007 (0.287)	0.0081 (0.237)
Farming experience	−0.0063 (0.799)	0.0013 (0.799)	−0.0011 (0.798)	−0.0002 (0.807)	−0.0172 (0.511)	0.0045 (0.509)	−0.0038 (0.508)	−0.0007 (0.532)	−0.0143 (0.485)	0.0053 (0.482)	−0.0004 (0.495)	−0.0049 (0.484)
Family size	0.2539 (0.022)**	−0.0551 (0.017)	0.0464 (0.013)	0.0086 (0.138)	−0.1180 (0.206)	0.0311 (0.199)	−0.0263 (0.199)	−0.0047 (0.281)	−0.0150 (0.852)	0.0056 (0.852)	−0.0005 (0.851)	−0.0051 (0.852)
Farm size	−0.1303 (0.000)***	0.0283 (0.000)	−0.0238 (0.000)	−0.0044 (0.067)	0.0948 (0.083)	−0.0250 (0.077)	0.0211 (0.079)	0.0038 (0.179)	0.0542 (0.799)	−0.0203 (0.799)	0.0016 (0.799)	0.0186 (0.799)
Family structure 1.single 2. joint	−0.6735 (0.023)**	0.1462 (0.019)	−0.1231 (0.024)	−0.0230 (0.069)	0.8324 (0.003)***	−0.2196 (0.001)	0.1858 (0.002)	0.0338 (0.085)	0.0265 (0.078)*	−0.0099 (0.072)	0.0008 (0.135)	0.0091 (0.080)
Distance from city	0.1248 (0.005)***	−0.0271 (0.003)	0.0228 (0.002)	0.0042 (0.100)	0.0397 (0.585)	−0.0104 (0.584)	0.0088 (0.584)	0.0016 (0.598)	0.0259 (0.574)	−0.0097 (0.573)	0.0008 (0.592)	0.0089 (0.573)
Distance from the main road	−0.4368 (0.003)***	0.0948 (0.001)	−0.0798 (0.001)	−0.0149 (0.053)	−0.0017 (0.985)	0.0004 (0.985)	−0.0003 (0.985)	−0.0000 (0.985)	0.1337 (0.178)	−0.0500 (0.170)	0.0041 (0.268)	0.0459 (0.172)
Distance from input/output market	0.8728 (0.013)**	−0.0189 (0.011)	0.0159 (0.014)	0.0029 (0.060)	−0.0851 (0.247)	0.0224 (0.243)	−0.0190 (0.243)	−0.0034 (0.312)	−0.0392 (0.397)	0.0146 (0.395)	−0.0012 (0.932)	−0.0138 (0.931)
Local market in the village	−2.1223 (0.000)***	0.4607 (0.000)	−0.3881 (0.000)	−0.0726 (0.050)	−0.2283 (0.676)	0.0602 (0.676)	−0.0509 (0.675)	−0.0092 (0.683)	−0.0402 (0.931)	0.0150 (0.931)	−0.0012 (0.932)	−0.0138 (0.931)
Drinkable water is available within 60 min walk	−0.2951 (0.613)	0.0640 (0.611)	−0.0539 (0.611)	−0.0100 (0.618)	−0.6331 (0.235)	0.1670 (0.229)	−0.1413 (0.230)	−0.0257 (0.300)	0.2397 (0.521)	−0.0897 (0.519)	0.0074 (0.545)	0.0823 (0.519)
Road to village 1.Yes, 2. No.	0.7841 (0.045)**	−0.1702 (0.042)	0.1434 (0.041)	0.0268 (0.137)	0.4590 (0.433)	−0.1211 (0.430)	0.1024 (0.430)	0.01864 (0.462)	−0.1049 (0.790)	0.0392 (0.790)	−0.0032 (0.792)	−0.0360 (0.790)
Crop diversity index	−0.5124 (0.073)*	0.1112 (0.075)	−0.0937 (0.062)	−0.0175 (0.077)	11.440 (0.168)	−3.0187 (0.163)	2.5540 (0.165)	0.4647 (0.247)	6.157 (0.024)**	−2.305 (0.019)	0.1905 (0.119)	2.114 (0.022)
Income diversity index	−3.1958 (0.010)**	0.6937 (0.007)	−0.5844 (0.013)	−0.1093 (0.038)	−0.1415 (0.082)*	0.0373 (0.075)	−0.0315 (0.080)	−0.0057 (0.079)	0.2092 (0.788)	−0.783 (0.788)	0.0064 (0.789)	0.0718 (0.788)
Family education index	1.1866 (0.139)	−0.2576 (0.129)	0.2170 (0.137)	0.0405 (0.171)	−2.9892 (0.865)	0.7887 (0.858)	−0.6673 (0.860)	−0.1214 (0.859)	−0.4772 (0.455)	0.1786 (0.453)	−0.0147 (0.503)	−0.1638 (0.451)
Cash crop group	0.1465 (0.005)***	−0.0304 (0.004)	0.0256 (0.003)	0.0048 (0.090)	−0.0079 (0.710)	0.0021 (0.709)	−0.0017 (0.709)	−0.0003 (0.716)	−0.0203 (0.224)	0.0076 (0.218)	−0.0006 (0.266)	−0.0070 (0.224)
Pulses crop group	0.1465 (0.036)**	−0.0318 (0.039)	0.0268 (0.032)	0.0050 (0.172)	0.0745 (0.262)	−0.0196 (0.258)	0.0166 (0.261)	0.0030 (0.314)	−0.0017 (0.973)	0.0006 (0.973)	−0.0000 (0.973)	−0.0005 (0.973)
Vegetables and fruits groups	−0.0830 (0.306)	0.0180 (0.309)	−0.0151 (0.318)	−0.0028 (0.310)	0.1324 (0.073)*	−0.0349 (0.065)	0.0295 (0.067)	0.0053 (0.169)	−0.0653 (0.252)	0.0244 (0.244)	−0.0020 (0.336)	−0.0224 (0.243)
LR chi2 (17) Prob> chi2 Log-likelihood	56.20 0.0000 −66.839				30.17 0.0251 −80.3042				13.84 0.6786 −149.1097			

Significance code: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

and Malawi (Ochieng et al., 2016; Shahbaz et al., 2017; Dessie et al., 2019; Williams et al., 2020). According to these findings, farmers who cultivate various crops and have strong ties to the markets where those crops are marketed may contribute to dietary diversity in rural Pakistan.

Considering the significance of other factors in our study, family education was significant in the districts. Previous studies have suggested that higher levels of education, particularly maternal education (Reinbott et al., 2016; Jones, 2017; Kuchenbecker et al., 2017; Luna-González and Sørensen, 2018; Murendo et al., 2018), have a positive effect on farmer households' dietary diversity.

Cash crop income has the most significant impact on DDS for children, but annual per capita income has the most significant effect on adults (PCAI). These findings demonstrate the importance of the income-to-nutrition relationship in fostering dietary diversity among farming households. The distance traveled by family members to reach food markets (DFM) was one of the most important determinants of each member's DDS, with greater DFM (distance to food markets) accessibility being associated with a higher DDS. This conclusion contradicts logic but is consistent with other research (such as Mbwana et al., 2016). It may accurately reflect that families who consume various foods must sometimes travel further to do so. In our experience, local village markets provide a limited selection of items from each food group. Individuals interested in unusual foods such as dark green leafy vegetables and vitamin A-rich vegetables and fruits may have to travel a considerable distance. Based on these findings, we hypothesize that increasing family education, higher farm revenues, and larger local village markets may contribute to a greater variety of foods consumed by farmer households.

According to the survey, one of the most pervasive instances of gender discrimination occurs in the food allotment industry (Choudhury et al., 2019; Gupta et al., 2019; Bonis-Profumo et al., 2021; Mengistu et al., 2021). Even among family members, women's DDS tends to be lower than men's, as evidenced by our findings (Table 1), which are consistent with those of other studies (Gitagia et al., 2019). Multiple factors may be at play here. First, in rural Pakistan, the male household head is frequently the primary source of income, providing him greater control over the available cash and maybe allowing him to purchase and consume a wider variety of meals (Hoek et al., 2021). Second, because rural Pakistani women are more likely to be vegetarians than men, they would have fewer food options. Women consume less meat and egg products than men, as shown in Table 1. To better understand the underlying causes of the gender imbalance, we analyzed the characteristics related to disparities in DDS between men and women residing in the same household. Increases in the educational attainment of farmer households could minimize the gender disparity in Pakistan's dietary diversity. We discovered that female DDS was more significant than male DDS in FEI. In addition, a shorter DFM has been associated with a larger DDS in females than males. We discovered no statistically substantial DDS differences between male and female adolescents and children. The analysis of adult DDS compared individuals within the same family, whereas the current study examined males and females from particular households, reducing statistical power.

Our work has various limits as well as potential future opportunities. Then, using the MDD-W (Minimum Dietary Variety

for Women) food groups, we assessed the dietary diversity of males and adolescents (FAO, 2016). There are presently no food group guidelines for men or adolescents, and we encourage future research to investigate whether the food categories for MDD women are suitable for the dietary variability of males and adolescents. Second, we do not employ panel data to assess changes in agriculture over time within the same farmer households; instead, our results are based on cross-sectional observational data. Therefore, our results are only correlative and not causal. An additional longitudinal study on the same farming households is required to determine the cause-and-effect relationship between crop and income diversity and household dietary diversity.

Third, we have lost sight of the proportion of our food that comes from farms instead of supermarkets. The trade-off is that we better understand the consumption and revenue channels through which increased crop variety leads to a more diverse diet among farmer households. We randomly surveyed localities to account for the likelihood of neighboring daily local markets. Even if the nutritional type is likely to be more significant in the days after the establishment of a local market, our results may be skewed in regions where markets are not constantly open. We could not include a dummy variable for market presence due to a lack of information regarding the days on which local markets were open (i.e., whether a specific monthly or weekly market was available on the day of the survey). We do not believe that the fact that we randomly picked locations for our surveys based on a market's proximity affected the reliability of our findings. Future research should take this new variable into account. Due to cost and time constraints, the survey design only included a small number of teenagers or children from each farmer's household; therefore, their numbers were lower than those of adult (male and female) respondents. Although the data size for child regressions was considerably smaller than that for adult regressions, our regressions were able to find the correlations between CDI and distance traveled to the markets that exhibited the most vital connections with DDS for other family members (male, female, and adolescent). We acknowledge the possibility that the sensitivity of these regressions was insufficient to detect the effects of additional factors with smaller effect sizes. We could not obtain seasonal agricultural and nutritional data due to a lack of time and resources (such as during the monsoon and winter). Seventh, it was not always straightforward to determine, for instance, why CDI was associated with child and adolescent DDS in Layyah but not in Bhakkar and Khushab. Future research would benefit from speaking more with farmers to appreciate the context of these results properly. Lastly, we would like to emphasize that just three locations in Pakistan were selected for this case study, as each represents a distinct agricultural transition. Rather than generalizing our findings to other regions, we wish to highlight the potential effects of two different agricultural transition approaches on dietary diversity. Future research should focus on the several Pakistani states whose variation stretches along a gradient to comprehend the causal linkages between diversification routes and nutritional diversity.

Our findings indicate that adults in Layyah and Bhakkar and adolescents and children in Khushab consumed a more diverse diet with greater crop diversification. Our research reveals that when crop diversity is high, farmer households with more diverse diets

are more likely to be permitted to vary their meals. Although the variation in Layyah's dietary diversity has been influenced by her income diversity, we could not detect a correlation between the two. According to our data, diversifying farmers' revenue sources may have a minimal effect on households' diversity of foods consumed. We find that greater dietary diversity is associated with higher income production among farmer households in the states, whether through crop sales, increased cash crop yields, or paid professional activities. The education level of the household's head, the extent to which farmers are connected to the market, and the family's annual income are significant drivers of the variety of foods consumed. Future programmes that enhance the variety of foods consumed by farmer households cannot utilize a one-size-fits-all approach, as the essential factors vary between homes and locations. It demonstrates complicated connections between dietary diversity among farmers, socioeconomic indicators, and crop and revenue diversification.

5. Conclusion

This study examined the income, crop diversification, livestock production and food diversity of 450 farmer households in Layyah, Bhakkar, and Khushab in Pakistan. Because rising crop specialization and revenue diversification may reduce the nutritional diversity of farmer households, we set out to learn more about this potential relationship. Adults, adolescents, and children in Layyah, Bhakkar, and Khushab exhibit a statistically significant positive correlation between crop diversification and DDS. According to this knowledge, Pakistan's food diversity and livestock production decrease if farmers focus on fewer crops. The development of DDS in males, females, and adolescents was most strongly influenced by educational attainment and family financial stability. The distance to food markets, the household's education level, and the crops farmed were the essential factors in deciding how each individual's DDS was explained. According to our findings, having a more diverse diet may be a viable strategy for increasing economic output. This will allow to boost farmer's income through selling food, cultivating cash crops, livestock production and other subsistence activities. Diversifying crops and building more diversified local food markets may be more beneficial to boosting farmer households' dietary diversity. Several factors, including the socioeconomic status of the farmer, the state of the market, and the types of crops they cultivate, can substantially impact the nutrition of a farmer's family. We conclude that dietary diversity and livestock production among farmer households in rural area of Pakistan is beneficial for sustainable production, food security, nutrition and farmer's livelihoods.

According to the overall finding, the following policy is suggested regarding crop diversity and livestock production in Pakistan: Crop diversity in agriculture applies to both the public and private sectors. The public sector can improve household nutrition, food production, and sustainable agriculture production through the development of crop diversity and livestock production in rural areas of Pakistan. The government should provide an enabling environment and subsidies to smallholder farmers in the rural areas of Pakistan. Pakistan must prepare a national policy to ensure the conservation of food security and national resources and to improve the agriculture performance in the rural areas of Pakistan.

5.1. Limitation and future research

There are several limitations in this study. This empirical research only addresses the crop diversity and livestock production to smallholder intra-household dietary diversity, nutrition and sustainable food production, in the rural area of south Punjab, Pakistan. The future studies should consider other parameters and include some other social demographic characteristics with new results in other developing areas around the world.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

MW, AHMSI, and MHR reviewed the literature, proposed the research model, and conceptualized and designed the study. XL conducted the literature search, preceded with the data extraction process, and involved in the development of the manuscript. MW, IJ, and QA conducted the statistical analysis and revised the manuscript critically for important content. XL, AHMSI, and IJ revised the whole manuscript according to the comments of the reviewer and rechecked the relevant data of the manuscript. XL and ME put forward many constructive suggestions on promoting the revision of the manuscript and supervised the entire writing process of the manuscript. All authors have equal contribution and approved the final manuscript to be published.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2023.1143774/full#supplementary-material>

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Looking up and going down: Does sustainable adaptation to climate change ensure dietary diversity and food security among rural communities or vice versa?

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Sustainable food systems are essential to ensure food security and mitigate climate change. Adaptation to climate change is part and parcel of sustainable food systems. Prior literature merely documented the climate-smart agricultural practices and explored the relationship with food security of adopters without taking the period of the strategies into account. Therefore, this study explored the factors affecting sustainable adaptation to climate change and created a further link between sustainable adaptation to climate change and the food security of rural households. The cross-sectional data were collected from 384 farmers through a face-to-face survey in Pakistan, selected by a multistage random sampling method. An ordered probit model and propensity score matching technique were used to analyze the data. Education, farm size, credit access, extension services, internet use for agriculture information, women's participation in farm-related decision making, and considering climate change a significant problem for agriculture were all positively influencing the sustainable adaptation to climate change at farms. The results indicated that farmers with a higher level of sustainable adaptation to climate change consumed more diversified diets and more daily calories as compared to those with a lower level of sustainable adaptation. Similarly, farmers with a lower level of sustainable adaptation to climate change had significantly lower food security than farmers with a high level of sustainable adaptation at their farms. This research indicated that farmers can gain food and nutrition benefits by becoming more sustainable adapters to climate change. This study has important policy implications for achieving sustainable development goals (SDGs) of zero hunger (SDG 2) and climate action (SDG 13) in developing countries.

KEYWORDS

SDGs, sustainable food systems, integrated resource management, ecological sustainability, food and nutritional security, food diversity

1. Introduction

Climate change is widely considered one of the key challenges to sustainable food systems and world food security (IPCC, 2014). The concentration of greenhouse gas (GHG) emissions, which are the primary cause of climate change worldwide, is increasing continuously despite mitigation efforts. Globally, GHG emissions have raised average temperatures and altered precipitation distribution (IPCC, 2018).

CO₂ emissions are continuously increasing in the atmosphere (Jackson et al., 2018), which has made the target of stabilizing global warming at 2 or 1.5°C difficult to achieve (Brown et al., 2019; Yang et al., 2020). As a result of the failure to develop an effective global framework to achieve the targeted level of global warming, 4°C of global warming by 2100 appears likely (Adger and Barnett, 2009; Parry et al., 2009). The continuous rise in warming and precipitation results in changes in the management of natural resources such as land and water, which subsequently affect agricultural productivity (Kurukulasuriya and Rosenthal, 2013). Similarly, the unavoidable rise in temperature has increased the chances of droughts, heat waves, uneven rainfall, floods, and other extreme events happening around the globe. The effects of climate change are already visible in different sectors, including agriculture (Arora, 2019). The changing climate severely affects crop productivity because these are very sensitive to temperature change (Mendelsohn and Dinar, 2009), which results in a decline in farm production and revenue (Mendelsohn, 2014). If the current trend of global warming and climate change continues, increasing crop losses in the future may contribute to lower food production and higher food prices, making it difficult to meet global food demand (Arora, 2019).

Climate change threatens food and nutrition security because it has negative effects that last for a long time. For example, it lowers agricultural productivity and destroys natural resources on farms. Climate variability, such as droughts and floods, etc., increases the chance of a poor harvest, which creates a situation of food insecurity. Similarly, water and land are the most critical resources for balancing farm production and the growing demand for food, and both are threatened by climate change. For example, with rising temperatures globally, the glaciers are melting at a high pace and the snow cover is disappearing quickly, which creates a shortage of water. Similarly, a temperature rise, on the other hand, generates many side effects for the crops as well as for the farm. It affects crop duration, changes pest survival and distribution, disturbs soil nutrients and mineralization, and affects fertilizer use efficiency (Jat et al., 2016).

Climate change has a significant impact on food security, farming, and the income of stakeholders all over the world. Lake et al. (2012) described that climate change has notable impacts on food and nutrition security, which is defined as “access to sufficient, nutritious, and safe food to sustain a healthy and active daily life.” Summer temperature increases have serious implications for food production, potentially affecting nearly half of the world’s population who live in the tropics and subtropics (Battisti and Naylor, 2009). Moreover, in light of the impacts of climate change on food and nutrition security as well as food diversity, a rise in prices due to the shortfall in farm production

appeared. The crop prices are tending to increase more than the already published calculations (Easterling et al., 2007). For example, in 2006, climate vulnerability in the form of extreme weather contributed to the decline in world cereal production. Piesse and Thirtle (2009) described this decline in the yield of cereal crops as partly due to the rise in food prices globally. Similarly, in 2003, after the European heat wave, a 25% reduction in French fruit production appeared. Extreme weather events cause local and regional food shortages (Lake et al., 2012). Thus, the rise in prices due to the shortfall in food production under the impact of climate change diverts consumers toward low-cost and low-quality food items.

Agricultural production is dependent on the natural resources that are adversely affected by climate change and variability. This ultimately threatens food and nutrition security (Crumpler and Bernoux, 2020) at the local and regional levels. Moreover, the low probability of crop harvest (Tolossa et al., 2020), low chance of cultivating diversified crops on the farm, high agricultural business risk, and soil degradation are the outcomes of climate change (Makate et al., 2016). Thus, these adverse outcomes affect households’ food and nutrition security as well as the food diversity of families (Jones et al., 2014).

With the growing concern of scholars and different stakeholders regarding climate change and its impacts on sustainable food systems, adaptation to climate change is inevitable (Berrang-Ford et al., 2011). Therefore, the necessity of adaptation to cope with climate change is becoming increasingly well known (de Coninck et al., 2018). Without coping strategies, the vulnerability and harshness of climate change will increase, and it will become a major challenge for securing food and sustainable agricultural development around the world (Fanzo et al., 2018; Haq et al., 2021). Climate change direct impact and vulnerability on food systems limited families’ ability to meet their food and nutrition needs globally (Lobell et al., 2008). These adverse impacts of climate change on food systems are expected to grow continually. Therefore, climate change is one of the fundamental challenges that the agricultural and food systems face currently (Pielke Sr et al., 2007). All the stakeholders who participated in the food systems have multiple objectives, such as livelihood, profit, and securing food (Fanzo et al., 2018). Food systems are unstable worldwide and highly affected by demand-side drivers (changing consumption patterns, increasing urbanization, growing population, and income distribution) and food supply. All these demand- and supply-side drivers are associated with climate change (Godfray et al., 2010). Therefore, the food system is unable to control malnutrition and food insecurity, as evidenced by the 178 million stunted children, primarily in Africa and South Asia (Vermeulen et al., 2012). Thus, the food system incorporates all features of the food supply chain, from food production at the farm to the preparation and consumption of food at home (Fanzo et al., 2018). The climate-smart food system describes the efficient decision-making of producers and consumers to experience a “triple win” situation that increases food productivity with minimum food losses, reduces the emissions from agriculture, and implements adaptation strategies (Lipper et al., 2014). Adaptation, rather than mitigation, is widely regarded as a critical component of policy responses to mitigate the effects of climate change on

agriculture, according to Deressa et al. (2009) and Gbetibouo (2009).

The adoption of climate-smart practices in agriculture can enable the farming community to withstand the detrimental effects of climate change and can make agriculture a more resilient and sustainable food system (Manda et al., 2016). Hundreds of such techniques and practices are available, including crop diversification, growing drought-resistant crops, integrated soil nutrient and fertility management practices (Faurès et al., 2013; Campbell et al., 2014), water harvesting, livestock diversification, and mixed farming (Shahbaz et al., 2020). Scholars concerning the vulnerability and unfavorable impacts of climate change on welfare, food, nutrition, and livelihood have largely favored the adoption of a sustainable food system (Makate et al., 2016). The adoption of climate-smart agricultural practices is based on three principles: (i) it should reduce the risk of climate change while improving income, food, and nutritional security; (ii) it should not hurt livelihoods or productivity; and (iii) the strategies and practices should be tailored to the area (Rosenstock et al., 2016).

A number of prior studies explored the factors influencing climate-smart agricultural practices and linked the adopted strategies with food and nutrition security all over the world, as well as in Pakistan. None of the studies considered the years throughout which the adopted practice has been applied by the farmers in determining the relationship between adopted strategies and food and nutrition security. Thus, this study goes one step further by taking into account the years of adopted strategies by constructing a sustainable adoption index and then creating a link between the food security of rural families and their sustainable adaptation to climate change. The current study has the following objectives: The first objective is to explore the practices being taken by the farmers to make their farms more resilient to climate change. The second objective is to explore the determinants of sustainable adaptation to climate change. The third objective was to analyze the effect of sustainable adaptation to climate change on food and nutrition security.

From a practical perspective, this paper offers a valuable methodology to take into account years of applied climate-smart agricultural practices for creating a link between sustainable adaptation and food security. The findings of this research will assist national and international agencies in their ongoing efforts to make agriculture a more sustainable food system and improve food security under a climate-changing scenario. So, all government agencies and international groups working to improve food security around the world, especially in developing countries, could benefit from this study.

2. Materials and methods

2.1. Study area and sampling technique

People in developing countries are more vulnerable to climate change and its consequences (Morton, 2007). Thus, poor people in developing countries are disproportionately affected by climate change because they rely on agriculture for income, food, and survival (Amole and Ayantunde, 2019). Similarly, Pakistan is a developing and agricultural country that is ranked as the world's

seventh most affected by climate change (Kreft et al., 2016), with nearly 42 million (20.3%) of its population undernourished (Haq et al., 2021). During the last era, the country's average temperature has increased by 0.6°C (GoP, 2019). This rise in temperature and other climatic happenings such as floods, droughts, uneven rainfall, heatwaves, etc., affected agricultural productivity, crop yields, and water availability, which resulted in low farm produce in the country (GoP, 2019), decreasing the country's food security (Ahmed et al., 2008; Menhas et al., 2016). Similarly, most cereal crops are very sensitive to changes in temperature and climate. For example, wheat and rice are very sensitive cereal crops to temperature change and water shortage (Mahmood et al., 2019), and these make up more than half of the daily nutrition of rural families. Punjab has a major share in the production of grain crops such as maize, rice, and wheat, etc. (PBS, 2020). The targeted population of the current study was the rural population of Punjab, because this is the second-largest and most populated province of the country.

Punjab province has been bestowed with very fertile land, and it has a very expansive irrigation system. It has a very suitable climate for the cultivation of all types of field crops, and crop cultivation covers almost 10.81 million hectares (53% of the net sown area) of the total geographical area of the province. Among all provinces in the country, Punjab contributes the most to agricultural output ((Pasha, 2015)). Furthermore, it employs more than 42.30% of the province's labor force. The annual mean temperature remained in the range of 19.37 to 21.87°C (CCKP, 2022).

To determine the sample size for the current study, the following formula by Krejcie and Morgan (1970) was used:

$$n = \frac{X^2 \times N \times q \times (1 - q)}{d^2 (N - 1) + (X^2 \times q \times (1 - q))}$$

Where n is the sample size, X^2 is the chi-square, and N is the population size (the total number of rural households in Punjab). Due to the large population of the province, we did not know the proportion of the population that adapted the practices, and we assumed that $q = 0.50$ was the maximum variability in sample size determination for the current study. Here, d describes the margin of error, which was assumed to be equal to 5%. Based on these values, a total sample size of 384 was acquired.

Multistage random sampling technique was employed in the current study to select the representative sample. In the first stage, three agro ecological zones, namely the rice-wheat zone, the maize-wheat zone, and the mixed cropping zone, were selected from the province. Each zone was made up of numerous small administrative units. To allocate the sample size to the lowest administrative unit, a top-down strategy was used in the current study. In the second stage, one district from each agro-ecological zone having the largest number of rural families or households was selected. In the third stage, we have selected two tehsils from one district and two union councils from one tehsil based on the number of rural households. The union council consists of several villages, and four villages were selected randomly from each union council. At the end, a total of 48 villages were ready to be approached for data collection. The total sample size was equally distributed among each village, and a total of 8 respondents from each village were selected randomly.

2.2. Data collection and survey instrument

The data collection was conducted through a well-designed questionnaire. A questionnaire survey is a systematic approach to collecting primary data (Sher et al., 2019). A face-to-face interview with respondents was conducted to collect the data. A well-trained and experienced team of female and male researchers was sent to the field of study. Before starting the interview, the researcher asked the respondents to give their consent verbally.

The questionnaire used for data collection was developed using insights derived from subject experts, researchers, and literature. The appropriateness of the questionnaire was confirmed before starting the survey. The questionnaire was reviewed extensively by five experts with research experience in climate change and food and nutrition security. Moreover, the pilot study was also conducted by interviewing 25 farm households. The questionnaire was finalized by incorporating the feedback of the experts and respondents. The final questionnaire was arranged in many sections. The first section consisted of the socio-economic characteristics of the respondents, such as education, age, experience, family size, etc. Questions regarding the adopted strategies being practiced in the study area were incorporated in the second section. The third section contained the standardized set of questions to measure the food security of the households. These standardized questions consisted of nine questions that considered all dimensions of food security (Kerr et al., 2019). The questions related to the measurement of food diversity were incorporated into the fourth part of the questionnaire. This section was adjusted according to the six different food groups existing in the country, i.e., (i) vegetables, (ii) fruits, (iii) cereals, (iv) meat and pulses, (v) fats and oils, and (vi) milk and milk products (FAO and GoP, 2018). Seasonal availability of fruits and vegetables was also considered in this section and arranged accordingly. Thus, data from 42 food items were obtained for estimating daily energy intake and the food diversity of the rural families. Some food items, such as sweets, chocolates, biscuits, and cakes, were not incorporated in the questionnaire because they are only used on unusual occasions in the villages like weddings, birthdays, and the arrival of guests at home.

2.3. Outcome variables

2.3.1. Food diversity

We used the Simpson index for measuring food diversity. This index serves two purposes: it describes food diversity and it measures the nutritional adequacy of rural families (Ruel, 2003; Nguyen and Winters, 2011). Food diversity is very important for health because it provides the essential nutrients that are necessary for the growth of the human body. To maintain body growth and a healthy life, food diversity requires the consumption of food items from all six different food clusters. Consuming different food items from different food clusters describes the maximum level of food diversity. In the current study, food diversity was measured by considering the calorie share of each food cluster. The formula for

measuring food diversity is as follows:

$$FD = 1 - \sum_{g=1}^m p^2$$

Where FD denotes the food diversity, p shows the calorie share of the i^{th} food cluster, m is the total number of food groups, and g is equal to 1 to 6. Therefore, resulting score of the food diversity index was in range of 0 and 1. This implies that the index value near 1 means higher food diversity and 0 means lower food diversity.

2.3.2. Daily energy intake

In the current study, the daily energy intake was also computed based on the daily calorie intake. The calorie intakes were measured from the quantity of each food item consumed by the household. For this purpose, the composite food table index was used to convert the consumed quantities of the food items into calorie and iron intakes. This table was prepared jointly by the government of Pakistan, and the Food and Agriculture Organization (FAO and GoP, 2001).

2.3.3. Food security

The household food security was measured by 9 different standardized questions, and a scale was used for categorizing the food security level of households: 1 for “food security,” 2 for “mildly food insecure,” 3 for “moderately food insecure,” and 4 for “severely food insecure.” In the current analysis, the “1” was assigned to food-secure households, while the mildly, moderately, and severely food-insecure households were numbered as “0.” This method of measuring food insecurity was also adopted by Kerr et al. (2019).

2.4. Sustainable adoption index

The sustainable adoption index was measured by adapting the method used by Demiryürek et al. (2017) for calculating the innovation sustainability index. The method resulted in the “sustainable adoption index,” which refers to the adapted and applicable practices of the respondents. The sustainable adoption index not only considers the adopted practices but also the years throughout which each adopted practice has been implemented by the farmer. Therefore, the index values increase, and the sustainability of the practices that the farmer has adapted increases accordingly. A higher value of the index means a higher level of sustainable adaptation to climate change by the farmer. The following formula was used to measure the “Sustainable adoption index.”

$$\text{Sustainable adoption index (SAI)} = \frac{\text{No. of adopted practices} \times \text{No. of adopted years}}{\text{Total number practices}}$$

The practices that the farmers adopted are crop diversification, farm diversification, improved seed varieties, changing planting dates, green manuring, crop rotation, crop covers, minimum tillage, drip irrigation, bed raising, solar panels, and agro-forestry. The

resulting SAI value was in the range of 10.37 to 59.45. The cluster k-mean analysis was applied to the SAI, and three homogeneous groups of farmers were determined. The farmers with an SAI score of <20 were categorized as low-sustainable adopters (69 farmers, 17.97%). Those farmers with an SAI score in the range of 21 to 40 were named moderately sustainable adopters (173 farmers, 45.05%). The third group of farmers was classified as highly sustainable adopters (142 farmers, 36.98%), and they had scores >40. These groups of farmers were further used as the dependent variable of the ordered probit model.

2.5. Empirical analysis

The dependent variable was coded as 0 for farmers belonging to the low-sustainability adopter group, one for the farmer from the moderately sustainable adopter group, and two for the farmer in the highly sustainable adopter group. The ordered probit model for the current study was specified as

$$\begin{aligned} Z^* &= \alpha' X_i + \varepsilon, \varepsilon \sim N(0, 1) \\ Z &= 0 \text{ if } Z^* \leq 0 \\ Z &= 1 \text{ if } 0 < Z^* \leq \rho_1 \\ Z &= 2 \text{ if } \rho_1 < Z^* \leq \rho_2 \end{aligned}$$

In this case, the dependent variable Z^* is the probability of the rural family belonging to the category of sustainable adoption; α' is coefficient's vector to be estimated; X_i describes the independent variables' vector; ε is normally distributed error term [0, 1], Z depicts the observed dependent variable, which indicates the likelihood of the respondent having higher level sustainable adoption; and ρ describes the cut-off points that signifies the inclination. It emphasizes the natural ordering among the three groups of the dependent variable of the model.

2.5.1. Impact of sustainable adaptation to climate change on food and nutrition security

To estimate the average sustainable adaptation to climate change effect on food security, food diversity, and energy intake for three groups, we applied the propensity score matching (PSM) technique. The PSM pairs the treated (farmers with high sustainable adoption status), and control (farmers with low sustainable adoption status) groups according to their observable characteristics (Dehejia and Wahba, 2002). The assumption of common support was also confirmed for each outcome variable (food security, food diversity, and energy intake) before applying the kernel matching method. The common support assumption was satisfied for each outcome variable as there was a significant overlap among the propensity scores of the control and treated groups.

In the matching technique, the two highly interesting estimates are the average treatment effect on adapters (ATT) and the average treatment effect on non-adapters (ATU). Therefore, ATT describes how the average outcome would have changed if a respondent with a high level of sustainable adaptation to climate change had a low level of sustainable adaptation. Therefore, the ATT

is used to compare the expected food security, food diversity, and energy intake outcomes of higher sustainable adoption with the counterfactual outcomes of lower sustainable adoption. The outcomes of higher sustainable adaptation to climate change are described as follows:

$$E(Y_{ik}|I_i = k) = \beta_k X_{ik} + \alpha_k \lambda_{ik}$$

The counterfactual outcomes of lower sustainable adaptation to climate change instead of higher sustainable adaptation to climate change.

$$E(Y_{ij}|I_i = k) = \beta_j X_{ik} + \alpha_j \lambda_{ik}$$

The average sustainable adaptation to climate change effect on food security, dietary diversity, and energy intake outcomes is conditional on a higher sustainable adaptation to climate change is as follow:

$$ATT = E(Y_{ik}|I_i = k) - E(Y_{ij}|I_i = k) = X_{ik}(\beta_k - \beta_j) + \lambda_{ik}(\alpha_k - \alpha_j)$$

The average sustainable adaptation to climate change effect is measured by calculating the difference between factual and counterfactual food security, food diversity, and energy intake scores or values. Therefore, we compared the food security index, food diversity index, and energy intake values of the households with higher sustainable adaptation to climate change with the households with lower sustainable adaptation to climate change. Consequently, the average treatment effect on all three variables is the difference between their two (factual and counterfactual) outcomes.

3. Results and discussion

3.1. Sample background

Socioeconomic characteristics provide important information about the samples' background and their abilities to counter climate change. The average age and education of the farmers were more than 41 and 8 years, respectively. Farmers were found to be rich in farming experience, with more than 20 years of working experience in the agricultural fields. Large family sizes are common in Pakistan, especially in rural areas, because of the joint family system (Shahbaz et al., 2020). In the study area, the average family size was nearly seven people. Agriculture is the mainstay of livelihood for a large majority of the population residing in rural areas of the country. More than one-third of the total family members were involved in agricultural activities for their livelihood in the study area. The average landholding was only 2.07 hectares. This may be because a large majority of the farming community in the country has land smaller than 2 hectares (Bryan et al., 2013).

More than two-fifths of the total farmers also mentioned agriculture as their primary source of livelihood. The reason may be that more than one third of the total Pakistani population is engaged in agriculture for their livelihood (GoP, 2021). More than half of the participating farmers in this study were owner-operators. Land distribution is highly skewed in Pakistan, and more than one third are tenant farmers with no agricultural land ownership

TABLE 1 Sample background.

Socioeconomic characteristics	Mean
Age (years)	41.35 (8.77)
Education (years)	8.56 (3.29)
Farming experience (years)	20.11 (7.67)
Family size (numbers)	6.77 (1.23)
Agricultural labor force (numbers)	2.33 (0.88)
Farm size (hectares)	2.07 (0.74)
Household head (1 = farmer is the household head, 0 = otherwise)	0.61
Main source of income (1 = agriculture, 0 = otherwise)	0.41
Tenancy (1 = farmer is owner cultivator, 0 = otherwise)	0.52
Credit access (1 = yes, 0 = otherwise)	0.34
Extension access (1 = yes, 0 = otherwise)	0.26
Internet use for agriculture information (1 = yes, 0 = otherwise)	0.21
Women participation in agricultural decision making (1 = yes, 0 = otherwise)	0.20
Training/workshop participation (1 = yes, 0 = otherwise)	0.11
Climate change is a significant problem for agriculture	0.89

The values in parenthesis are standard deviations. The standard deviations are presented only for continuous variables.

(GoP, 2015). A large majority of farmers (66%) mentioned credit accessibility issues during needy times. Extension services play a critical role in technology dissemination and creating awareness among farmers about climate change. But a large majority of the farmers mentioned that their farms were never visited by the extension agents. The Internet is also a source of information for the farming community, and they can access information about agricultural activities, market prices, and climate anytime (Mahmood et al., 2020). Only 21% of the farmers were using the internet to obtain agriculture-related information. The reason may be the lower education level of the farmers. Women are an essential part of agricultural activities, but their role in agricultural decision-making in the country is very limited. Moreover, women also play a critical role in ensuring food security and climate change adaptation (Asadullah and Kambhampati, 2021). Only one-fifth of the farmers stated that their women are involved in agricultural decisions. Cultural barriers and patriarchy in society are to blame for women's lower participation in agricultural decision-making. Similarly, only one-tenth of the farmers participated in the agriculture-related seminars and trainings. A large majority of the farmers (89%) consider climate change a significant problem for agriculture (Table 1).

3.2. Climate change adoption status

Farmers are well aware of the implications of climate change on agriculture. Therefore, they are adopting different strategies

to minimize the climate change repercussions on agriculture depending on the capability and skills of farmers (Anser et al., 2020). Moreover, agriculture is labor intensive, and farmers use traditional strategies to minimize the impact of climate change in Pakistan (Shahbaz et al., 2021). Farm diversification was the most commonly adopted strategy by the farmers to minimize the impacts of climate change on the food system and make agriculture more resilient to climate change. This was followed by crop diversification, which was adopted by more than three-fourths of the farmers. Pakistan is facing one of the worst energy crises, and farmers are also confronting this problem in rural areas. The farming community is looking for new and cost-efficient solutions for sustainable food systems. Solar panels were the least adopted measure by the farmers. The use of solar panels for producing energy at farms reduces emissions and limits climate change. The green manure strategy was also adopted by more than two-thirds of the farmers. Pakistan has scarce water resources, and the adoption of water-efficient techniques is absolutely necessary for sustainable food systems and ensuring food security in the country (Razzaq et al., 2019; Ashfaq et al., 2020). The majority of the farmers (64%) adopted a traditional strategy (bed raising) to counter the implications of climate change on irrigation water (Figure 1). Drip irrigation was adopted by only a little more than 3%. Crop rotation is also important to maintain the soil fertility and nutrients necessary for better crop productivity. This practice was adopted by almost three-fifths of the total farmers. Improved seed varieties and changing planting dates were adopted by more than half and two fifths of the farmers, respectively, to counter the impacts of climate change on food systems.

3.3. Determinants of sustainable adaption to climate change

With a log likelihood ratio of chi square value of -756.40 and a probability of chi square value of $<1\%$, the overall ordered probit model was significant (Table 2). Only seven explanatory variables out of a total of thirteen were significantly affecting the sustainable adaptation to climate change. The significant variables were education, farm size, tenancy, extension services, internet use for agriculture information, women's participation in agricultural decision-making, and considering climate change a significant issue for agriculture.

The education level of farmers plays a critical role in the adoption of measures to minimize the impacts of climate change on food systems. Education was found to be positively associated with sustainable adoption status. A 1-year increase in the education level of the farmers increases the likelihood of belonging to a higher sustainable adoption group by 1.79 times. Abid et al. (2015) also reported a positive relationship between climate change adaptation and farmer education. Farm size is an important indicator of a farmer's wealth. Farm size was also directly associated with the sustainable adoption status of the farmers. A one-hectare decrease in farm size reduces the chances of belonging to a higher sustainable adoption group by 1.14 times. The findings related to farm size and climate change adaptation are in line with the prior studies conducted by Belay et al. (2017) and Fadina and Barjolle (2018),

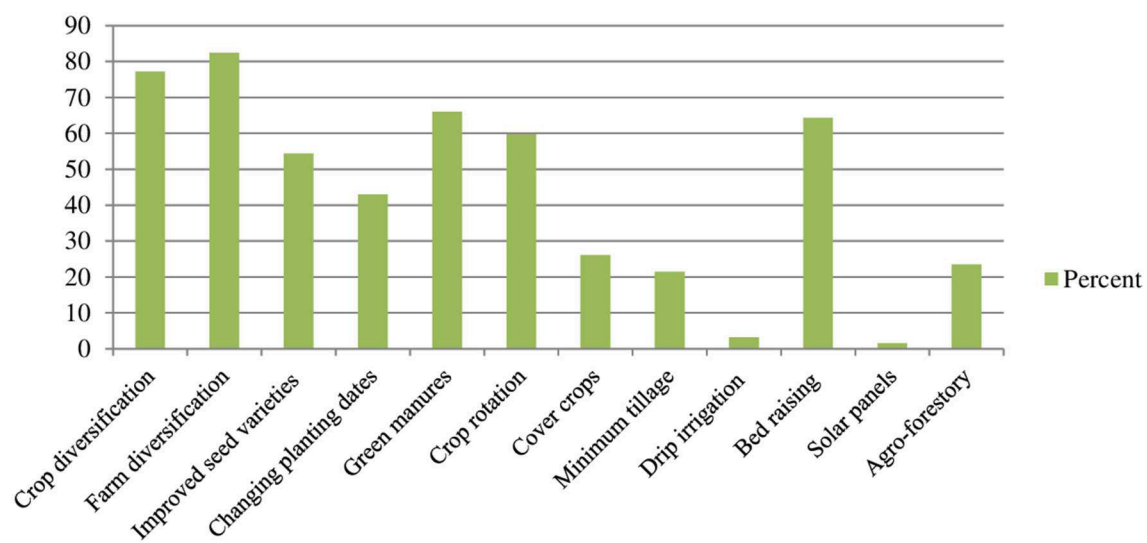


FIGURE 1
Climate change adoption status in the region.

TABLE 2 Determinants of sustainable adaptation to climate change.

Variables	Coef.	Std. errs.	Odd ratios
Education (years)	0.58***	0.36	1.79
Farming experience (years)	0.13	0.32	1.13
Agricultural labor force (numbers)	0.46	0.77	1.58
Farm size (hectares)	0.17**	0.08	1.14
Household head (1 = farmer is the household head, 0 = otherwise)	0.33	0.29	1.39
Main source of income (1 = agriculture, 0 = otherwise)	−0.98	0.80	0.38
Tenancy (1 = farmer is owner cultivator, 0 = otherwise)	1.30*	0.17	3.67
Credit access (1 = yes, 0 = otherwise)	0.08	0.06	1.08
Extension access (1 = yes, 0 = otherwise)	1.01*	0.24	2.75
Internet use for agriculture information (1 = yes, 0 = otherwise)	0.09*	0.03	1.09
Women participation in agricultural decision making (1 = yes, 0 = otherwise)	0.96**	0.47	2.61
Training/workshop participation (1 = yes, 0 = otherwise)	0.26	0.43	1.29
Climate change is a significant problem for agriculture	0.65**	0.29	1.92
LR chi2	−756.40		
Prob > chi2	0.00		
Pseudo R2	0.69		

*, **, and *** represents significance level at 1%, 5%, and 10% respectively.

who also stated a positive association between landholding and the adoption of climate-smart agricultural practices.

The results also showed that an owner farmer is 3.67 times more likely to be in a higher sustainable adoption group than a tenant farmer. Extension services were also found to be positively influencing sustainable adaptation to climate change. The results of the study related to tenancy and climate change adaptation positively align with those of [Iheke and Agodike \(2016\)](#) and [Fahad et al. \(2020\)](#). A farmer with extension services is 2.75 times more likely to be in a higher sustainable adoption group than a farmer without extension services. Similarly, internet use for agricultural purposes was positively related to the sustainability of the adoption status of the farmers. [Abegunde et al. \(2019\)](#), [Makate et al. \(2019\)](#), and [Mahmood et al. \(2020\)](#) also reported a significant positive relationship between extension services and climate change adaptation. A farmer using the internet for agriculture information has 1.09 times more chances of belonging to the high sustainable adoption category as compared to a farm not using the internet for agriculture purposes. [Thinda et al. \(2020\)](#) and [Antwi-Agyei and Stringer \(2021\)](#) also found that information and communication technology can assist farmers to increase climate change adaptation on farms. Women's participation in agricultural decision-making also positively influences sustainable adaptation to climate change. A farm with the involvement of women in decision-making is 2.61 times more likely to be a sustainable adopter than a farm without women's participation in decision-making. These findings positively align with those of [Shahbaz et al. \(2022\)](#), who also found that women's empowerment in agricultural decision-making can enhance the adoption of climate change measures on farms. Similarly, a farmer who considers climate change a significant problem for agriculture is 1.92 times more likely to belong to a higher sustainable group than a farmer who does not consider climate change a significant problem.

TABLE 3 Sustainable adaptation to climate change impact on food security.

Sustainable adoption status		Average difference
High	Moderate	
0.67	0.59	0.08 (0.04)**
High	Low	
0.67	0.55	0.12 (0.06)**
Moderate	Low	
0.64	0.57	0.07 (0.03)*

* and ** represents significance level at 1% and 5%, respectively.

3.4. Impact of sustainable adaptation to climate change on food security

The results presented in [Table 3](#) indicated that farmers with higher sustainable adoption status have higher levels of food security than farmers with lower sustainable adoption status. Another important result that can be extracted from the below findings is that all the farmers with higher sustainable adoption status would have had less food security if they had not belonged to a higher sustainable category. Another key finding is that the average difference between the food security of the high sustainable adoption group as compared to the low sustainable adoption group is higher than the average difference between the high sustainable adoption group as compared to the moderate sustainable adoption group. For example, belonging to a high-sustainability adoption group as compared to a moderate-sustainability group increases food security by 8%. Similarly, belonging to a high-sustainability adoption group instead of a low-sustainability adoption group can increase the farmers' food security by 12%. On the other hand, belonging to a moderately sustainable adoption group instead of a lowly sustainable adoption group can increase the farmers' food security by 7%. These findings also show that farmers in low-sustainable adoption groups can benefit more from food security by becoming highly sustainable rather than moderately sustainable. Previous literature ([Brown et al., 2015](#); [Douxchamps et al., 2016](#); [Jat et al., 2016](#); [Ali and Erenstein, 2017](#); [Smith et al., 2020](#)) also reported similar results as in this study: adaptation to climate change at the farm level positively contributes to the food security of rural households.

3.5. Impact of sustainable adaptation to climate change on food diversity

Dietary diversity is important for nutritional status and health. [Fanzo et al. \(2018\)](#) and [Niles et al. \(2021\)](#) reported that climate change will adversely affect food security and dietary diversity in rural households by negatively affecting food systems. Therefore, adaptation to climate change is necessary to maintain food security and dietary quality (diet diversity, nutrient density, and safety). [Table 4](#) presents the impact of sustainable adaptation to climate change on the food diversity of the farmers. Farmers belonging to the high sustainable adoption group have (0.09) greater food

TABLE 4 Sustainable adaptation to climate change impact on food diversity.

Sustainable adoption status		Average difference
High	Moderate	
0.71	0.62	0.09 (0.01)*
High	Low	
0.71	0.58	0.13(0.02)*
Moderate	Low	
0.65	0.55	0.10 (0.04)**

* and ** represents significance level at 1% and 5%, respectively.

TABLE 5 Sustainable adoption impact on daily energy intake.

Sustainable adoption status		Average difference
High	Moderate	
2489.60	2211.76	277.84 (47.87)*
High	Low	
2489.60	2145.43	344.17 (41.43)*
Moderate	Low	
2265.88	2221.56	44.32 (35.30)

*represents significance level at 1%, respectively.

diversity than the farmers in the moderately sustainable adoption category. Similarly, farmers belonging to the low-sustainability adoption group have lower food diversity than the farmers in the high-sustainability adoption group. A farmer in a low-sustainable adoption group can increase its food diversity by 0.10 by belonging to a moderately sustainable adoption group. Similar findings were reported in the previous relevant literature ([Rahman, 2010](#); [Kanter et al., 2015](#); [Kumar et al., 2015](#)), which found that adaptation to climate change at the farm level assists farmers in improving their daily dietary diversity.

3.6. Impact of sustainable adaptation to climate change on daily energy intake

The farmers belonging to the highly sustainable adoption group would have had less 277.84 kcal/day if they had belonged to the moderately sustainable adoption category. Similarly, farmers belonging to the low sustainable adoption group can increase their daily energy intake by 344.17 kcal by becoming highly sustainable adopters ([Table 5](#)). The results of the study corroborate with [Haq et al. \(2021\)](#), who also reported that farmers can increase their daily energy intake by adapting to climate change at farms. [Issahaku and Abdulai \(2020\)](#) also reported that adaptation to climate change at farm levels positively contributes to the food and nutrition security of the rural community. Additionally, the findings of this study are also in line with the study conducted by [Amare and Simane \(2018\)](#), who also estimated a positive relationship between climate change adaptation and daily nutrition intake.

4. Conclusion and policy recommendations

Climate change vulnerability has a negative impact on agriculture and food systems. The food system's demand and supply drivers are extremely vulnerable to climate change. From the time food is grown on the farm until it is consumed at home, it is threatened by the multifaceted effects of climate change. This causes instability in agricultural production and threatens the sustainability of food systems, which increase food insecurity; reduce food diversity, and lower energy intakes among rural inhabitants. Climate change adaptation has gained the primary support of stakeholders as the appropriate future trajectory to cope with the impact of climate change and enjoy secure food, more nutrition, a healthy diet, and required energy intakes. The current study is planned to explore the sustainable adaptation to climate change and its implications on the food security, food diversity, and energy intake of rural households. A sample size of 384 small farmers was interviewed by the trained and well-experienced researchers. The farmers were well experienced, and a large majority of them clearly understood the importance of climate change and its impact on agriculture.

Almost 12 sustainable practices were adopted by the farmers; among those, farm diversification was one of the most adopted practices by the small farmers, followed by crop diversification, green manure, bed raising, and crop rotation, respectively. The results of the ordered regression analysis described that the extension services were positively contributing to sustainable adaptation to climate change. Women's participation in agriculture and internet use for agricultural information was also positively associated with sustainable adaptation to climate change. Moreover, the farmers' perception about the significant impact of climate change on agriculture also contributes positively to sustainable adaptation to climate change.

The positive association between sustainable adaptation and food security, food diversity, and energy intake describes the importance of sustainable adaptation to climate change, which ensures secure, diversified, and full of nutrients food for rural households. The farmers with low sustainable adaptation to climate change consumed less diversified food, had a lower energy intake, and experienced higher food insecurity as compared to the farmers with high sustainable adaptation to climate change. This study has important policy implications for achieving sustainable development goals (SDGs) of zero hunger (SDG 2) and climate action (SDG 13) in developing countries.

The results of the current study have significant policy implications. First, this study describes the role of farmers' awareness and knowledge of climate change in minimizing the effects of climate change on sustainable food systems. Second, it also highlights the importance of extension services and internet for sustainable adaptation to climate change. The sustainable adaptation to climate change may also assist the government in making effective policies for addressing daunting challenge of food and nutrition insecurity in the country. Therefore, the government should increase awareness of sustainable food systems and climate-resilient agriculture benefits to cope with climate change in the country through serious awareness campaigns.

Moreover, sustainable food systems should be promoted by raising awareness through extension services and short videos on the internet. Even though this study was conducted with the utmost care, it is not without limitations. First, the cross-sectional nature of the collected data does not allow for the development of a causal relationship between the sustainable adoption of climate change practices and the food diversity and nutrition of the households. Secondly, the food items used to estimate daily calorie consumption and food diversity did not include those that were not part of daily kitchen items in the country. Thirdly, the research included only farmers as participants in this study, which might not be representative of the whole rural population. Despite the study's limitations, the findings revealed important information about the implications of sustainable climate change practices on food diversity and the calorie consumption of farmers, and the findings will help to understand the implications of sustainable adoption on household nutrition.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by University of Education Lahore, Pakistan. The patients/participants provided their written informed consent to participate in this study.

Author contributions

SH and PS: conceptualization. SH, PS, AA, and NN: methodology, formal analysis, resources, data curation, and funding acquisition. PS, AA, BA, and NN: software and writing—original draft preparation. RN and NN: validation. BA and RN: investigation. SH, PS, AA, BA, and RN: writing—review and editing. All authors read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Resource-use efficiency and environmental sustainability in the village tank cascade systems in the dry zone of Sri Lanka: An assessment using a bio-economic model

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Introduction: Village tank cascade systems (VTCSs) were built in ancient Sri Lanka as autonomous and climate-resilient agro-ecological systems. This study examines crop choices, farming profitability, and environmental sustainability under alternative rainfall regimes and market interventions in the Mahakanumulla VTCS of the Anuradhapura district.

Method: A bio-economic model was developed to represent farming activities in the VTCS for the 2018–19 *Maha* and 2019 *Yala* cultivation seasons with data gathered from secondary sources and a key informant survey. The objective function of the model was the maximization of profits from farming. Resource limits were set for four types of land (highlands and lowlands in the *Maha* and *Yala* seasons), two types of labor (hired and family), and twelve-monthly water constraints. Six different models were developed for the six sub-divisions of the VTCS, considering the water-management hierarchy of the system. The models were simulated under alternative rainfall regimes and market interventions. The optimal crop mixes, farm profits, and shadow prices of resources associated with the baseline scenarios were compared with those of the counterfactual scenarios.

Results and discussion: This analysis clearly illustrated that water and labor are the key determinants of the system. Also, when 922 ha of lowlands and 205 ha of uplands were allocated per annum for crop cultivation under normal environmental conditions, the annual profitability of the VTCS was LKR 111 million. During drought periods, a sharp reduction in profits was observed in the *Maha* season. Year-round drought caused a 77% profit reduction compared to the baseline. The *Maha* drought alone caused a reduction of 47%. The introduction of a buy-back arrangement for chili and maize helped farmers to increase profits by 185 and 28%, respectively, under normal climate scenarios, turning to 954 and 5% during extreme drought scenarios, compared to the baseline. The least nitrate leaching and soil losses occurred in green chili cultivation. The introduction of market-based solutions is recommended to address extreme climate events experienced by the rural communities dependent on the VTCSs in Sri Lanka.

KEYWORDS

village tanks, bio-economic modeling, crop mix, irrigation, Sri Lanka

Introduction

The immense diversity of climate and geography in Sri Lanka has resulted in correspondingly varied agricultural systems. The tank-based systems in the dry zone, termed village tank cascade systems (VTCSs), play an important role in the agrarian communities associated with them. VTCSs are interconnected small-tank systems which efficiently stored, conveyed, and used rainwater in the past. Distinctive crop-livestock systems and land-use patterns grew up around them. These systems have begun to degrade due to numerous natural and manufactured threats (Dharmasena, 2010). For example, rainfall data for the Mahailuppallama area during the last century reveals that the dry zone faced frequent climate shocks due to unpredictable rainfall patterns.

Additionally, macro-level policy changes have affected the system. After the Food and Agriculture Organization (FAO) declared VTCSs to be Globally Important Agricultural Heritage Systems (GIAHS), there were various technological and market interventions by the private and public sectors for their restoration. Nevertheless, there is a dearth of scientific investigation to evaluate the effects of such interventions on the profitability and environmental sustainability of VTCSs, except for two recent studies by Weerahewa and Dayananda (2023) and Dayananda et al. (2021) which used bio-economic models for the evaluation.

Bio-economic models, which may be developed as extensions of Linear Programming (LP) models, can assess farm innovations and government policies, considering the economic and ecological constraints in agricultural systems. Janssen and Van Ittersum (2007) introduced an integrated economic-hydrologic modeling framework that accounts for the interactions between water allocation, farmer-input choices, agricultural productivity, non-agricultural water demand, and resource degradation to estimate the social and economic gains from improvements in the allocation and efficiency of water use. There is also the Rosegrant et al. (2000) application of a bio-economic model to the Maipo river basin in Chile. The latter evaluated the economic benefits to water use for different demand management instruments, including markets in tradable water rights, based on the production and benefits functions of water in the agricultural and urban-industrial sectors (Rosegrant et al., 2000).

The objective of this study is to examine the profitability changes and environmental degradation of selected market interventions under alternative climate scenarios using a bio-economic model.

Study site

The Mahakanumulla VTCS in the Thirappane Divisional Secretariat was selected for this study. This VTCS is a branched cascade consisting of 27 village tanks spread across nearly 40 km² in the Anuradhapura district (Figure 1). The village tanks in the VTCS drain to the Nachchaduwa tank, the last in the system, according to the elevation difference. The Department of Agrarian Services maintains the irrigation infrastructure of the Mahakanumulla VTCS which spreads across the six Grama Niladhari (GN) divisions of Mahakanumulla, Indigahawewa, Sembukulama, Wellamudawa,

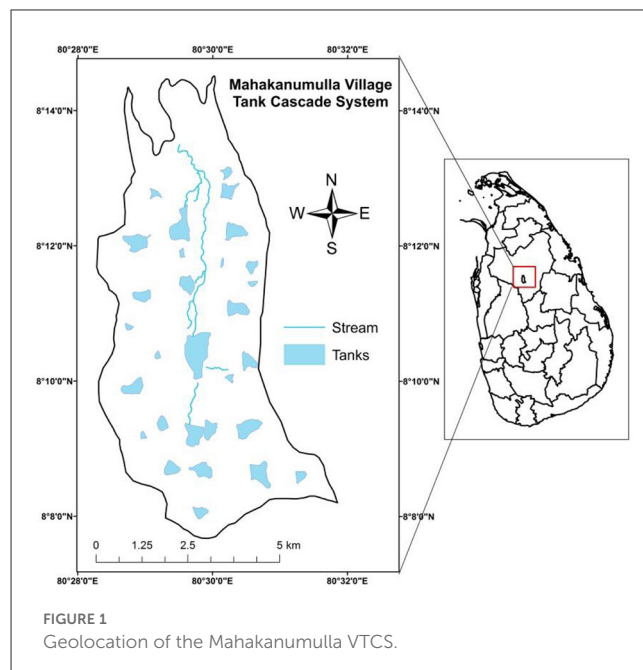


FIGURE 1
Geolocation of the Mahakanumulla VTCS.

Paindikulama, and Walagambahuwa. A total 1,359 households live across the cascade; the community of 3,840 individuals breaks down to 53.6% women and 46.4% men (Department of Public Administration, 2019).

In keeping with the bi-modal rainfall pattern in the dry zone, there are two cultivation seasons, the *Maha* (wet season with high rainfall) and the *Yala* (dry season with low rainfall). There are different geographical and social characteristics across the VTCS, as well as individual agriculture systems based on its water-management hierarchy.

Model and data

Structure of the bio-economic model

The basic LP model was adopted to develop a bio-economic model for the Mahakanumulla VTCS. The general form of the LP model is as follows.

Objective function:

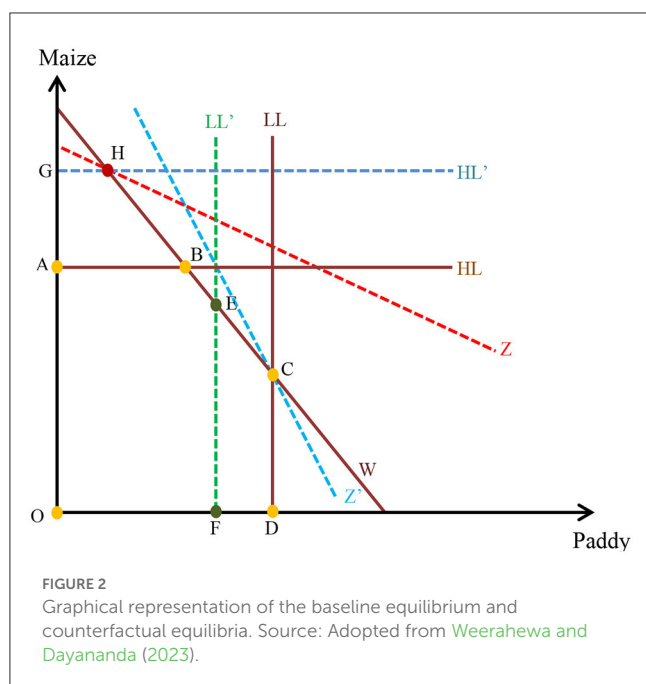
$$\text{Max } Z = \sum_{j=1}^n C_j x_j$$

Subject to,

$$\sum_{j=1}^m a_{ij} x_j \{ \leq, =, \geq \} b_i \forall i$$

$$x_j \geq 0$$

The above model presents: Z as profit; C_j as the co-efficient of the j^{th} decision variable; a_{ij} as the j^{th} coefficient of the i^{th} constraint; X_j as the j^{th} decision variable; and, b_i as the i^{th} resource limit. The additional profits that may be reaped by increasing one unit of a limiting resource are indicated by the shadow price. A zero shadow



price implies that no profits can be reaped by expanding use of the resource, i.e., the relevant resource is not binding. The shadow prices are the additional cost incurred over and above the market price by the decision maker when the resources are constrained as the cost of the resource is included in the coefficients of the objective function.

The basic version of the model is described below. Suppose that there are two types of crops, paddy and maize, and three constraints limit their production—lowland (LL), highland (HL), and water (W). For simplicity's sake, let us assume that the type of land is crop-specific. Maize uses HL and W to produce its output, while paddy uses LL and W for its output. Figure 2 shows the baseline equilibrium and counterfactual equilibria for this model. The feasible region is given by OABCD, and B or C will become the optimal solution in the initial equilibrium, depending upon the slope of the iso-profit line. If the relative price of maize is higher, as shown in Z, B becomes the optimal solution. If the relative price of paddy is higher, as shown in Z', C becomes the optimal solution. If the availability of LL is restricted, the feasible region shrinks to OABEF, and B or E will be the optimal solution status quo, with a lower profit compared to the initial equilibrium. If the availability of HL is expanded, the feasible region expands to OGHCD, and H or C will be the optimal solution in the status quo, with a higher profit compared to the initial equilibrium.

Decisions concerning administration of the cascade, water resource management, and cultivation are taken at the GN level. Accordingly, six different linear programming models were developed, treating the six GN sub-divisions as different agricultural systems. Of the six sub-divisions, three divisions show hydrological interconnections (WS 1, WS 2, and WS 3) and the connectivity was modeled through the water constraint. Each sub-division consists of available lands for cultivation, including lowlands and highlands. The total cultivation extents of each sub-division are presented in Table 1.

Model calibration

The extents of land cultivated with paddy, maize, and vegetables (the crops most under cultivation) in the 2018–2019 *Maha* and 2019 *Yala* were used to calibrate baseline models in each sub-division.

The baseline equilibria were calibrated thus. First, data concerning cultivation costs obtained from the Department of Agriculture (Table 2) and discussions with the key informants were used to construct the coefficients in the profit equation (c_j) in the bio-economic model. Table 2 presents the data used to construct the baseline equilibria.

Next, the key constraints of the models of each sub-division were identified based on data from the key informant survey and secondary sources. The key informants were the Agriculture Research Inspectors for the Mahakanumulla VTCS, the presidents of the farmers organizations of the respective GN divisions, and the persons responsible for water operations in a season. Water, land, and labor are the significant constraints of the Mahakanumulla village tank system (Bandara, 2004; Withanachchi et al., 2014). Altogether, 18 constraints were identified, including two labor constraints, 12 monthly water constraints, and 4 land constraints representing lowlands and highlands in the *Yala* and *Maha* seasons.

The Crop Water Requirement (CWR) was calculated using the CROPWAT model (Food and Agriculture Organisation, 2022) and data from the Mahailuppallama weather station. The CWRs of the *Yala* and *Maha* seasons were calculated separately for each crop category. The starting date of the *Maha* season was taken as 1st October, and 1st March as the starting date for the *Yala*. The CWR was evaluated according to the crop growth stages. Table 3 illustrates the monthly CWR of paddy, maize, and vegetables in the dry zone.

The total water availability was computed using the CWRs and the crop mix generally adopted by the farmers in the study area. According to the literature and data from the key informant survey, cultivation is practiced using direct rainfall, tank irrigation, and groundwater resources in the VTCS. Groundwater is only used for chena cultivation (shifting, or slash-and-burn cultivation) in a few areas.

The average land extents of the VTCS were used in computing water usage during the two cultivation seasons: these numbers were then used to construct the water resource limits (b_i) of the baseline equilibrium of the model. According to the key informants, in a typical *Maha* season, farmers cultivate the total extent of available lowland with paddy. In a typical *Yala* season, only one-third of the lowland is cultivated. The total available water in the baseline scenario is presented in Table 4.

The average labor requirements for each crop category, obtained from the cost of cultivation reports produced by the Department of Agriculture, were used to construct the constraint coefficient of the labor. The limit on the total labor requirement was determined considering the labor required for each crop enterprise and was obtained from the cost of cultivation reports of the Department of Agriculture and the crop mix generally adopted by the farmers in the study area (Department of Public Administration, 2021).

TABLE 1 Tank distribution and land use in the Mahakanumulla VTCS.

Sub-division	Grama Niladhari division	Number of tanks	Total land extent (ha)	Total highland land area (ha)	Total lowland land area (ha)
WS 1	Walagambahuwa	6	596.91	48.46	133.35
WS 2	Paindikulama	4	1,104.67	60.70	127.48
WS 3	Mahakanumulla	3	459.10	18.21	97.21
WS 4	Indigahawewa	3	689.69	37.64	89.44
WS 5	Sembukulama	7	1,228.11	32.38	141.64
WS 6	Wellamudawa	4	588.25	113.31	153.78

Agriculture research and production assistant (ARPA) data (2018–2019) and district survey office, Anuradhapura.

TABLE 2 Crop budgets of paddy, maize, and vegetable categories in an average season.

Variable	Units	Paddy		Maize		Vegetables	
		<i>Yala</i>	<i>Maha</i>	<i>Yala</i>	<i>Maha</i>	<i>Yala</i>	<i>Maha</i>
Average yield	kg/ha	3,700	4,000	7,000	7,000	16,000	16,000
Producer price	LKR/kg	55	55	60	60	55	55
Total revenue	LKR/ha	203,500	220,000	420,000	420,000	880,000	880,000
Fertilizer cost	LKR/ha	35,721	35,721	51,447	51,447	47,560	47,625
Cost of production (including fertilizer cost)	LKR/ha	105,721	105,721	158,047	158,047	560,560	560,625
Profits (including imputed cost)	LKR/ha	97,779	114,279	261,953	261,953	319,440	319,375

Authors' calculations.

TABLE 3 Monthly crop water requirement (CWR) (m³/month).

Season	Month	Rice	Maize	Vegetables
<i>Maha</i>	September	1,868	0	–
	October	2,582	733	1,045
	November	2,005	1,282	1,720
	December	1,927	1,850	3,000
	January	1,712	1,740	708
	February	0	58	0
<i>Yala</i>	March	1,703	0	0
	April	2,713	702	985
	May	2,553	1,570	2,103
	June	2,500	2,470	3,667
	July	2,708	2,600	1,265
	August	0	655	0

Authors' calculations.

Appendix 1 presents the model tableau for the baseline scenario for a single sub-division in the Mahakanumulla VTCS.

Development of simulation scenarios

The profitability of crop cultivation under market interventions was tested under alternative climate scenarios experienced in the dry zone during the past decade.

TABLE 4 Total water available for cultivation in the six sub-divisions in the baseline scenario (m³).

Month	WS1	WS2	WS3	WS4	WS5	WS6
September	181,055	188,992	181,626	167,069	287,268	287,268
October	278,820	295,314	254,479	242,352	420,140	458,863
November	242,107	260,939	200,783	198,432	347,378	412,489
December	266,194	286,119	196,577	204,115	358,968	465,504
January	197,865	229,008	171,891	165,889	296,520	345,399
February	587	1,526	145	235	822	1,878
March	137,839	34,460	67,337	68,919	51,690	51,690
April	230,401	65,715	110,268	113,207	88,609	103,124
May	230,012	74,842	107,401	110,751	90,890	122,141
June	242,023	90,686	109,884	113,592	99,140	152,657
July	239,943	70,751	112,332	117,412	90,925	115,753
August	2,651	795	544	1,325	265	2,651

Authors' calculations.

Development of climate scenarios

Climate impacts on the VTCS were tested as an external shock. Rainfall data from the Mahailluppallama weather station for the 1976–2019 period, obtained through the Anuradhapura District Survey Office, were taken into account to generate the drought

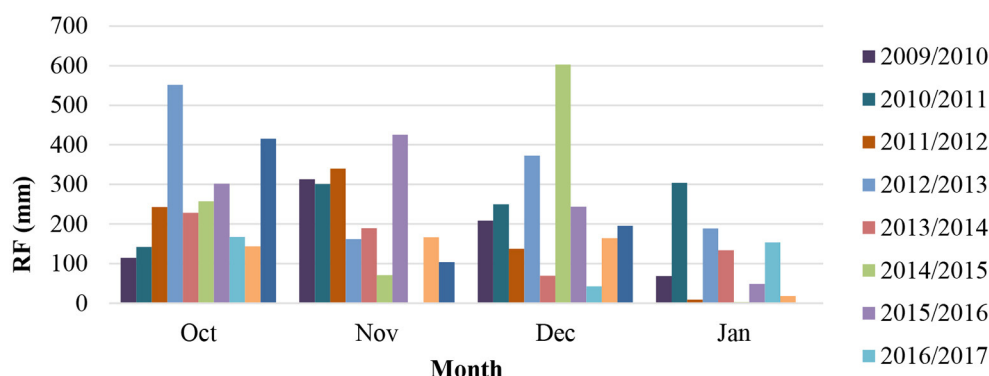


FIGURE 3

Rainfall distribution in the *Maha* season (2009–10 to 2018–19). Source: District survey office, Anuradhapura.

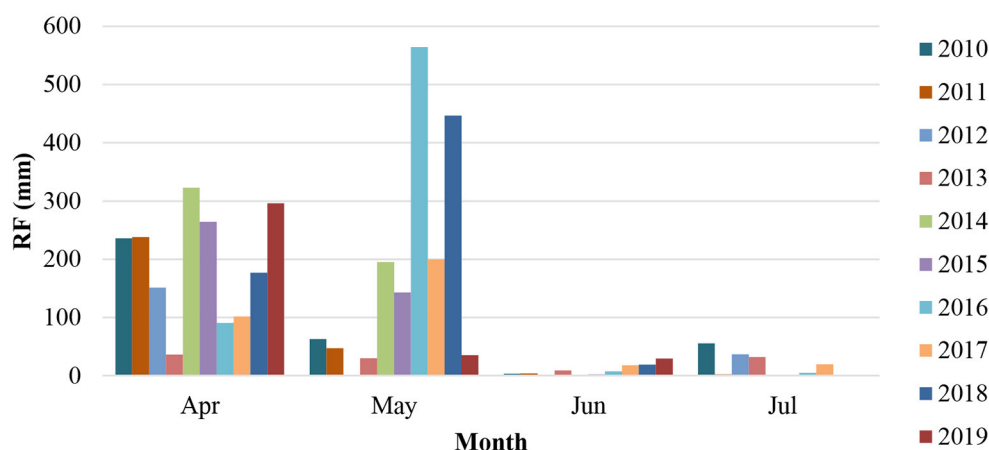


FIGURE 4

Rainfall distribution in the *Yala* season (2009–2019). Source: District survey office, Anuradhapura.

scenarios. Figures 3, 4 present monthly rainfall distribution during the Maha and Yala seasons from 2009 to 2019.

Of the *Maha* seasons, 1986–87 and 2012–13 recorded the lowest and highest rainfall, respectively. Therefore, the 1986–87 *Maha* rainfall was considered the *Maha* drought period. From the *Yala* seasons, the 1979 and 2018 seasons received the lowest and highest rainfall, respectively; thus, the 1979 *Yala* rainfall was taken as the *Yala* drought period.

The baseline scenario was developed considering the rainfall received during the 2018–19 *Maha* and 2019 *Yala* seasons which depict rainfall in an average rainy year. In determining the past decade's rainfall data, six rainfall scenarios were developed to test the effect of climate shocks on the Mahakanumulla VTCS. Table 5 presents the above rainfall scenarios and the monthly average rainfall for the above scenarios.

In order to calculate direct rainfall to the crop cultivation area, the extent of land cultivated in each sub-division was used. Then, the baseline models simulated the total available water under each scenario. Profitability, land use, environmental sustainability, and shadow prices were calculated for each subdivision and the entire cascade.

Development of market intervention scenario

Government policy, as articulated in the *National Policy Framework Vistas of Prosperity and Splendor*, *Overarching Agricultural Policy*, and *National Agricultural Policy*, emphasize the need to introduce market interventions to uplift rural lives without compromising environmental sustainability. Accordingly, one initiative by the private sector in many dry zone areas has been a buy-back system for maize and chili. Even though tobacco was also introduced as a commercial crop, in compliance with World Health Organization (WHO) guidance on tobacco control, the government has decided to disincentivise tobacco cultivation. In this study, we tried to assess the profitability changes, considering the buy-back systems for maize, dried chili, and tobacco.

The baseline bio-economic models were extended by including the above crop categories to evaluate the effects of market interventions. Tables 6–8 represent the data used for the market intervention scenario.

TABLE 5 Monthly rainfall for climate scenarios (m).

Month	2018–2019 <i>Maha</i> and 2019 <i>Yala</i>	2012–13 <i>Maha</i> and 2018 <i>Yala</i>	2012–13 <i>Maha</i> and 2019 <i>Yala</i>	2018–2019 <i>Maha</i> and 2018 <i>Yala</i>	1986–87 <i>Maha</i> and 1979 <i>Yala</i>	1986–87 <i>Maha</i> and 2019 <i>Yala</i>	2018–2019 <i>Maha</i> and 2018 <i>Yala</i>
	Baseline	Year-round heavy rainfall	Heavy <i>Maha</i> rainfall and normal <i>Yala</i>	Normal <i>Maha</i> and heavy <i>Yala</i> rainfall	Year-round drought	Drought <i>Maha</i> rainfall normal <i>Yala</i>	Normal <i>Maha</i> and drought <i>Yala</i> rainfall
September	0.05	0.25	0.25	0.05	0.07	0.07	0.05
October	0.15	0.26	0.26	0.15	0.00	0.00	0.15
November	0.28	0.27	0.27	0.28	0.00	0.00	0.28
December	0.37	0.60	0.60	0.37	0.00	0.00	0.37
January	0.27	0.13	0.13	0.27	0.01	0.01	0.27
February	0.18	0.01	0.01	0.18	0.02	0.02	0.18
March	0.09	0.07	0.09	0.07	0.01	0.09	0.01
April	0.07	0.18	0.07	0.18	0.12	0.07	0.12
May	0.05	0.45	0.05	0.45	0.03	0.05	0.03
June	0.02	0.02	0.02	0.02	0.00	0.02	0.00
July	0.04	0.00	0.04	0.00	0.02	0.04	0.02
August	0.05	0.03	0.05	0.03	0.00	0.05	0.00
Total	1.62	2.27	1.84	2.05	0.28	0.42	1.48

Mahailluppallama weather station (1976–2019).

TABLE 6 Labor usage of tobacco, maize, and green chili (Man days/season).

Labor category	Tobacco	Maize	Green chili
Hired	100	35	100
Family	100	41	108
Total	200	76	208
Data source	Arunathilake and Opatha (2003)	Department of Agriculture (2021), Cost of cultivation bulletins	

Computation of the extent of environmental degradation

The extent of environmental degradation associated with different crop plans was evaluated using estimations of soil loss and nitrate leaching for each crop mix. According to Mapa et al. (2007), the lowlands of the dry zone consist of Low Humic Glay (LHG) and Reddish Brown Earth (RBE) soils. According to the data, 70.5% of the available lands for cultivation in the Mahakanumulla VTCS are lowlands. Soil loss was estimated using published soil loss estimations by various scientific studies (Table 9). The nitrate leaching amount was calculated using estimates from Kanthilanka (2022). Nitrate leaching at the field level for rice and maize during the *Yala* and *Maha* seasons for the varied rate of N application in LHG poorly-drained soil is as follows.

$$\text{Nitrate leaching of poorly} - \text{drained LHG soil in Maha season} = 21 * \exp^{0.005 * N \text{ rate}}$$

TABLE 7 Monthly CWR of tobacco, maize, and green chili (m³/month).

Cultivation season	Month	Tobacco	Maize	Green chili
<i>Maha</i>	September	–	–	–
	October	754	733	627
	November	1,020	1,282	1,032
	December	1,062	1,850	1,132
	January	495	1,740	425
	February	–	58	–
<i>Yala</i>	March	–	0	–
	April	721	702	651
	May	1,251	1,570	1,300
	June	1,390	2,470	1,472
	July	869	2,600	651
	August	–	655	–

Authors' calculations.

$$\text{Nitrate leaching of poorly} - \text{drained LHG soil in Yala season} = 12 * \exp^{0.006 * N \text{ rate}}$$

Nitrate leaching and soil loss were calculated for each sub-division and summed up to obtain the entire system's environmental degradation (Table 9).

TABLE 8 Crop budgets of tobacco, maize, and green chili in an average season.

Variable	Units	Tobacco		Maize		Green chili	
		<i>Yala</i>	<i>Maha</i>	<i>Yala</i>	<i>Maha</i>	<i>Yala</i>	<i>Maha</i>
Average yield	kg/ha	20,000	20,000	7,000	7,000	10,200	10,000
Producer price	LKR/kg	36	36	60	60	214	214
Total revenue	LKR/ha	720,000	720,000	420,000	420,000	2,182,800	2,140,000
Cost of production	LKR/ha	385,000	385,000	158,047	158,047	1,182,800	1,290,000
Profits (including imputed cost)	LKR/ha	335,000	335,000	261,953	261,953	1,000,000	850,000

Authors' calculations.

TABLE 9 Summary of the environmental sustainability calculation.

	Parameter	Paddy	Maize	Vegetable	Green chili	Tobacco	Data source
Soil loss estimation	Soil loss per ha (tons)	5	10	10	10	75	Krishnarajah, 1982
Nitrate Leaching	Urea usage (kg/ha) YaraMila fertilizer for tobacco (Kg/ha)	228	311	226	368	600	DOA
	N% in Fertilizer	46%				12%	DOA
	Estimated N rate (kg/ha)	105	143	104	169	72	Author calculation
	Nitrate leaching in <i>Maha</i> (kg/ha)	35	78	67	49	30	Author calculation based on Kanthilanka (2022)
	Nitrate leaching in <i>Yala</i> (kg/ha)	23	71	54	33	18	

TABLE 10 Profitability and extents of crop mix under the baseline scenario.

Sub-Division	Profit (LKR Million)	<i>Maha</i> (ha)			<i>Yala</i> (ha)		
		Rice	Maize	Vegetable	Rice	Maize	Vegetable
WS1	20.08	96.92	10.12	12.73	80.94	4.05	5.43
WS2	17.51	101.17	26.31	8.91	20.23	1.21	5.97
WS3	12.46	97.21	2.50	0.88	39.54	0.76	1.49
WS 4	12.95	89.44	4.05	5.09	40.47	2.02	1.19
WS 5	19.16	141.64	14.16	11.11	30.35	0.40	3.90
WS 6	28.54	153.78	32.38	29.45	30.35	4.05	17.02
VTCS	110.71	680.16	89.52	68.17	241.88	12.49	35.00

Authors' calculations.

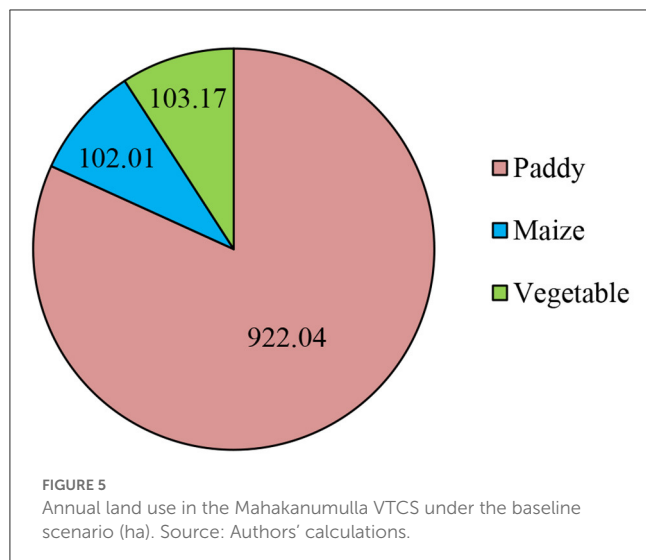
Results and discussion

The baseline model was calibrated drawing on cultivation data for the 2018–2019 *Maha* and 2019 *Yala* seasons. During these two seasons, the Mahakanumulla VTCS received a total annual rainfall of 1.63 m. This was a good year, compared with the average rainfall for the years 1979–2019. According to records from the Mahailuppallama weather station, the average rainfall during this period was 1.4 m, with a 0.3 standard deviation.

Table 10 shows the results of the profitability and decision variables of the six sub-divisions. The total profitability of the entire cascade system was derived from the profitability value of the six sub-systems. Profitability was determined by the amount of water, lowlands, and highlands and the number of person-days available for agriculture activity in each subsystem.

As indicated earlier, the 2018–19 *Maha* and 2019 *Yala* seasons show the baseline scenario, and this is a year with average rainfall. In such an year, the cascade has earned around LKR 111 million in annual profit through cultivating 922 ha of lowlands and 205 ha of highlands. Figure 5 depicts the annual land use of the three major crops cultivated in the Mahakanumulla VTCS, as shown by the above results, in a year where average rainfall and lowlands are utilized thoroughly during the *Maha* season in each sub-division. However, the entire lowland area is not cultivated in the *Yala* season due to insufficient water. The same pattern can be seen with the cultivation of the highlands.

The analysis underlines the comparatively low net profits from rice cultivation, despite it being the dominant crop in both seasons. The sub-divisions with the larger lowland areas generate higher profits than the rest. The sub-divisions located near the



Nachchaduwa tank (at the lower end of the VTCS) show higher profitability, compared with sub-divisions at the upper end, due to the high availability of water.

In terms of shadow price, it is clear that irrigation water is a constraint in the upper sub-divisions. Similarly, the profitability of the sub-divisions near the Nachchaduwa tank is limited by the scarcity of land, despite water availability. Therefore, the analysis results highlight irrigation water and land as the key determinants of the optimal crop mix and profitability of the Mahakanumulla VTCS under the current scenario.

The results of the shadow prices in Table 11 show that the eight-monthly water constraints were binding. Both the *Maha* and *Yala* end-season water constraints were binding, which will affect the late growth stages of the crop cycle and ultimately result in lower harvests. The most significant effect was caused by water limitation in February. Water constraints at the end of both seasons directly affected the cultivation of maize in that area.

The possible environmental impact of the current cultivation pattern on the Mahakanumulla cascade is presented by Figures 6, 7. Following Kanthilanka's (2022) equations, given the nature of the dry zone soil and other external factors, the nitrate leaks and soil loss in this LHG-rich system are demonstrated here. Accordingly, about 6,662 tons of soil are removed from the system annually due to cultivation during the regular rainy season and about 34 tons of nitrates are leaked.

Similarly, there is high profitability and environmental damage in the lower section of the cascade. Wickramasinghe et al. (2023) and Kulasinghe and Dharmakeerthi (2022) have supported this finding in the same cascade, indicating that high accumulation of nitrate and phosphate in lower watersheds. Further, this finding supports Bandara et al. (2010) who indicated higher nitrate, PH, and sulfate accumulation at the lower end of the Parana Halmillawa, Navodagama, Sandamal Eliya, Kahagollewa, and Puwarasankulama cascades in the dry zone. Among the baseline crop mix, maize causes the highest nitrate leaching, followed by paddy and vegetables. However, soil loss is comparatively lower in paddy than in the other two crop categories. Thus, the cash crops

TABLE 11 Shadow prices of the baseline scenario.

	Constraint										
	Hired labor (LKR/Man day)	September water (LKR/m ³)	October water (LKR/m ³)	December water (LKR/m ³)	February water (LKR/m ³)	March water (LKR/m ³)	May water (LKR/m ³)	June water (LKR/m ³)	August water (LKR/m ³)	Low land – Maha (LKR/ha)	Upland- Maha (LKR/ha)
WS1	1,200	33.35		3.33	2,559.64	40.36			273.80		
WS2	1,200	25.36	9.57		2,545.03	40.35			273.80		
WS3				43.33	1,999.52	1.47		32.72	176.04	826	
WS4			0.43	43.18	1,998.16		2.25	31.43	175.52		
WS5					1,312.74		2.25	31.43		84,330	120,000
WS6				4.66	2,667.67	40.13			249.34	59,337	

Authors' calculations.

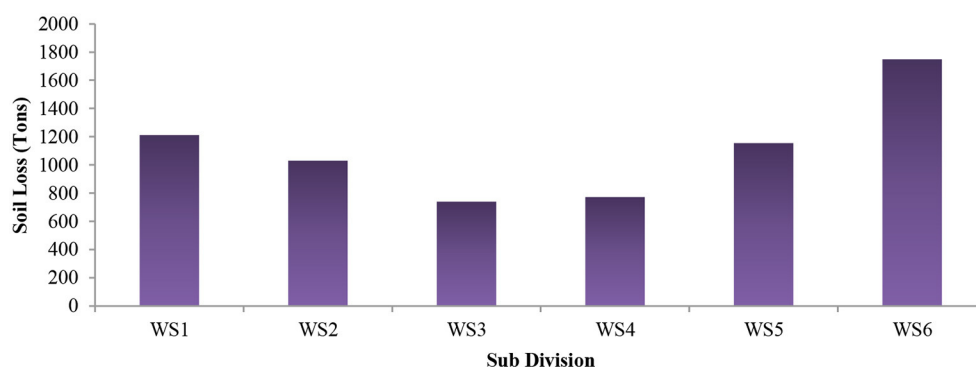


FIGURE 6
Soil loss of each subdivision under the baseline scenario. Source: Authors' calculations.

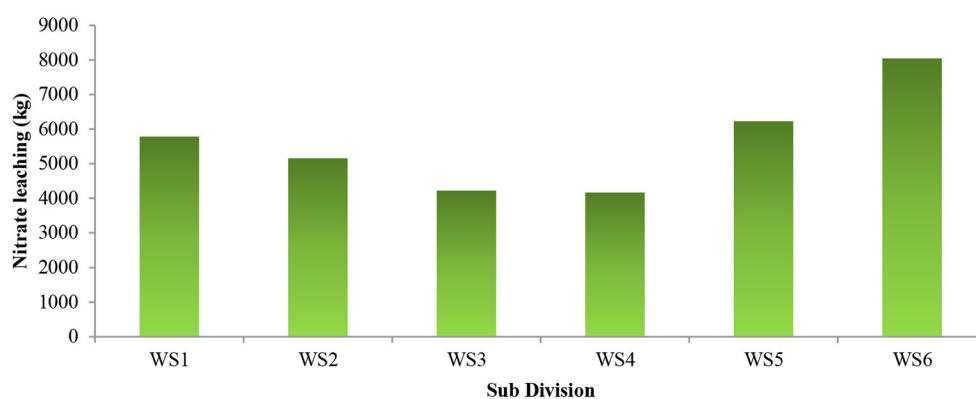


FIGURE 7
Nitrate leaching of each subdivision under the baseline scenario. Source: Authors' calculations.

are more environmentally damaging. As a result, higher profits are always associated with more significant environmental damage.

Effects of climate shocks

The Mahakanumulla cascade system is subject to constant climatic influences. Based on the variation in rainfall over the last century, it showed extreme changes in rainfall. The equilibrium in the baseline was simulated with lower or higher water availability in the cultivation seasons to obtain the equilibrium under each climate scenario. Table 12 presents the profitability of farming in the Mahakanumulla VTCS under a good rainfall year, good *Maha* rainfall, good *Yala* rainfall, *Yala* drought, *Maha* drought, and year-round drought scenarios, respectively. The total profitability of the VTCS was taken using the summation of the profitability under each sub-division scenario.

The rainfall data used for this analysis show that during the worst drought of the last century, the annual rainfall was 82.7% less than the average annual rainfall. Similarly, the highest annual rainfall in the last century shows an increase of 40.1% over the average annual rainfall.

The profitability results of the Mahakanumulla VTCS demonstrate water availability to be the driving factor of the cascade system. Table 12 presents crop cultivation patterns under extreme weather events. Profits resulted in the higher rainfall regimes being higher than average rainfall years. Year-round good rainfall generates the highest return to the cascade. Marques et al. (2005) similarly reported that the reliability of increased water supplies raised the probability of higher crop economic returns.

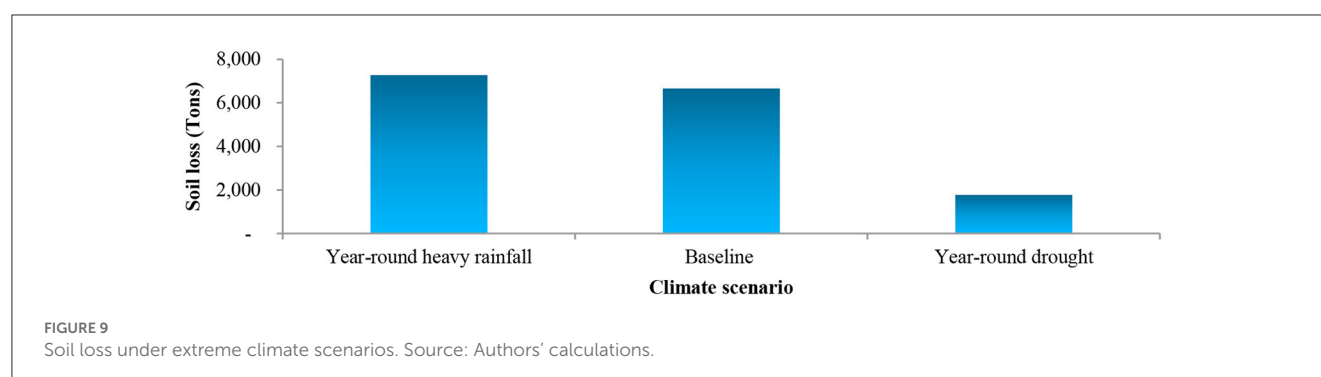
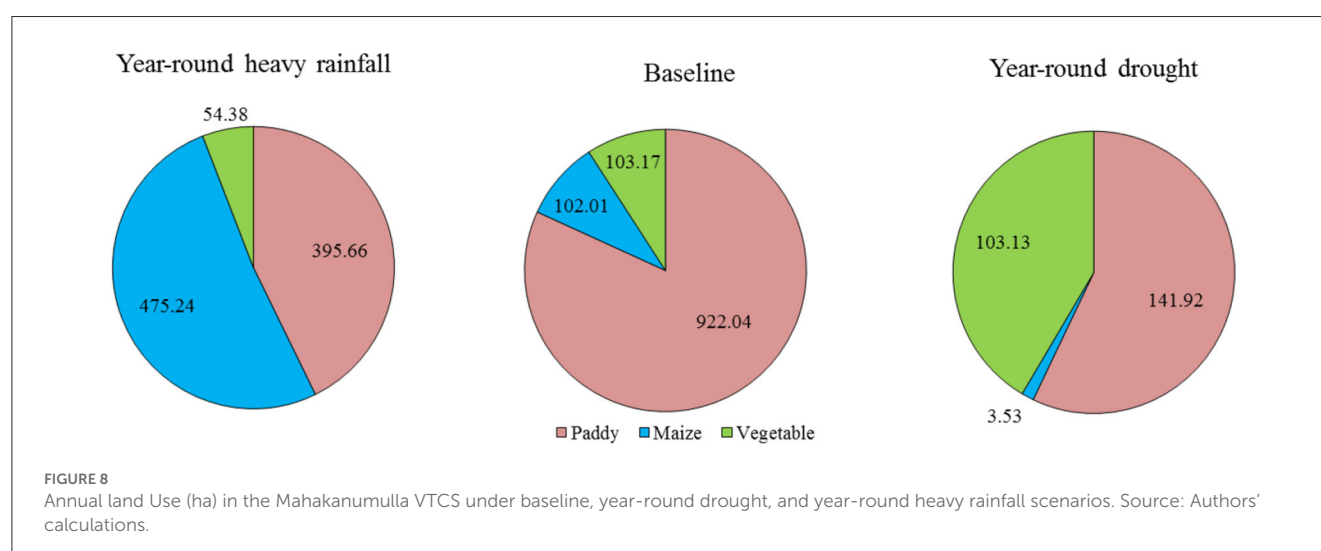
As might be surmised, there were lower profits associated with drought situations than during good rainfall regimes (Table 12). Furthermore, the profit results reflect that drought during the *Maha* season had a higher impact on profitability than in the *Yala* season. The results of each sub-division show that farmers moved on to crops requiring less water than paddy in dry spells. At the same time, smaller extents of land would be cultivated in the *Yala* season due to lower water availability. There is a higher profit during the *Yala* drought than in the other two drought scenarios: the reason is that water scarcity leads to the selection of crops requiring less water, like maize and vegetables, over paddy.

Figure 8 presents the extents of land cultivated annually with the three major crops in the Mahakanumulla VTCS. Culturing high-income generation crops, such as maize, under high water availability resulted in higher returns to the system. 71.4% of

TABLE 12 Total profitability of sub-divisions and VTCS under climate scenarios (LKR million).

Sub division	Year round heavy rainfall	Heavy Maha rainfall and Normal Yala	Normal Maha and Heavy Yala rainfall	Baseline	Normal Maha and Drought Yala rainfall	Drought Maha and Normal Yala rainfall	Year-round drought
WS1	25.35	26.94	19.45	20.08	23.51	13.40	7.49
WS2	20.37	24.43	24.69	17.51	22.32	8.63	2.83
WS3	13.54	14.67	16.63	12.46	14.99	6.13	3.37
WS4	18.08	19.24	21.94	12.95	17.10	8.44	3.53
WS5	20.99	23.11	24.13	19.16	21.35	7.95	2.99
WS6	34.73	40.67	42.38	28.54	39.63	13.87	4.81
VTCS	133.06	149.06	149.22	110.7	138.9	58.42	25.02

Authors' calculations.



highlands were utilized under heavy rainfall, a 51.7% increase compared with the baseline scenario. There is only 13.9% of highland cultivated under a year-round drought scenario. The largest extent of lowland cultivated under the baseline scenario is 62% of the total available lowlands in the VTCS. Annual lowland cultivation will reduce to 26.6% under heavy rainfall conditions and to 9.5% under year-round drought.

The following figures show the environmental damage during the climate scenarios.

As per the calculations of soil loss and nitrate leaching under alternative climate scenarios, the highest soil loss resulted under a heavy rainfall year. According to Figures 9, 10, it is evident that environmental degradation is proportionate to profitability. Drought leads to less soil loss than the baseline. Figure 10 shows that nitrate leaching is high in the baseline scenario compared with the heavy rainfall year. Farmers are moving toward maize farming rather than other crop cultivations with heavy rainfall.

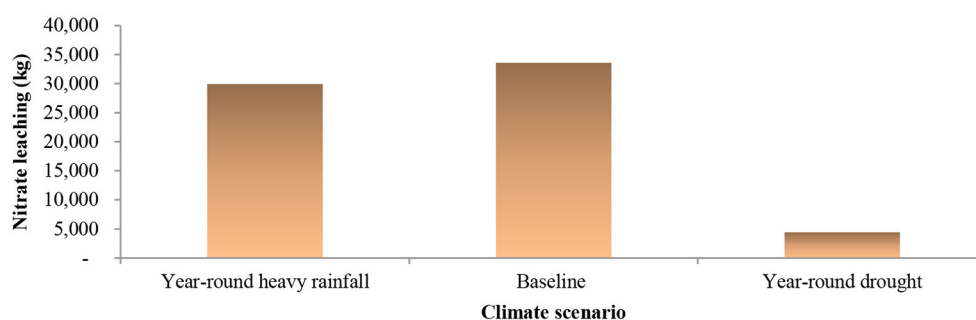


FIGURE 10
Nitrate leaching under extreme climate scenarios. Source: Author's calculations.

TABLE 13 Profitability changes according to various market interventions.

Scenario	Profit (Mn LKR)						
	Year-round heavy rainfall	<i>Maha</i> heavy and normal <i>Yala</i> rainfall	Normal <i>Maha</i> and heavy <i>Yala</i> rainfall	Baseline	<i>Maha</i> drought and normal <i>Yala</i> rainfall	Normal <i>Maha</i> and drought <i>Yala</i> rainfall	Year-round drought
Without market intervention	133.06	149.06	149.22	110.70	138.9	58.42	25.02
Introduction of tobacco to the VTCS	165.23	177.29	178.48	152.12	107.76	163.16	95.06
With a maize buy-back arrangement	284.21	319.37	310.90	141.74	134.43	234.40	26.18
With a chili buy-back arrangement	317.13	320.28	317.13	316.20	269.04	308.93	263.72
With tobacco, maize, and chili buy-back arrangements	389.61	405.67	389.89	332.03	286.71	351.12	264.42

Author's calculations.

Benefits of market interventions under alternative climate scenarios

Dry zone agricultural systems are directly affected by changing political and trade policies. As mentioned earlier, tobacco could invade the crop lands in the dry zone as a commercial crop, and the government suggested introducing maize and green chili buy-back arrangements as potential alternatives for this issue.

The changes in profitability under these market interventions were estimated under several assumptions: the introduction of buy-back arrangements ensuring the availability of inputs for cultivation, certified farm-gate prices and a well-established market for farm outputs. We examined the extent to which market interventions affect the profitability of the Mahakunumulla VTCS under the above conditions. The profitability changes in the Mahakanumulla VTCS under different market interventions and alternative climate scenarios are presented in Table 13.

As shown in the table above, any market intervention can increase the profits reaped in the baseline scenario. The same pattern can be found in all the sub-systems, and similar results can be shown in all climate scenarios. The comparison of profits under alternative market interventions illustrates that annual profits are higher when maize, tobacco, and green chili crops are cultivated simultaneously. Similar results were reported by Chianu et al.

(2009) with reference to soybean farming in Kenya and by Reddy and Suresh (2009) in India with regard to oil seed crops.

Of the three market interventions, chili provides relatively higher returns than the buy-back arrangements for the other two crops, with higher profits in the drought periods when compared with periods of excellent rainfall. According to the results, introducing a cash crop, such as green chillies, into a cascade system would yield the highest returns. However, the other crops of the *Maha* season would not come into the crop mix, farmers would be tempted to cultivate green chillies using all available resources. Green chili cultivation increases the profitability of this VTCS system by about 185% during a regular rainy season.

Introducing maize buy-back arrangements with a well-established market will lead to high profits for the VTCS. However, at that time all crop choices came to the crop mix in VTCS based on the available resources. Accordingly, the increase in the profitability from introducing maize buy-back cultivation during an average rainfall period is 28%.

Tobacco also shows a similar pattern, suggesting that buy-back arrangements would be profitable in each climate scenario. This would enable farmers to cultivate under less water availability. However, while tobacco yields higher economic returns than maize during the baseline year, maize yields higher economic returns under extreme climatic conditions.

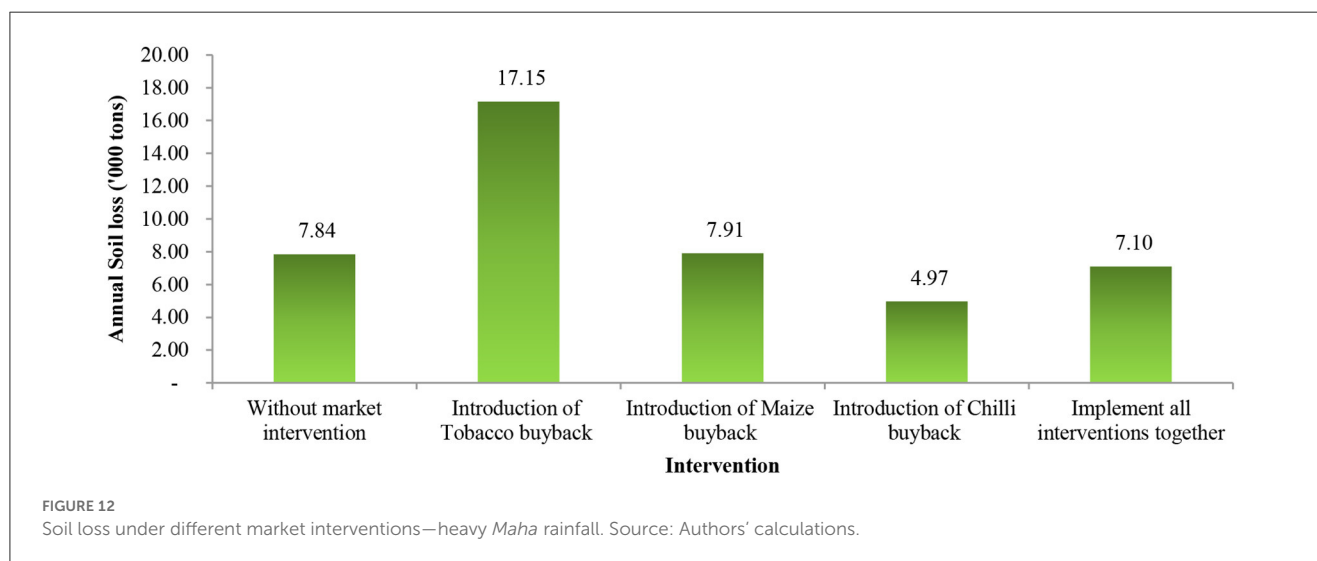
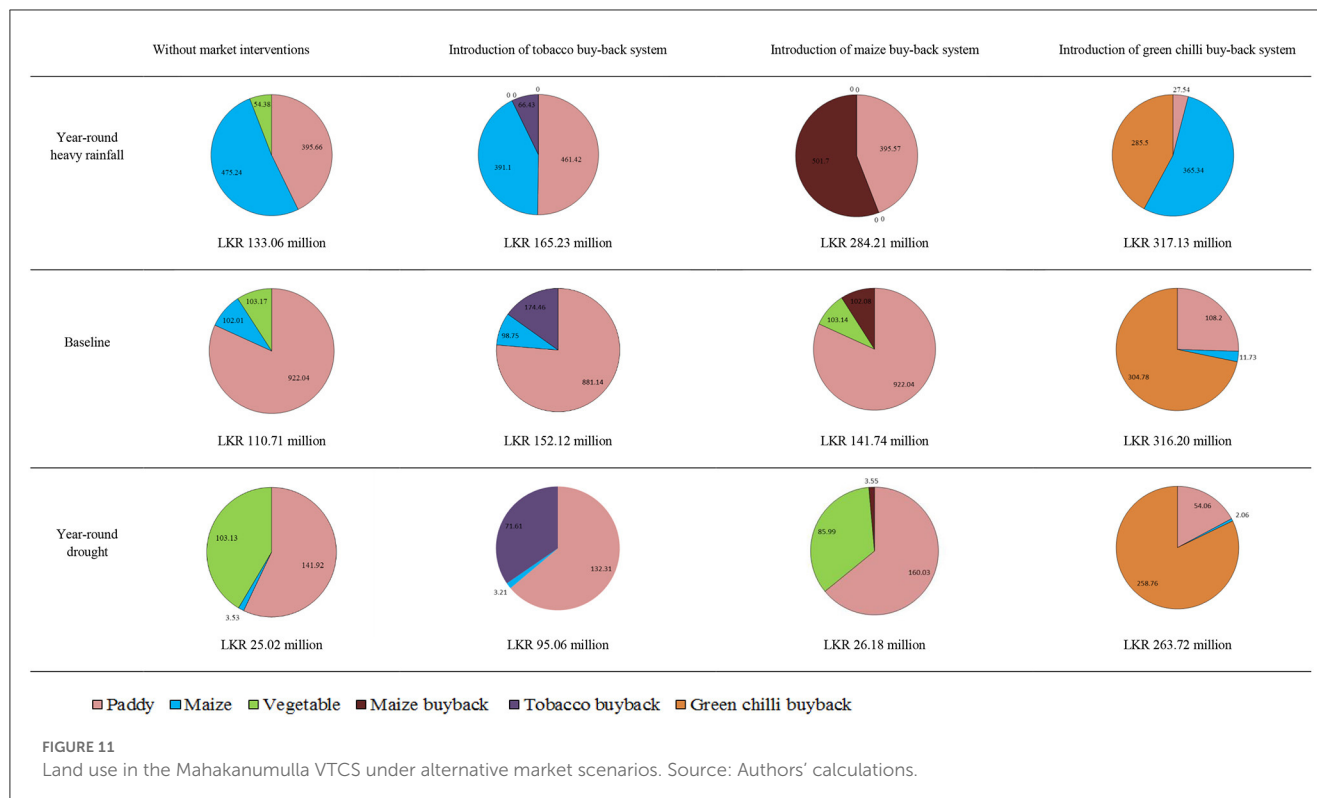


Figure 11 summarizes land use under alternative climate and market interventions. According to the results, paddy cultivation accounts for the most annual use of land in the VTCS, except when green chili is grown. But when maize buy-back arrangements are introduced under heavy rainfall years, then maize dominates up to 22.5% of total available lands. As shown in Figure 11 tobacco becomes more dominant in land use under droughts than in the other two climate scenarios. Even though the introduction of green chili dominates annual land use in all three climate scenarios, the greatest extent resulted under the baseline scenario. However, under the above market interventions, dry zone vegetables no longer enter the annual land use pattern.

According to the results of the soil loss and nitrate leaching calculations, introducing green chili is the most environmentally sustainable intervention under a good *Maha* rainfall scenario (Figures 12, 13). Also, Figure 12 shows that tobacco cultivation causes very high soil losses. Similar findings were reported by Thomaz and Antoneli (2022) in southern Brazil. However, nitrate leaching and soil losses due to market interventions other than tobacco are lesser or similar to losses under the current crop pattern. These trends have been observed in every climate scenario.

The results of the simulations revealed that green chili and maize buy-back systems are possible alternative crops for tobacco.

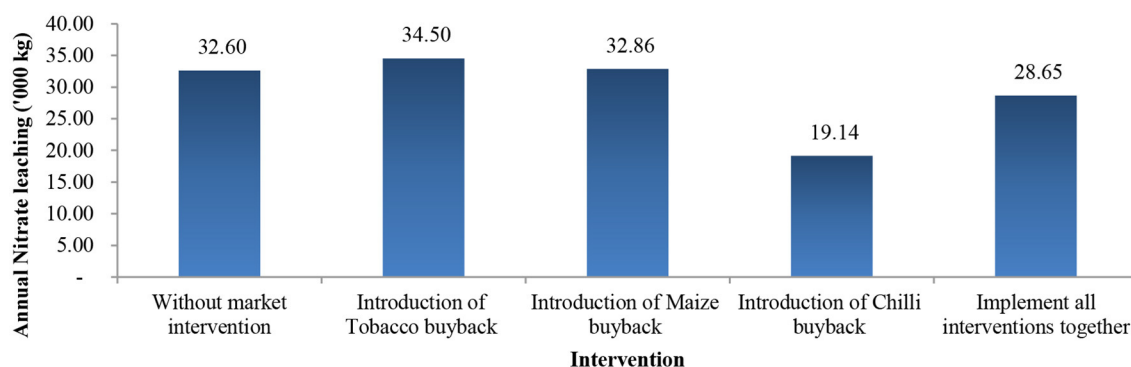


FIGURE 13

Nitrate leaching under different market interventions—heavy *Maha* rainfall. Source: Authors' calculations.

With green chili crops present, tobacco will not enter the system under the climate scenarios examined in this study.

Summary and conclusion

In light of the key findings of the simulation exercises, several conclusions may be drawn. The results demonstrate irrigation water to be the key determinant of the optimal crop mix and, hence, the profitability of farming in the Mahakanumulla VTCS. Therefore, drought conditions lead to severe economic losses in this system, with year-round and seasonal droughts having the most significant impact. Water availability at the mid-stage is the most binding, resulting in a drastic reduction in crop cultivation in this area.

The following policy recommendations are proposed based on the conclusions of this study.

- I. *Develop drought risk profiles at the national level to capture risk and assess damage.* Dry zone VTCSs face drought shocks which lead to drastic profit losses and food insecurity. The introduction of possible alternatives to mitigate profit losses, along with identified damages, is a viable solution.
- II. *Introduce buy-back market arrangements to the VTCSs.* Resources can be used to maximum potential and profitability restored under extreme climate scenarios by introducing buy-back arrangements for maize and chili.
- III. *Discourage tobacco cultivation and introduce alternative crops.* Though tobacco generates relatively high profits in cascade systems, it also causes tremendous soil loss and nitrate leaching compared with other alternatives.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

DD, JW, and SW designed the model and the computational framework and analyzed the data and carried out the implementation. DD performed the calculations and wrote the manuscript with input from other two authors. JW and SW conceived the study and were in charge of overall direction and planning. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

TABLE 1 Model tableau for the baseline scenario (WS3).

Resource use coefficients of the constraint										
Constraints ^a		<i>Maha</i>			<i>Yala</i>				Resource Limits	
		Paddy	Maize	Vegetables	Paddy	Maize	Vegetable		Value	Units
Labor	Hired Labor	13	35	100	13	35	100	<=	6000	Mandays
	Family Labor	20	41	145	20	41	145	<=	9000	Mandays
Water	September	1,121						<=	181,626	m ³
	October	1,549	440	627				<=	254,479	m ³
	November	1,203	769	1,032				<=	200,783	m ³
	December	1,156	1,110	1,800				<=	196,577	m ³
	January	1,027	1,044	425				<=	171,891	m ³
	February		35					<=	145	m ³
	March				1,022			<=	67,337	m ³
	April				1,628	421	591	<=	110,268	m ³
	May				1,532	942	1,262	<=	107,401	m ³
	June				1,500	1,482	2,200	<=	109,884	m ³
	July				1,625	1,560	759	<=	112,332	m ³
	August					393		<=	326	m ³
Land	Lowland - <i>Maha</i>	1	0	0				<=	97.21	ha
	Highland - <i>Maha</i>	0	1	1				<=	18.21	ha
	Lowland - <i>Yala</i>				1	0	0	<=	97.21	ha
	Highland - <i>Yala</i>				0	1	1	<=	18.21	ha

^aUnits of constraint co-efficient for labor is mandays/ha and for water is m³/ha.



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Overcoming the efficiency paradigm—The challenges of introducing local organic beef in canteens

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Introduction: In recent years, there has been a growing recognition that public canteens can play an important role in supporting the transformation toward sustainable food systems and providing access to sustainable and healthy food for everybody—including the most vulnerable groups of the population. One important way in which canteens can contribute to this transformation is by increasing the share of organic and local products. These new political and public demands contrast with the organizational development of canteens over the past few decades, which has mainly been characterized by an increase in economic efficiency and a reduction in costs. Based on a project that was carried out in the Berlin-Brandenburg region (Germany), this paper exemplifies some of the challenges canteens face in the process of introducing organic and local products.

Methods: The empirical results are based on 31 qualitative interviews with canteen managers and kitchen staff as well as with the processing company involved. In addition, a survey of 500 canteen guests was conducted in the participating canteens.

Results: The analysis shows that the canteens had to adapt various organizational practices to ensure a healthy and sustainable diet at manageable cost. Introducing local organic beef in the canteens requires close cooperation with local farmers and processors, a change in procurement practices, transparency around the origin of the products, as well as adapted menu planning.

Discussion: Based on the empirical results, the paper discusses how these challenges can be met and which supportive measures can be taken on different governance levels. To change entrenched practices, process facilitators who support local cooperation along the value added chain are needed, and practical knowledge and professional training must be provided. The article concludes that there is a great potential to foster a sustainable and healthy diet via public and private canteens if the tension between efficiency and sustainability orientation can be overcome by adapting framework conditions.

KEYWORDS

canteens, public procurement, local products, kitchen management, public catering, efficiency paradigm, sustainability transformation, organic beef

1. Introduction

Since the beginning of the 2000s, public food procurement and catering have gained recognition for their potential to enhance the transformation toward a sustainable food system (Lehtinen, 2012; Ashe and Sonnino, 2013; Smith et al., 2016). There is a growing awareness that purchasing decisions can promote a healthier food system (Marsden and Morley, 2014) and contribute to issues of public health, economic development, democracy

and environmental integration (Morgan and Sonnino, 2013). Other authors stress the high potential for health prevention due to the fact that (public) canteens can reach a great diversity of people with different socio-economic and cultural backgrounds (Pfefferle et al., 2021).

Yet, as Sonnino (2019, p. 21) states, this “multifunctional potential of public food procurement has often been overlooked due to a priority generally placed on short-term cost saving and economic efficiency in public institutions [...]” In recent decades, (public) canteens have taken on the challenge of increasing economic efficiency and reducing costs that has accompanied the economization of public services in general (Ewert, 2009). This development has taken place in parallel with rationalization, specialization and concentration processes in agriculture and food processing (Marsden, 2012; Tregear et al., 2022).

The pressure to reduce costs has resulted in modified organizational practices throughout the entire process of menu planning, food processing and product procurement (Göbel et al., 2017).

Procurement departments usually aim for cooperation with a few nationally or internationally oriented suppliers who are able to offer a broad product assortment all year round (Roehl and Strassner, 2011; Lopez et al., 2019). The concentration on a few large suppliers reduces the number of administrative tasks and negotiations for the canteens. In addition, institutions with several canteens often bundle their procurement within a central department in order to increase purchasing power, obtain a discount and ensure convenient conditions for claims (Roehl and Strassner, 2011; Fitch and Santo, 2016). At the same time, this development poses a barrier for purchasing products from smaller suppliers or local farmers and processors (Arens-Azevedo, 2012). Furthermore, trans-regionally oriented suppliers rarely offer local products and are often unable to guarantee transparency around the origin of the products (ibid.).

Regarding the types of products used in canteens, a tendency to “outsource” processing can be observed: canteens use more convenience and pre-processed food and ingredients (such as peeled potatoes, pre-cooked vegetables, pre-prepared meat products like burger patties, meat balls, etc. as well as pre-prepared mixtures for sauces, broths, and desserts) (Roehl and Strassner, 2011; Langen et al., 2017). This allows canteen managers to reduce the number of employees and to work with personnel who are not formally trained. At the same time, it makes it easier for them to offer complex and standardized meals. Some authors report a reduction in trained personnel of 30 to 50% and a tendency toward more flexible working conditions, while knowledge and competence around the preparation and processing of food decreases with a lower percentage of trained employees (Rapp and Liesen, 2007; Langen et al., 2017). Besides the reduction in personnel, the limited infrastructure for preparing, processing, and storing food is another reason for the extensive use of convenience products (Steinmeyer, 2018). For meat processing—which is of special interest in this article—this means that only certain parts of the animals are ordered (often in a pre-processed form) and therefore that the skill of using the complete animal “from nose to tail” is largely being eroded (Roehl and Strassner, 2011). This goes hand in hand with the changing preferences of consumers, who are no longer used to eating meals containing offal, such as kidneys or liver (Tucker, 2014).

This article analyses the challenges of canteens in the light of the conflicting demands placed on them, focusing on the barriers canteens face when aiming to introduce more organic and local food into their menus. Specifically, the paper describes the changes in organizational practices in four canteens in the Berlin-Brandenburg region as they transitioned their offer from conventional beef to regionally produced organic beef from pasture-fed animals. After presenting the background to the case study and outlining the structure and approach of the transdisciplinary project (Section 2), we detail the methods applied (Section 3) and present the empirical results (Section 4). The challenges of flexing organizational practices toward providing more sustainable food, and how these challenges can be overcome by adapting framework conditions on different governance levels, are dealt with in the discussion (Section 5).

2. Background to the case study and characteristics of the transdisciplinary research project

The case study on which this paper is based was conducted within a transdisciplinary research project aimed at accompanying the establishment of a local value-added chain in the region Berlin-Brandenburg.¹ To this end, the project team sought to motivate (public) canteens to introduce local, organic, pasture-fed beef into their daily menus and support them in the process of establishing cooperation along the local value-added chain and overcoming any challenges that may arise. Finally, the researchers analyzed the barriers to introducing the innovation and the measures taken by canteens to deal with the difficulties encountered. The following sections give an overview of the background to the case study, the characteristics of the participating organizations, as well as the structure and approaches of the transdisciplinary research project.

2.1. Socio-political background

The study took place in the metropolitan region of Berlin-Brandenburg in north-east Germany. While Berlin is densely populated and has almost no agricultural production, Brandenburg—the federal state that surrounds the German capital—has a low average population density and includes many areas with agricultural production and natural reserves. Due to the low-yielding soils and the high proportion of grassland areas, suckler cow husbandry is of particular importance in north-east Germany (AMI, 2021; Statistik Berlin Brandenburg, 2022). However, a lack of regional infrastructure for slaughtering, processing and logistics, as well as fluctuating market prices, are leading farmers to sell

1 The project GanzTierStark was funded from 2020 to 2023 by the Federal Ministry of Food and Agriculture as part of the Federal Programme for Organic Agriculture (BÖL). It was managed by the Federal Office for Agriculture and Food (BLE). Further information can be found under www.ganztierstark.de.

the majority of the offspring of suckler cows to fattening farms in other regions of Germany or Europe (Baumgarten, 2020). Despite good agricultural conditions for pasture grazing, there is therefore low availability of local meat products in the German capital region.

By contrast, locally produced food and species-appropriate husbandry have become increasingly important issues for both consumers and policy makers in recent years. Urban food policies as well as objectives at federal state or national level aim to promote a more sustainable diet for people and the environment (Doernberg et al., 2019). Especially in Berlin, but also increasingly in the state of Brandenburg, public canteens are politically incentivised to raise the share of organic and local products they use, while being, at the same time, subject to the demands of economic efficiency described above.

2.2. Description of the participating organizations

As part of the transdisciplinary research project, cooperation between four public and private canteens, a local medium-sized processor and local farmers was established. This section characterizes the organizations involved.

2.2.1. Canteens in Berlin and Brandenburg

The project aimed to reach canteens with different characteristics in terms of size, organizational form and target canteen guests. Table 1 gives an overview of the central characteristics of the four canteens involved in the project.

During the lockdown in the COVID-19 crisis, the canteens were completely closed for some of the time, or only offered takeaway meals. In contrast to pre-pandemic times, the canteens were mostly closed to external guests. The number of guests thus decreased drastically in that period and has generally not recovered since then (due to a higher percentage of people who work from home).

2.2.2. Local processing company

In addition to the canteens, a local meat processor took part in the project. With around 60 employees, the company is the biggest meat processor for organic beef in the region and mainly procures meat from Brandenburg and the surrounding federal states. It sells most of the meat and processed meat products (e.g., sausages, beef patties) *via* an organic supermarket chain. The cooperation with the canteens established in the course of the research project was developed as a second marketing channel. Due to the various marketing channels of the processor and the possibility of using leftovers for sausage production, it was not necessary for the canteens to use all parts of the animals “from nose to tail.”

The processing company purchases the organic pasture-fed beef from a range of smaller and bigger organic farms in Brandenburg and the surrounding federal states.

TABLE 1 Characteristics of the participating canteens.

Type of canteen	Characteristics (as of 2022)
Canteen 1: Public University	<ul style="list-style-type: none"> • Catering for university students and employees at 6 locations, • Altogether 2,000 meals/day, • Central procurement and meal planning for all locations, • Introduction of organic meat is embedded in a new sustainability strategy; focus on more vegetarian and vegan dishes, • Current share of organic products: 15% (beef, potatoes, rice, coffee, tea), organic certification, • Meal prices for students are subsidized, • Subject to public procurement rules.
Canteen 2: municipal waste company	<ul style="list-style-type: none"> • Catering for employees in 10 locations, • Altogether around 1,250 meals/day, • Central procurement and meal planning for all locations, • Canteen guests with different professional foci (administration vs. waste collection) and significant age differences, • Current share of organic products: 39% (beef, vegetables, dairy products, eggs), organic certification, • Meal prices are subsidized, • Subject to public procurement rules.
Canteen 3: public hospital	<ul style="list-style-type: none"> • Catering for employees of the hospital, • The canteen belongs to a bigger provider responsible for canteen management at numerous locations; central procurement of food, but canteen managers have leeway to order some of the products on their own, • Altogether approx. 250 meals/day for employees, • A few components in organic quality (beef, yogurt, occasionally milk and vegetables), • Meal prices for employees are subsidized, • No need for public tendering.
Canteen 4: newspaper publisher	<ul style="list-style-type: none"> • Canteen restaurant providing employees of a daily newspaper and external guests with food, • Altogether around 350 meals/day, • Beef of organic quality (not certified yet), other meat and poultry from species-appropriate husbandry, • Meal prices for employees are subsidized and much higher for external guests, • No need for public tendering.

2.3. Structure and approaches of the transdisciplinary research project

The transdisciplinary research project runs from February 2020 to May 2023. Besides two research partners, three intermediate organizations within the organic sector received funding to offer supportive services to the partners within the value-added chain (canteens, processor, and farmers).

The main instrument for knowledge transfer and the exchange of experiences between the canteens consisted in regular “kitchen talks” that focused on a certain topic and motivated the exchange between the participating canteen and kitchen managers. If necessary, there was input from the project team or—more often—pioneering canteen managers from other regions of Germany. They were invited to talk about their experiences of dealing with upcoming challenges, such as higher prices of organic beef, by adapting the menu planning, using different cuts of the beef,

TABLE 2 Interviews carried out from April 2020 to November 2022.

Project partner		Type of interview partner (number of interviews)
Canteens	Public University (canteen 1)	<ul style="list-style-type: none"> • Management/Head of Procurement (4) • Kitchen manager and employees (8)
	Municipal waste management (canteen 2)	<ul style="list-style-type: none"> • Management/Head of Procurement (3) • Kitchen manager and employees (2)
	Public hospital (canteen 3)	<ul style="list-style-type: none"> • Kitchen manager (3)
	Newspaper publisher (canteen 4)	<ul style="list-style-type: none"> • Kitchen manager and employees (8)
Processor	Meat-processing company	<ul style="list-style-type: none"> • Management/Head of Sales (3)

motivating the kitchen staff, dealing with public procurement requirements, etc. In the period between May 2020 and November 2022, nine kitchen talks were organized, focusing on different topics. Due to the COVID-19 crisis, these meetings were usually conducted online. In 2021, it was possible to meet in person in one of the canteens and exchange experiences as well as have a meal together.

In addition to the “kitchen talks,” the project offered support by designing communication material and public relations strategies as well as coaching related to public procurement regulation, organic certification, and menu planning. It also organized two workshops for the kitchen employees that provided information on the special qualities of organic meat and the characteristics of pasture-raised, animal-friendly husbandry. In these workshops, illustrative material such as a video interview with a local organic farmer was used. One additional workshop for the kitchen staff dealt with the basics of healthy nutrition and the techniques of how to present the food on the plate. Between 2020 and 2022, two excursions to local organic farms and three excursions to the local processing enterprise were organized for canteen management and kitchen staff. During these excursions, the participants also tasted meat products. The project team went into the canteens on several occasions, providing information to the canteen guests on the new offer, the origin of the organic meat, and the project itself, as well as carrying out a guest survey. On these occasions, posters with information on the project and a map displaying the participating farms were presented.

Parallel to offering these different forms of support to the business partners involved, the project encompassed accompanying research, the material and methods of which are described in the next section.

3. Material and methods

The empirical data were derived from the transdisciplinary research process covering the period from April 2020 to November 2022.

At the beginning of the project, a participatory monitoring plan was developed based on literature research, best-practice interviews and a workshop with the respective case study actors. The monitoring plan included regular interviews and data collection

about the progress and challenges of the transformation process. To be able to trace the organizational changes, information on the status quo in the respective canteens was collected first, and the interviews were repeated every 8–12 months. The semi-structured interviews (Schnell et al., 2013) of approximately 1 h focused on the adaptation strategies of the canteen kitchens in the process of introducing local organic beef into their meal planning.

Based on the monitoring criteria, the following topics were covered during the interviews (see interview guidelines, [Supplementary material 1, 2](#)):

- Development in numbers of meals and guests.
- Involvement of employees in the implementation process; feedback of kitchen staff.
- Satisfaction with the quality of the meat and the cooperation between the kitchen and the local processor.
- Learning processes and opportunities for optimization in the areas of procurement, meal planning, employee involvement and guest communication.

Empirical data for the case study were obtained from $n = 28$ qualitative interviews with the canteen managers and kitchen staff of four canteens in Berlin and Brandenburg as well as from $n = 3$ interviews with the meat-processing company (see [Table 2](#)).

Additionally, data from participatory observation of different workshops (especially the kitchen talks) was included. These workshops allowed us to observe mutual learning processes between the participants from a scientific perspective. At the end of the workshops, the participants were asked to fill out an anonymous digital evaluation sheet. Empirical data (interview transcripts, protocols from workshops and documentation of multilateral exchange) were analyzed *via* content analysis, using the categories of the monitoring concept.

In addition, guest surveys were conducted in the participating canteens with a total of 500 guests. The guest survey addressed the following topics (see questionnaire, [Supplementary material 3](#)):

- Frequency of canteen visits.
- Satisfaction with the beef dishes on offer and the menu in general.
- Preferences regarding the quality and origin of the beef served.
- Attitude toward the use of organic and local products in the canteen.

The data from the guest survey were analyzed using SPSS Statistics.

The results of the monitoring and the guest survey were used to give regular feedback to the cooperating canteens and the processor for the purposes of organizational optimization, improving both the menus on offer, and communication with kitchen staff and canteen guests. They were also used for public relations and publications in practice-oriented as well as scientific media.

4. Results

The results section deals with the challenges the canteen managers faced when introducing local, organic, pasture-fed beef. It begins with the changes in procurement practices,

encompassing also the issue of building trust between the partners along the value-added chain and including local products in public tender procedures (4.1). Section 4.2 deals with the challenge of guaranteeing the local origin of the products and transparent communication processes, followed by Section 4.3, which encompasses changes in meal planning as well as the reaction of the canteen guests to those changes.

To start with a general observation, in most of the canteens the introduction of local organic beef was embedded in an overarching strategic process of responding to political and public demands for an increased contribution to preventive health provision and climate protection goals. When the project team offered to work with the canteens, they therefore took the opportunity to acquire support in an already ongoing process and to overcome the initial barriers of the intended transformation process.

“Since the strategy of our company is focused on sustainability, climate and environmental protection, it is logical that sustainability and healthy nutrition are also of great importance in catering for our guests.” (management of canteen 2)

4.1. Change in procurement processes and public tender procedures

4.1.1. Changing procurement processes

Before the project's work with the canteens, they purchased beef together with other products from trans-regional suppliers. Only one of the canteens was cooperating with a local meat processor for conventionally produced meat. From the canteens' point of view, the advantages of buying food from a nationwide wholesale company are that the purchasing process is quick and easy, and products for the needs of canteen kitchens are available at any time and at favorable prices. The interviewees confirmed scientific literature findings that large suppliers operating nationwide are generally not able to provide products with a guaranteed local origin (Arens-Azevedo, 2012). One of the main barriers to increasing the share of local (and organic) products therefore is that additional suppliers have to be found and contacted. As also described in the literature (ibid.), the canteen managers were very willing to increase the share of local organic products, but they did not have detailed knowledge about who could supply them with the quality and quantities they needed. Integrating those deliveries of rather small quantities in the daily procurement processes is another time-consuming challenge for the canteen managers.

4.1.2. Building trust and learning processes between canteens and local suppliers

As pointed out by the canteen managers, the external support provided by the project, which included information on possible local suppliers and bringing actors together, was very helpful for them in overcoming initial barriers and taking the first steps.

“It was a very good combination of participants—a consultant with a lot of experience on the topic, speakers from the field, and interested canteens facing the same challenges.” (comment by a participating canteen manager in the anonymous evaluation after the kitchen talk on 9 July 2020)

As described above, the organization of visits to farms with pasture-fed husbandry and to the local organic processor was another important element in providing practical knowledge. The possibility of getting to know the living conditions of the pasture-reared cattle and the motivations and efforts of the farmers led to an increase in trust and emotional attachment. Also, getting to know the manufacturing procedures in the processing enterprise and having the opportunity to taste different products helped to build trust, which played a part in convincing the decision-makers of the quality of the pasture-raised beef. The enhanced knowledge about the differences between conventional stall-feeding and organic pasture-reared husbandry enabled partners to find compromises on the pricing of the high-quality beef.

After reaching agreements on products, quantities, prices and delivery dates between canteens and the processing company, the implementation was tested in the canteens. The local supplier had to meet the requirements of the canteens in terms of product quality and customer orientation. Likewise, canteens had to learn that not all the products would be available every day in a local value chain, and that orders must be placed in advance.

“Of course, there are also things that are not available [...], but we are talking about food that also has a special background [...]. And I accept that not everything is always available somewhere.” (kitchen manager of canteen 1)

4.1.3. Including local products in public tenders

Following the decision to purchase local organic beef on a regular basis, the public canteens had to initiate an official invitation for a public tender process. Due to EU regulation, the local origin of products cannot be mentioned as a quality criterion in public tenders—this is to avoid distortion of competition. EU procurement regulation shows a strong focus on economic parameters such as the price, and does not take characteristics such as ecological, social and health criteria sufficiently into account. With Green Public Procurement, the EU has created a voluntary tool which allows public authorities to demand more sustainable goods and services. However, especially when it comes to the procurement of food and catering services, public authorities rarely include any “green” criteria in public tenders (Renda et al., 2012; Haack et al., 2016). One reason is that sustainability criteria are seen as difficult to implement correctly, and contracting authorities fear the legal uncertainty (Schebesta, 2018).

To give smaller regional suppliers the chance to apply for the tender, the procurement managers were coached on how additional qualities could be included. Interesting differences could be observed: in one of the bigger public companies the procurement department was not involved in the project before dealing with setting up the tender; in the other one it was involved at a very early stage. In the first case, it was much more difficult to

convince the person responsible in the procurement department to include further quality criteria in the tender (e.g., a distance that would allow staff to visit the site easily). Another challenge was to implement the formal requirements for the tender (e.g., submission deadlines, indication of references) as well as other content-related requirements (e.g., minimum order quantities, delivery days) in such a way that the effort required to submit the offer is feasible for smaller local suppliers. One of the canteen managers stresses that small and medium-sized enterprises need support to be able to compete with bigger suppliers in those tender processes.

“There is the need to make enterprises fit, also from the political side, to ensure a certain fairness. The whole tender process is about competition... – and the competition is distorted for the small and medium-sized enterprises, since right now they don’t have the possibility of keeping up with the bigger players.”
(manager of canteen 1)

4.2. Guaranteeing the local origin of the beef and transparent communication

One of the challenges of the project was to define “locally produced” and to ensure transparency around the origin of the organic beef for canteens and guests. So far, there is no consensus on the definition of “local origin” in Germany or throughout the EU. The EU quality policy concentrates on specific product qualities that are linked to geographical origin, a product’s traditional character or organic production method (Becker, 2009; Verbeke, 2013). In some German federal states, labels for local products which refer to the boundaries of the respective federal state have been introduced over the past two decades. These labels combine the indication of origin from a specific region with a defined quality (Hauck and Becker, 2015). In these cases, certifications and external controls are needed in order to ensure the defined quality criteria for “locally produced products” are respected. In the region of Berlin-Brandenburg, there was no such legal framework or best-practice example of a definition that the project could directly refer to for the purpose of providing canteens with local organic beef.

4.2.1. Finding a suitable definition

As mentioned in Section 2.1, the production of beef in north-east Germany is characterized by very low slaughtering capacities, especially for organic beef. At present, Brandenburg does not provide a medium-range slaughter for organic beef, but only some small-scale capacities aligned to single farms. The participating meat processor therefore only has the option of cooperating with slaughterhouses in one of the neighboring federal states, Mecklenburg-Western Pomerania or Saxony-Anhalt. To be able to guarantee continuous supply of beef from pasture-reared husbandry, the processor also purchases beef from farmers in the neighboring federal states. Beef is a special case, since increase or decrease in production has to be planned a rather long time ahead due to the 2-year period that is needed to rear the animals.

After some chaired discussions about the expectations of the canteen managers and the practical necessities of the processing

company, the project partners agreed on a definition of “locally produced” as a radius of 200 km around the Berlin television tower. This is a definition that is easy to communicate and can also be monitored effectively on an internal level. It was also agreed that the processor would inform the canteens 1 week before delivery which specific farm the beef would be coming from. This allows the canteen managers to forward the information to the kitchen staff, who can communicate it to the canteen guests. It took quite some time to establish these routines of transparent flows of information, since neither partner was used to it. Internal monitoring of the supplier farms showed that the definition was met in 96% of the cases. Only in exceptional cases—when the availability was limited—did the beef come from farms beyond the 200 km radius.

4.2.2. Communication with canteen guests

The definition was communicated to the canteen guests via a map on the project’s website, on a poster, and via leaflets on special occasions when information was presented in the canteens and a survey was being conducted. The questionnaire also included a question about the guests’ preferential definition of regional origin. In addition to “Brandenburg” as a boundary for local origin, “Brandenburg and the neighboring federal states” and “a radius of 200 km” had a high level of acceptance among the respondents.

4.3. Adaptation of meal planning and reactions of the canteen guests

The canteen managers had to meet the challenge of higher prices for purchasing local organic beef. The additional costs for the purchase of local organic beef were between 30 and 100%, depending on the cut (e.g., minced meat, goulash) and the comparative offer (conventional fresh/frozen meat from national/international production from wholesalers/local butchers). The additional costs per meal, e.g., for a goulash dish, would thus amount to about 1 Euro per meal (assuming a 100% increase in the purchase price of beef and an average meat weight of 155 grams).

4.3.1. Strategies for compensating additional costs

All partner canteens had to consider restrictions on their ability to raise prices for regular meals, as these are subsidized with the goal of providing food at low cost for employees and students. Canteen managements pursued different strategies in their attempt to offer high-quality meat under the given economic restrictions. Overall, three strategies were observed, which were also used in various combinations: (1) reducing the number of meat dishes per week, (2) reducing meat content per dish, and (3) using more economic cuts.

In one of the canteens the weekly number of meals with meat was reduced and new recipes were introduced which included lower quantities of meat. Dishes such as “Asian ragout” or “Summer bowl” contained a higher percentage of vegetables and less meat (80 g) than more meat-based dishes such as a traditional goulash

(160 g). In addition, these traditional dishes were modified by replacing parts of the meat with vegetables, legumes or cereals.

“Such dishes [with a reduced] amount of meat are interesting for canteens when they are introducing organic meat into the menu planning. You don’t have to have 100% meat on the plate—it’s substituted with eggs and breadcrumbs. We even put small cubes of root vegetables in. [...] This is how you reduce the costs and make it possible to sell the meal at a reasonable price.” (kitchen manager of canteen 4)

Another canteen whose guests were used to rather high quantities of meat maintained those quantities but experimented with more economic cuts and increased the price of the beef meals moderately. Purchasing the more economic parts of the animal and changing recipes was a useful strategy for all partner canteens. To reduce the purchasing prices, canteens also ordered fresh meat instead of convenience food (e.g., pre-breaded escalope or ready-to-cook meatballs) as they did before.

In addition to the three strategies found to be applied in the case-study canteens, another approach that—according to the experience of nationwide canteens—has economic and ecological advantages consists in using the whole animal from “nose-to-tail.” The aim is to utilize as many parts of the animal as possible, thus reducing costs and food waste. Due to organizational barriers such as a lack of personnel and space, as well as restrictions in menu planning, none of the canteens could be motivated to follow a “nose-to-tail” strategy of using all cuts of the animal. For the menu planning in canteens, large quantities of a specific cut of the animal are needed. Using different cuts for one dish requires flexibility and additional skills (Tucker, 2014). The approach of planning the menus based on the available ingredients (and not vice versa) seems to be difficult to implement in canteens. However, some of them could be motivated to use cuts they had not used before and offer meals such as liver or tongue. Furthermore, as described in chapter 4.1, the kitchens showed flexibility in menu planning when not all cuts they wanted to order were available.

An exception to these cases of successful implementation was the catering for patients by the hospital canteen. While the kitchen manager succeeded in using local organic beef in the meals for the hospital staff by applying the strategies described, this was not transferable to the catering for hospital patients due to the low food budget for this target group.

4.3.2. Reception by canteen guests and kitchen staff

Most of the new recipes were received very positively by the canteen guests, resulting in a high percentage of meals with beef sold on the respective days. Depending on the canteen and the number of alternative dishes, beef dishes were chosen by an average of 30% of the guests—a similar percentage to that of conventional beef. Only experimental meals such as beef tongue were not as well received by the canteen guests. Overall, the survey amongst the canteen guests showed a very high level of approval for introducing local organic beef from pasture-reared husbandry. Besides “organic” and “local,” “animal welfare” was a very important quality criterion for the guests. The survey also

showed that guests expect the whole meal to be of high quality: they consider fresh and appealing side dishes such as vegetables and potatoes particularly important.

In the first few months, a number of canteen managers reported that some of the kitchen staff were still rather skeptical about introducing local organic beef and worried that there would be low take-up by the canteen guests. In particular, the reduction of meat in the dishes seemed to represent a major change for the kitchen staff.

“I think it is sometimes so unpleasant for our employees, because for years they have put a large portion on the plates and now they are putting a thin slice of roast meat there. It is actually compliant with the principles of the German Association for Nutrition to have 80 grams of meat on the plate and no longer 150 grams. But of course, it is a change and it is unpleasant for some people.” (management of canteen 1)

This example shows that changing societal norms about the composition of meals play an important role in this type of transformation processes. During the project, the kitchen staff became more receptive due to the canteen guests’ positive response (choice of beef meals and feedback in the surveys). The interviews with the kitchen staff also showed that they appreciated cooking with more fresh products and were able to use their creativity and skills. In the interviews, the canteen managers nevertheless emphasize that a single training session or workshop for kitchen staff is not enough. They point out that it is a constant learning process, and it is the responsibility of the canteen management to stay tuned and to further involve their employees in important change processes.

4.3.3. Comparison of the challenges for the canteens

A comparison of the challenges of the four canteens and the ways they chose to overcome these yields some interesting insights. The public canteens were under greater pressure to offer economic meals than the private canteens. In particular, the newspaper company—which is situated in the center of Berlin and has a lot of external guests (including tourists)—was able to compensate the low prices for the employees with rather high prices for the external guests. In the public canteens (the university and a public waste management company), the committees of the employee representatives have to agree to an increase in meal prices. So far, they have had a strong focus on keeping the meal prices as low as possible. The economic pressure on public institutions is especially high in the health sector, which results in very low standard amounts for meals in hospitals. Within the project, the local organic beef therefore could not be offered to the most vulnerable group, the patients of a public hospital, and was served to the hospital employees only.

Introducing local organic beef and meals with a lower percentage of meat was easier in those canteens with younger canteen guests (such as students) and in companies with a clear sustainability focus. It was also easier to convince the staff in smaller organizations than those in bigger companies, who had to invest quite some time in training and motivating the kitchen

staff. The skills of the staff played an important role in maintaining the high quality of the meat during the cooking process. This is more difficult in bigger canteens where the components of the meals have to be prepared some hours before serving them, and are sometimes also transported from a central canteen to smaller locations.

5. Discussion and conclusion

The empirical results exemplarily point out some of the challenges public canteens face when aiming to introduce more local organic products into their daily menus. In this section, we offer some reflections on the transferability of the results (5.1), why the transformation of organizational routines is so difficult (5.2) and which measures can be taken to support it (5.3), as well as more general concluding remarks on why the provision of healthy and sustainable food should be understood as a societal challenge (5.4).

5.1. Transferability of the results

The empirical data are derived from a transdisciplinary research process with four canteens in the metropolitan area of Berlin-Brandenburg. Although the canteens had different characteristics in terms of size, organizational form and the target canteen guests, a broader spectrum would have been useful for obtaining results that would be transferable to a broad range of canteens. Especially in the case of catering for vulnerable target groups (e.g., hospitals, nursing homes), we see a need for further research on how to implement catering with sustainable and healthy food.

The results show the canteens used different strategies to compensate for the additional costs of organic beef, e.g., by implementing changes in the menu planning. At this point, it would be interesting to study to what extent these strategies can also be applied to other types of meat, since, for example, organic pork and chicken have a higher additional price in comparison with products from conventional animal husbandry than is the case with organic beef.

A further possible limitation in the transferability of our results consists in the regional characteristics of the study region. Within the project, the canteens began cooperating with a medium-sized organic processing company that supplies meat from local animal husbandry. Due to the processor's already existing marketing channels, the availability and deliverability of the required quantities and cuts could mostly be guaranteed. The canteens did not have to take the whole animal, as might have been necessary in the case of direct cooperation with a farm or a smaller processor. A “nose-to-tail” approach would have been linked to further implications for the kitchens.

Another aspect requiring further research is the impact on the development of local added value. Due to the small number of canteens in the project and the limited number of meals because of the COVID-19 pandemic, on average only two to three cattle per month were needed during the project period.

As a final limitation for the transferability of the results, we would like to emphasize that the participating canteens were already forerunners, since the introduction of local and organic beef was part of an overarching strategic process toward more sustainability. Reaching a broader variety of less sustainability-oriented canteens would therefore require further effort and more supportive framework conditions (see Section 5.3).

5.2. Challenges of transforming organizational routines in public canteens

The empirical results showed that the canteens were faced with the challenge of changing organizational routines that thus far had been strongly shaped by efficiency principles. The centralized procurement of food products, meal planning and choice of recipes, as well as the use of convenience instead of fresh products, had mainly followed the logic of reducing costs in terms of e.g., prices for the menus, the quantity and quality of the necessary kitchen staff, and spatial capacities for preparing and storing food. However, our survey also showed that the canteen managers are—at the same time—increasingly faced with further demands to contribute to the provision of healthy and sustainable food for a broad range of the population, including vulnerable groups, as well as to supporting the necessary transformation of the food system.

Searching for new suppliers and integrating these new procurement processes into the overall management, introducing meals with new recipes into the regular planning, using fewer convenience products in the kitchen, and communicating the sustainable qualities of the local organic products to the kitchen staff and the canteen guests are time-consuming efforts, which are opposing the dominance of efficiency principles. The complex challenges for communal caterers that go hand in hand with a transformation toward sustainability are mentioned by several authors (Lopez et al., 2019; Kretschmer and Dehm, 2021). Kretschmer and Dehm (2021, p. 3) stress that “it requires not only a change in sourcing and procurement but also a shift in mindset regarding the philosophy, organization, and management of the respective canteen system.”

Literature on changes in organizational routines points out that these are only partly dependent on the individual motivation and knowledge of the staff responsible. Organizational routines, understood as bundles of closely connected and interdependent practices (Castelo et al., 2021), are formed by norms, standards and regulation as well as material conditions (e.g., space for preparing and storing food) and equipment (e.g., kitchen equipment to process food products vs. equipment to prepare convenience products) (Nicolini, 2012; Hennchen, 2021).

Dealing with the challenge of minimizing food waste in public canteens, Hennchen (2021) shows, for example, that the size of portions is influenced by standards, by the training provided as part of the standard apprenticeship in cookery, but also by certain kitchen equipment. He also points out that the question of what counts as a portion is no longer decided only by the kitchens themselves but instead predetermined by suppliers further up the food chain for e.g., convenience products. Together with the use of kitchen equipment, the practice of portioning therefore extends

beyond the organizational context of a single kitchen and points to more general developments in the catering industry. Similar observations were made in the case of integrating more local organic products. Regulation around procurement processes on the EU and national level, societal norms such as “canteen food has to be cheap” or “a complete meal contains meat,” and the training of cooks (with a focus on convenience products and meals containing meat) have a strong influence on organizational routines in canteens and cannot be changed from 1 day to the next.

The following sections deal with some of these aspects in more detail.

5.2.1. Influence of public procurement regulation

Tregear et al. (2022) point out that besides the regulation at EU level, the WTO precepts for Most Economically Advantageous Tenders (MEAT) in procurement contract awards place strong emphasis on low cost and efficiency, which represents a challenge in terms of providing quality food that also meets social and environmental criteria. In recent years the European Commission (EC) has developed environmental procurement criteria in the form of tools such as the Green Public Procurement (GPP) or the Sustainable Public Procurement (SPP) agendas (European Commission, 2019). The criticism is often leveled that giving consideration to social and environmental criteria in procurement has so far been voluntary (Kretschmer and Dehm, 2021) and that this notion stands in contrast to the EC Treaty and other conventions that call for the “free movement of goods and equal rights for all market participants” (Krivašonoka, 2017, p. 1). Another problem is that in public institutions the management and decision-making for catering service delivery are often separated from the management of procurement contracts, which makes it difficult to broaden the perspective beyond cost efficiency toward sustainability aspects (Tregear et al., 2022). This problem also occurred in one of the participating institutions, in which the procurement department did not share the vision of purchasing more local products and instead interpreted the leeway for including more quality criteria in the tender in a very narrow way.

As an additional barrier, Kretschmer and Dehm (2021) mention the personnel costs arising from dealing with too many individual deliveries of fresh products from single farms or small enterprises. The higher effort and cost motivate procurement departments to aim for aggregated deliveries by a conventional wholesaler—which often however are not able to guarantee a local origin.

5.2.2. Identification and definition of regional origin

Neither has it been easy thus far for canteens to identify local products, for information on the origin of food products has not yet been standardized. In a study on the difficulties of purchasing more food of local origin, Arens-Azevedo (2012) reports that big suppliers who are active on a national level are not able to mark the products of their huge assortment with the regions of origin due to limited time resources. Concerning the purchase of locally produced meat, only smaller suppliers were able to give reliable information about the farmers they purchase the meat

from. Kretschmer and Dehm (2021) also mention the difficulty of precisely delineating what determines a local or regional product, since the term “of local origin” cannot be uniformly defined. It may be defined as a fixed geographical radius concerning a given location, or it may be defined as a certain district, province, state or country (Clancy and Ruhf, 2010). In the accompanying case study, one of the major challenges was to define regionality in a way that took the specific contextual conditions into account and allowed transparent communication with the canteen guests. By involving the stakeholders along the local value-added chain, the project was successful in defining “local origin” in a way that could be easily communicated, was accepted by canteen managers and guests, and was compatible with the organizational necessities of the processing company.

5.2.3. The influence of training

The lack of certain skills among the kitchen staff is mentioned in the literature. In a study on reducing meat consumption in community catering, Lopez et al. (2019) identify one of the major barriers as the fact that the preparation of low-meat dishes is not sufficiently addressed in the training of staff in the catering sector. Since the higher prices of using more organic and local food in canteens are often compensated by reducing the percentage of meat in the meal, these skills are crucial (ibid.). As we also observed in the participating canteens, this is even more the case, since the design of menus must be fundamentally changed when aiming to reduce meat quantities. Lopez et al. (2019) conclude that offering low-meat dishes entails abolishing the classic three-component structure of menus—meat, satiating side dish and vegetables/salad. The authors identify a severe existing knowledge gap in the out-of-home catering industry in this regard.

To sum up, the complexity of influential factors in organizational routines in canteens helps to understand why introducing locally produced organic products is a challenge, and why none of the kitchen managers involved could be motivated to follow a “nose-to-tail” strategy and use more—or all—parts of the beef. A nose-to-tail strategy would imply a rather radical transformation of daily routines and would require even more extensive changes in practices, including the acquisition of new skills, new kitchen equipment and the willingness of the canteen guests to consume less prominent parts of the beef. Pioneering canteen managers who have adopted this strategy report that the process took several years (statement of a canteen manager who is applying a “nose-to-tail” strategy in a Bavarian canteen, kitchen talk 12.5.2020).

5.3. Measures to support the sustainability transformation of canteens

As shown in Section 5.2, different measures and adaptations on various levels would be necessary to facilitate steps toward the sustainability transformation of canteens. While some changes of procurement regulation, for example, have to be taken on the EU or national level, there are also supportive measures that can be taken

on a local/regional level or by the institutions the catering facilities belong to.

5.3.1. Importance of supportive process facilitators/“caretakers”

In the case study analyzed, the transdisciplinary research project took the role of a “caretaker” who puts the actors along the value-added chain in contact and facilitates the process of getting to know each other’s demands and needs as well as acquiring experience in introducing regional local products into the canteens. Without the support of the project, the canteen managers would probably not have had the staff capacity to search for new suppliers and take the necessary steps to integrate locally produced organic beef into their regular meal planning. The issues that were raised by the project—providing information on the characteristics of organic and pasture-reared husbandry in the region, developing an acceptable definition of local origin, clarifying the terms of trade between the processor and the canteens, developing communication measures for the kitchen staff and the canteen guests, as well as ensuring a long-term perspective by dealing with the issues of certification and procurement processes—served as a guiding frame to ensure canteen managers did not overlook important elements of the transformation process. The successful introduction of local organic beef depended on the mixture of several strategic elements. If the canteens had left out part of them (e.g., communication with the guests or training of the staff) due to restricted resources, there would have been a greater risk of failure. Also, the processing enterprise reported that they did not have enough staff capacity to search for new market partners, especially where these might have different needs and demands in comparison to the existing ones.

The need for external support in overcoming initial barriers and a “caretaker” who structures the process of establishing a new regional value-added chain has also been described in the literature (Ingram et al., 2020; Tuijter, 2021; Braun et al., 2022). Braun et al. (2022, p. 13f.) refer to this intermediate position as “value chain developer” and describe their tasks as “bringing together value chain actors from a specific region and creating a social space in which these actors can work in a collaborative innovation process”. Value chain developers enable the actors to build trust, identify the potential for collaboration, and develop concrete partnerships along the value chain by organizing and facilitating regular activities (ibid.). Gray and Purdy (2019) differentiate three phases of value chain development with different foci on the activities of the value chain developers. The first phase primarily focuses on activities that serve to establish new contacts among local value chain actors, explore the challenges and potential of the value chain, discuss the needs and expectations of the participating actors, and negotiate common goals. Braun et al. (2022) emphasize the importance of getting to know each other personally and establishing trust among the participants in this phase. In our case study, getting to know each other was facilitated by the “kitchen talks”, which in this phase took place approx. every 2 months, and the organization of excursions to the processing enterprise and to farmers who delivered local organic beef to the processor. In particular, it was the excursions and the discussions accompanying

them that established trust between the canteen managers and the processor regarding the quality of the beef and the animal welfare on the participating farms.

The second phase typically contains activities in which the collaboration is tested and improved after gaining initial experience (Braun et al., 2022). In the case study analyzed, test-runs were organized in which the locally produced organic beef was offered in the canteens. These were accompanied by communication measures as well as analysis of the reaction and satisfaction of the canteen guests. As also described by Braun et al. (2022), the test-run revealed the need for specific training, e.g., the transfer of information to the kitchen employees about the characteristics of organic and animal-friendly husbandry, but also the collection of recipes with less meat to compensate for the higher prices of local organic beef. Any problems with the collaboration became transparent in that phase (e.g., providing transparent information on the origin of the beef, and reliable deliveries in terms of quality and quantity) and were dealt with in the period after the first test-run. In that phase, the kitchen talks served the purpose of filling existing knowledge gaps and finding solutions for the problems arising.

The third phase focuses on the incremental improvement of products and processes to ensure a long-term collaboration (ibid). In this phase, issues around preparing the public tender process or questions regarding product-specific organic certification gained in importance. As described by Braun et al. (2022), we too found that the role of the value chain developers or “caretakers” decreased in this phase and was limited to a few, mostly individualized, consultations offering support for more specific institutional challenges.

Besides transdisciplinary research projects, a variety of organizations can take on this intermediate facilitating role, e.g., the organic farming associations, managers of “eco model regions,” or actors engaged in a municipal food strategy. Recently, in Germany, several programmes have been launched on a national or federal level with the aim of establishing “value chain managers,” which shows that there is now increased political awareness of the importance of this facilitation and support (e.g., funding from the Bundesprogramm Ökologischer Landbau, the German government’s federal programme for organic farming and funding by the Ministry for Agriculture, Environment and Climate Change of the Federal State of Brandenburg).

5.3.2. Providing practical knowledge and adapting professional training

As discussed in Section 5.2, organizational routines are shaped by regulation, norms, standards, professional training and the given material conditions, and this has to be kept in mind when approaching canteen managers and kitchen staff with suggestions for integrating more locally produced organic products. Nevertheless, providing information and knowledge is often seen as a key element in motivating individuals and organizations to take transformative steps toward sustainability. Regarding canteens, several authors point out that it is important to provide practical knowledge that supports the modification of routines in direct ways (Lopez et al., 2019; Braun et al., 2022).

Lopez et al. (2019) mention support for the networking of relevant stakeholders *via* regional and local platforms as well as the transfer of experience from best-practice examples as useful elements.

As described in Section 2.3, the project made an effort to provide the canteen managers and staff with very practical knowledge and shared experiences regarding the choice of a local supplier, the changes in menu planning and recipes, ways of approaching the public procurement process, as well as the design of communicative elements for the kitchen staff and the canteen guests. As described above, the main instruments for the transfer of knowledge and experience were the regular “kitchen talks” and bilateral coaching measures. The benefits of canteen and catering service professionals sharing experiences are also stressed by Arens-Azevedo (2012).

Hennchen (2019) introduces the idea of “sharing knowledge by creating supportive cooperation as an alternative to teaching ‘top-down’” in order to make use of practical expertise, ethical values and experiences. Based on a project about avoiding food waste in canteens, he suggests that the exchange between actors in the gastronomic sector not only enables the circulation of knowledge and opportunities for sharing practical skills but also harbors the potential for sharing social norms about “being a good professional” and taking ethical responsibility. In the case study analyzed, the “kitchen talks” also strengthened the motivation of the participating canteen managers and reassured them they were not alone in dealing with the upcoming challenges.

Since the project provided the opportunity to carry out surveys with the canteen guests, this was another knowledge element that could be provided to the canteen managers. Being able to document the high level of approval for offering local organic meat, and communicate this to the central management and the kitchen staff, strengthened the position of the canteen managers in the transformation process.

Tregear et al. (2022) point out that considerable knowledge, skill and agility is demanded of the professionals who organize and operate procurement and catering services, as they are confronted with the challenge of prioritizing between the conflicting imperatives of cost efficiency on the one hand and sustainability and health aspects on the other (Grivins et al., 2018). Morgan (2014) mentions that the status of public sector procurement managers needs to be radically enhanced because these professionals play a key role in securing not just value for money in the narrow economic sense, but also “values for money” in the broader societal sense (see Section 5.3). Tregear et al. (2022) stress the importance of a higher valorization of catering service staff. Our study also showed that the kitchen staff play a central role in the process of introducing innovations such as local organic beef into canteens, and communicating these to the canteen guests. Well-trained kitchen staff also appreciate using their creativity and skills and are motivated by having the leeway to prepare meals with fresh instead of convenience products. We therefore agree with the authors that instruments that promote greater investment in frontline service staff, raise the status of the profession and provide more skills and training are necessary in order to support transformational change and the positive sustainability impact of public catering.

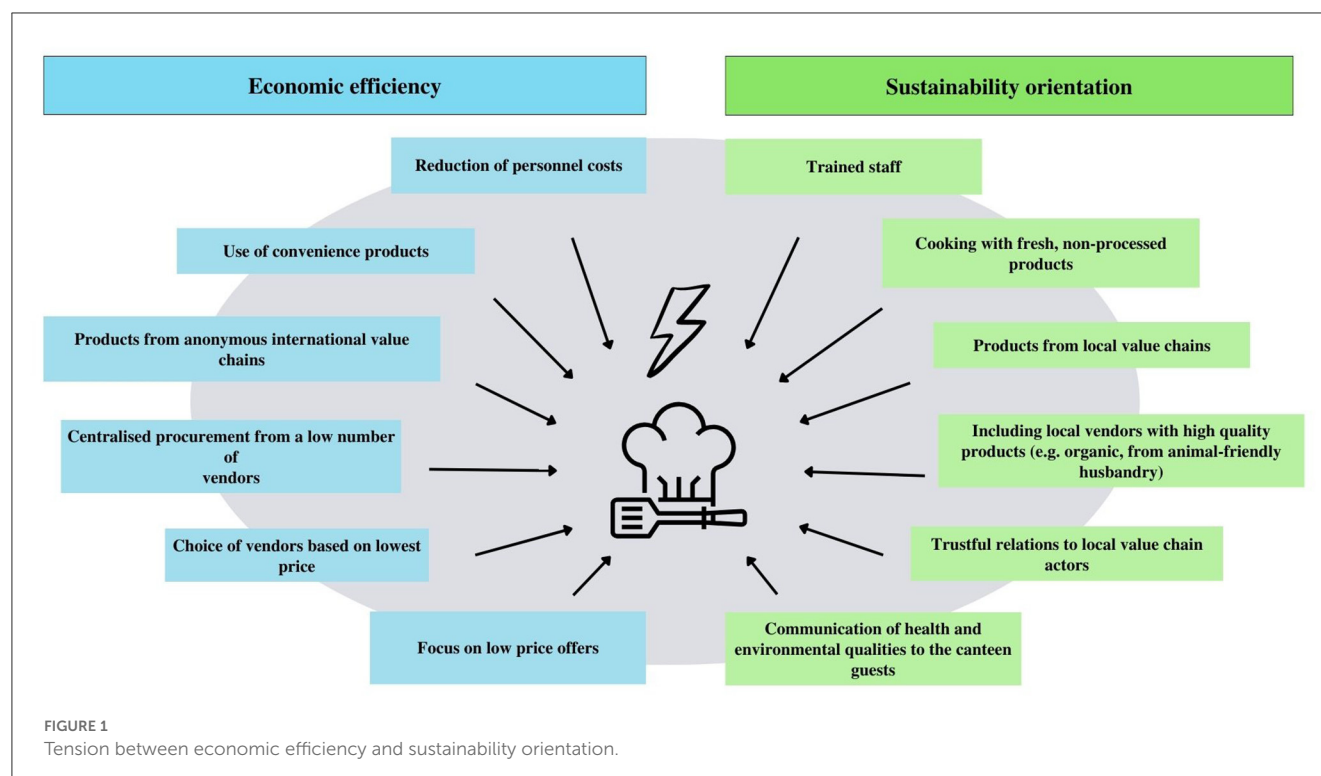
5.4. Provision of healthy and sustainable food as a societal challenge

The reflections in Sections 5.2 and 5.3 show that introducing local organic beef—as one example of a possible measure for improving the quality and sustainability of food in canteens—faces a lot of barriers due to the dominance of efficiency principles, which are inscribed into daily organizational practices in canteens and their regulation. Public catering facilities are increasingly confronted with demands that go beyond providing inexpensive meals for everybody. Morgan and Sonnino (2010) suggest that these emerging challenges call for a “new food equation,” one where the food system must be valued in broader terms than in the past, in order to account for its relation to the wider context of climate change, increasing energy costs, social unrest, financial instability and increasing environmental degradation. Figure 1 visualizes this tension between economic efficiency and sustainability orientation.

Morgan (2014) points out that appeals to individuals as consumers to change their attitudes and behavior by making healthier or more sustainable choices is an approach that will most likely fail because it does not recognize the strong social and economic forces that maintain the status quo. Since individuals are more likely to consider changing their habits and practices in the company of their friends, families and communities, public canteens are one of the societal settings in which sustainable diets should be fostered. This is of even greater relevance since canteens in schools, hospitals and care homes often feed the most vulnerable people in our societies (Marsden and Morley, 2014). The experiences of our case study show that the opportunity to use the provision of high-quality nutrition *via* canteens as a measure in preventive health care has not yet been given enough political priority.

As also shown above, these general reflections on the societal value that should be placed on providing healthy and sustainable food have consequences on different levels. Several authors stress that in future, public catering institutions need to adopt a more comprehensive perspective (Bratt et al., 2013), with better coordination across separate departments and functions (Testa et al., 2016). For public food provision in canteens, Tregear et al. (2022, p. 9) conclude that “this particularly means taking a more holistic view of procurement and service delivery functions to fully maximize their potential for enhanced environmental, economic and nutritional outcomes.”

The discussion about the societal challenge of changing the current food system has gained new momentum due to the publication of the report by the EAT-Lancet Commission on Healthy Diets From Sustainable Food Systems (EAT-Lancet Commission, 2019). The report states that food is the single strongest lever in the optimization of human health and environmental sustainability on a global scale. The health of both people and the planet is heavily shaped by how food is produced, what is consumed, and how much is lost or wasted. The group of scientists recommend a mainly plant-based planetary health diet, which would help avoid severe environmental degradation and prevent several million human deaths annually as part of a Great Food Transformation. Other authors also stress that the parallel consideration of environment and health is favored by the



current state of knowledge, since both dimensions require similar measures (Abrahamse, 2020; Strid et al., 2021; Speck et al., 2022). Public and private canteens can play an important role in this food transformation process if this societal goal is framed by supportive policies on different levels.

Data availability statement

The datasets presented in this article are not readily available because anonymization is very difficult due to the low number of involved canteens. Requests to access the datasets should be directed to schaefer@ztg.tu-berlin.de.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

MS and MH contributed to the conception of the research design. MH was responsible for data collection and analysis under the supervision of MS. MS prepared the initial draft for the manuscript and was responsible for the overall structure, the introduction and the discussion, while MH worked mainly on the results section. Both authors revised all parts of the paper. Both authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Perspective—Evaluating the impact of food waste reduction policies

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KEYWORDS

food waste (FW), food waste prevention and reduction, impact evaluation methodology, randomized controlled trial (RCT), Quasi-experimental design

1. Introduction

Food waste is increasingly recognized as a driving problem affecting high-income countries but is expected to be rapidly growing in emerging economies (van der Werf and Gilliland, 2017; Aschemann-Witzel et al., 2019). The identification and quantification of food waste generated throughout the supply chains, especially at the household level remain challenging and academic efforts are directed to address this gap. A shy but growing strand of empirical literature has proposed, tested and assessed methodologies to collect data on household food waste, quantify (Corrado et al., 2019; van Herpen et al., 2019), and model it (Gil, 2020). Several studies provide extensive coverage of primary data collection methodologies for quantifying household food waste. Self-reports via food waste diaries, kitchen caddies, coding of pictures, and food waste composition analysis are the most commonly applied methodologies (Leverenz et al., 2019; Quested, 2019; van Herpen et al., 2019). Besides, there is an interest to explore secondary data in addition to direct food waste measurements, either based on territorial or consumption-based approaches.

If the development of data collection methodologies and tools is a prerequisite to lay unbar the food waste problem, there is also an urgent need for more scientific reflection on the designs which can best help identify causal changes in consumers' behaviors and attitudes due to food waste prevention interventions. Indeed, there is a growing global policy- and grassroots-driven trend to develop policies and initiatives to reduce food waste and its impacts on the environment, driving for the more systematic use of evaluation and monitoring of food waste prevention initiatives. Although some studies took stock of existing interventions and their success factors, their actual food waste reduction impact remains unclear (Aschemann-Witzel et al., 2017). Several systematic reviews concluded on the lack of evidence about anti-food waste interventions along the supply chain (Stöckli et al., 2018), but also that there is little information available regarding what interventions have been evaluated, and how they have been evaluated (Goossens et al., 2019). Only isolated studies attended to quantify the effects of grassroots initiatives to reduce food waste but systematic impact assessment is lacking (Nikravech et al., 2020).

2. The necessity of determining causal inference to assess food waste prevention

There is an inherent difficulty in evaluating food waste reduction since it implies the measurement of something “that is not there [anymore]” (Zorpas and Lasaridi, 2013; p. 1055). In addition, measurement and quantification methods alone do not suffice to determine the causal inference to an intervention to bear an effect on food waste. We would

like to appeal to the research community and funding to direct further efforts and funds to the identification of the causal effect of food waste prevention interventions. This should be done with the application of robust research designs that can offer an objective assessment of the causal effect of food waste prevention interventions. More specifically, this is an appeal to the scientific community to reflect on the way to include an econometric impact attribution evaluation perspective in food waste research endeavors. Indeed, compared to observational contribution evaluation designs, such approaches allow identifying the causality of interventions leading to food waste reduction, disentangling and quantifying their effects. This paper provides food for thought about applying impact evaluation designs to food waste reduction interventions.

Existing food waste impact assessments were achieved mostly in the form of quantification (Schneider, 2013; Reynolds et al., 2015; Makov et al., 2020), whereby food and food waste inputs and outputs are measured up and downstream of the food waste prevention initiatives. Adding environmental economic and social dimensions to the assessment with the help of Life Cycle Assessment, social indicators such as the number of redistributed meals or jobs created were proposed to holistically evaluate interventions (Goossens et al., 2019). Such methodologies provide useful descriptive information about the flows of food and food waste policies and initiatives deal with or prevent, as well as about other social and economic outcomes. Yet, they do not allow *per se* a causal impact identification.

Another strand of food waste studies has sought to identify the impact of policies using multivariate regression frameworks on the food waste outcome, using a treatment status as an independent variable. This analytical framework allows exploratory analysis of the influence of individual, group, societal, and time factors on food waste amounts. Nonetheless, it does not account robustly for the impact of other factors that influence the change in food waste outcome nor can distinguish non-observable differences, for instance, motivations or personal goals (van Geffen et al., 2020). Before-after comparison designs with the same participants (longitudinal studies) (Lorenz-Walther et al., 2019; Wharton et al., 2021) or cross-section comparison designs (participant-nonparticipants) are also commonly used designs to identify the effects of anti-food waste interventions (Wharton et al., 2021).

3. Applying the golden standard of randomized control trials to food waste prevention

A deeper reflection should be conducted about a valid and feasible counterfactual condition against which the impact can be measured. This counterfactual seeks to mimic the hypothetical condition in which recipients of treatment did *not* receive the treatment. Ensuring its validity along the way is key to studying the causal impact of anti-food waste interventions. This reflection shall therefore consider the golden standards of impact evaluations to identify causal inference: randomized control trials. Popularized in the field of development economics, their use in the field of food waste policy has been so far marginal and reserved to

small-size pilots and nudges in the gastronomy and hospitality sector (Kallbekken and Sælen, 2013). There is little research about the potential to use such experimental methodologies to assess more large-scale food waste prevention interventions. Randomized control trials imply the randomization of eligible units into treatment groups, to which the intervention is allocated, and control groups. Such endeavors are costly to achieve because they imply strict control over the treatment status of the units and the compliance to remain valid and provide robust inference. Moreover, they involve a large number of sample units.

When engaging in such assignments, it is important to consider the levels at which a food waste prevention intervention is expected to “work”, possible spill-overs, and existing clustering, to decide on which level it makes more sense to randomize (Glennerster and Takavarasha, 2013). For example, food waste prevention taking the form of an “ugly fruits and vegetables” campaign (Hooge et al., 2017) is more appropriate to be randomized at the supermarket level while an intervention providing a kitchen food waste monitoring device may be randomized at the household level. Whether the randomization should be simple, pairwise, or stratified is also to be considered by food waste social scientists (Glennerster and Takavarasha, 2013).

Whenever random sampling and random treatment assignment are not feasible (because e.g., there are not enough eligible units or the treatment allocation was decided before the research started) or not desirable (taking the example of an extreme case: randomizing the access to food donation and preventing part of its eligible beneficiaries to access edible rescued food, even in a phase-in approach would be ethically inappropriate) other types of robust designs should be considered. Yet, before moving to quasi-experimental designs, one could consider the use of phase-in or rotation designs when everyone needs to receive the intervention, or encouragement designs, whenever the program is open to all and undersubscribed (Glennerster and Takavarasha, 2013) could find their application, when it comes to food redistribution.

4. Quasi-experimental designs as workable alternatives: opportunities and pitfalls

Quasi-experimental designs are more regularly employed to explore household food waste and can be a valid way to assess impact. Yet there is little methodological discussion existing about their opportunities, challenges, and how to use them when it comes to measuring the impact of food waste prevention interventions. In a natural experiment or an organized field experiment setting, the use of baseline measurements and of a sound control group to mimic the counterfactual bear the potential to identify an impact in a more robust way than simple difference designs. One path we suggest exploring is the use of difference-in-difference, propensity score matching, and matched difference-in-difference designs. By matching one unit from a non-random control group with one unit from a non-random treatment group based on their propensity to be exposed to the treatment conditional on covariates (Dehejia and Wahba, 2002), one could pair households and compare the food waste amount pairwise. Using propensity score matching

(PSM) is deemed appropriate in the case of small N to adjust for confounders which makes it a promising method for food waste social research. Moreover, PSM can be used in combination with the difference-in-difference in a matched difference-in-difference assignment (Abadie, 2005). So far, we found one study that explored the potential of a matched difference-in-difference to measure the impact of two local food waste disposal payment policies on food waste (Lee and Jung, 2017).

More generally, when assessing impacts in the field of food waste policy, it should be reflected how big the expected effects in terms of food waste reduction are, given the intervention type and its intensity, to consider the reasonable sample size, most importantly the number of clusters to integrate in order to detect the minimum effect. Holding such reflection is crucial since food waste measurements are highly likely to come along with high standard errors due to measurement imprecision, especially when they are based on self-report, and to their high variance, biasing the estimates. It is important to keep in mind what changes are expected and how to detect these changes, and therefore adapt the sampling strategy to the expected change. Studies on food waste have so far suggested diverging effect sizes in terms of food waste prevention depending on the interventions. Hence, they should be reviewed before engaging in evaluation endeavors to prevent disappointing false-negative. An experimental study showed a reduction in food waste of 15% due to the reduction of plate size (Kallbekken and Sælen, 2013). Reynolds et al. (2019) found in a review that nudge interventions in the hospitality sector could lead to up to 57% food waste reduction while information campaigns could reduce up to 28% of food waste.

Finally, as previous literature has highlighted, large-scale food waste data collection is challenging and often relies on low-cost participatory data collection methodologies which can endanger the validity of the results (attrition, tiredness, social desirability). Conducting impact assessments on food waste implies a consideration of how the measurements are carried out in control groups. Indeed, primary food waste data collection is often carried out based on self-report, be it with pictures, diaries, or kitchen caddies, and one should think about the best way to engage control groups in the study itself and the measurement activities. Avoiding differential attrition and receiving food waste information of the same quality both from control groups and the treatment groups is paramount to preserve the validity of the results. These questions, often raised in the field of impact evaluation have rarely found their place in the field of consumer studies and food waste. Researchers should monitor the quality of food waste measurements throughout the process to ensure balance.

5. Discussion and concluding remarks

This opinion piece highlighted the urgent need to gather robust evidence on the impact of food waste prevention interventions. It recalled that only few studies on the effectiveness of such interventions have questioned the causality identification methods. So far, most of the scientific literature in the field of food waste reduction used primarily non-experimental observational studies (e.g., pre-post, participant-nonparticipant designs), focused on quantification of food waste or explored the relationships between

individual and collective factors and food waste. This opinion piece suggested that exploring more systematically the potential of experimental and quasi-experimental studies is the next step to providing robust empirical impact evidence. The potential and challenges of employing randomized control trials to assess food waste reduction interventions were discussed, and alternative paths presented. Experimental designs allow to distinguish whether the reduction of the measured food waste is indeed strictly attributable to the intervention and not to sources of bias, such as differentiated self-reported food waste measurements, as long as compliance to the treatment status is controlled. By contrast, in alternative quasi-experimental designs, the differential measurement errors induced by the control or treatment conditions need to be utterly monitored by researchers willing to engage in such an endeavor.

Evaluating food waste reduction interventions presents similar challenges to other fields of policy impact evaluation to ensure causality identification. However, it additionally implies the challenge of opening the black box of households' kitchens and trashcans, and often dealing with self-reported food waste data. While the specific challenges related to measuring food waste still require to be addressed, removing systematic sources of impact bias by employing causality inference designs is necessary. Overall, this opinion paper contributes to the food waste prevention literature by calling up attention on this. We hope that it helped to highlight the need for a research and policy agenda to test experimental and quasi-experimental research designs in the field of consumer studies and food waste.

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MN: conceptualization, formal analysis, methodology, writing—original draft, and writing—review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Does rural industrial integration improve agricultural productivity? Implications for sustainable food production

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Although the literature demonstrates that rural industrial integration can enhance farmers' income, foster rural development, its impact on agricultural total factor productivity (ATFP), a critical aspect of sustainable food systems remains unclear. Using provincial-level data from 2008 to 2018, this paper constructs a composite index of rural industrial integration and examines its effect, heterogeneity, and spatial spillover on ATFP growth in China. The findings indicate that the levels of rural industry integration and ATFP experienced a gradual increase from 2008 to 2018. Rural industry integration promotes ATFP growth through technical progress and improved technical efficiency. An analysis of regional heterogeneity reveals that rural industry integration has the most significant impact on ATFP promotion in the western region, followed by the central region, with the least impact in the eastern region of China. Unconditional quantile regression suggests that rural industrial integration has a more considerable impact on ATFP in regions with higher ATFP. Furthermore, the spatial Durbin model results demonstrate that rural industry integration directly supports rural industry integration development in a region while simultaneously inhibiting ATFP growth in surrounding areas. Finally, the findings also reveal that enhancing rural industrial integration can have positive impacts on sustainable agricultural production in China. These findings offer valuable insights for other developing countries aiming to promote sustainable consumption and production.

KEYWORDS

rural industrial integration, agricultural productivity, spatial spillover effects, sustainable production, developing countries

1. Introduction

Meeting the food demands of the global population while promoting sustainable agriculture is a major challenge for humanity (Godfray et al., 2010; Springmann et al., 2018). China has been making substantial efforts toward food security and sustainable agricultural development (Huang and Yang, 2017). The growth accounting framework posits that agricultural growth is primarily determined by increases in agricultural factor inputs and agricultural total factor productivity (ATFP) growth (Solow, 1957; Bjurek, 1996). Furthermore, ATFP growth has contributed significantly to China's agricultural growth (Huang and Rozelle, 1996; Jin et al., 2010; Hu et al., 2021).

ATFP growth, which includes technological progress, technological efficiency, scale efficiency, and allocation efficiency, is the source of sustainable agricultural development (Beugelsdijk et al., 2018; Ren et al., 2019). Increasing ATFP can increase the supply of food and thus guarantee food sustainability. However, ATFP growth is influenced by many factors, and existing studies generally believe that agricultural policy reform is the decisive factor (Lin, 1992; Kumar et al., 2008; Po et al., 2008; Gong, 2018; Liu et al., 2020). As a result, policy innovation is essential for promoting national agricultural growth.

In recent years, rural industrial integration has emerged as a focus of China's national agricultural policy, emphasized by the Central Government's No. 1 document for six consecutive years (Chen, 2019; Han, 2019). The rural industrial integration refers to the process of organic integration of agricultural production, processing and circulation based on agricultural production, through the horizontal broadening and vertical extension of the industrial chain, multi-functionalization of industries, and agglomeration of elements (Zhang et al., 2020; Xiang et al., 2022). The objective of rural industrial integration is to promote rural development through the integrated use of rural land. This integration can affect rural land use, which may influence ATFP growth (Tian et al., 2020). This relationship is crucial for sustainable agricultural development. Furthermore, rural development through non-farm work opportunities can lead to positive synergies between sustainable agricultural production, off-farm employment and poverty alleviation. Therefore, this paper aims to answer three questions: First, will rural industrial integration promote ATFP growth? Second, will the impact of rural industrial integration on ATFP be heterogeneous? Third, is there a spatial spillover effect of rural industrial integration on ATFP? Answering these questions is essential for China and other developing countries seeking to promote sustainable agricultural development.

The literature relevant to this paper focuses on two main areas: The first is the calculation of ATFP. Currently, there are two primary methods for calculating ATFP: stochastic frontier analysis (SFA) and data envelopment analysis (DEA). The SFA method requires setting a specific production function and is a parametric estimation method (Aigner et al., 1977). In contrast, DEA calculates efficiency through a data envelope and is a nonparametric estimation method (Razzaq et al., 2019). Most literature uses a combination of DEA and the Malmquist index to measure ATFP (Grifell and Lovell, 1995; Tugcu and Tiwari, 2016). Additionally, some scholars have employed the F-P index for ATFP measurement (O'Donnell, 2010, 2012). The F-P index offers multiplicative completeness and transferability compared to the traditional Malmquist index, enabling better calculation and decomposition of multiple individuals' productivity (Fulginiti and Perrin, 1997). The F-P index method has been widely used to measure ATFP in Australia, the EU, and other countries (Baležentis, 2015; Baráth and Ferto, 2017).

The second major area of literature concerns the factors influencing ATFP. With the improvement of ATFP measurement methods, numerous studies have begun to focus on the determinants of ATFP, such as human capital, infrastructure, and agricultural policy innovations. Enhancing farmers' human capital enables them to adopt advanced technologies, which

significantly increases ATFP (Bachewe et al., 2018). Improved infrastructure can contribute to ATFP by ameliorating agricultural production conditions and increasing the scale of operations (Fakayode et al., 2008; Shamdasani, 2021; Zhang et al., 2022). Agricultural subsidies help farmers increase ATFP by investing more or adopting advanced production technologies (Zhu and Lansink, 2010; Yi et al., 2015). Agricultural policy innovations can promote technological progress and improvements in technical efficiency, thus increasing ATFP. Existing studies suggest that agricultural policy innovations, such as the family responsibility system, agricultural tax reform, and land system reform in China, have played a vital role in ATFP growth (Fan, 1991; Kumar et al., 2008; Gong, 2018).

This study contributes to the literature in three ways. First, little research has been conducted on measuring rural industrial integration. Therefore, we construct a comprehensive index of rural industrial integration based on Chinese government documents, which can serve as a reference for other countries. Second, although existing literature has addressed the impact of rural industrial integration on rural development (Li and Ran, 2019; Zhong et al., 2020; Cao et al., 2022), there is limited research on its effect on ATFP. We systematically analyze the impact and heterogeneity of rural industrial integration on ATFP. Thirdly, as the agglomeration of rural industries, the integration of rural industries is likely to have a spatial effect on ATFP growth. Consequently, we employ the spatial econometrics method to investigate the total effect of rural industrial integration on ATFP growth, exploring both the direct effect and spatial spillover effect.

The overall objectives of this study are to examine the impact of rural industrial integration on sustainable agricultural development and its spatial spillover effects. Specifically, we use ATFP to measure agricultural sustainable development, which is consistent with the approach employed in most existing literature. First, we calculate the levels of rural industrial integration and ATFP in China's provinces. Next, we investigate the impact and heterogeneity of rural industrial integration on ATFP. Finally, we examine the spatial spillover effect of rural industrial integration on ATFP. In summary, our research can provide valuable insights for the sustainable development of agriculture in developing countries.

2. Theoretical framework and hypotheses

2.1. Influence mechanism of rural industrial integration on ATFP

Existing literature (Färe et al., 1994) suggests that ATFP growth arises from improvements in agricultural technology change and technical efficiency. We decomposed ATFP into these two components, and the impact mechanisms are shown in Figure 1.

The first impact mechanism proposes that rural industrial integration promotes technological progress, leading to increased ATFP. The integration of rural industries can improve farmers' incomes (Li and Ran, 2019; Tian et al., 2020; Zhang et al., 2020; Cao et al., 2022), which in turn encourages them to invest more in agricultural production, such as selecting improved varieties and utilizing more machinery (Lazaroiu et al., 2019). This integration

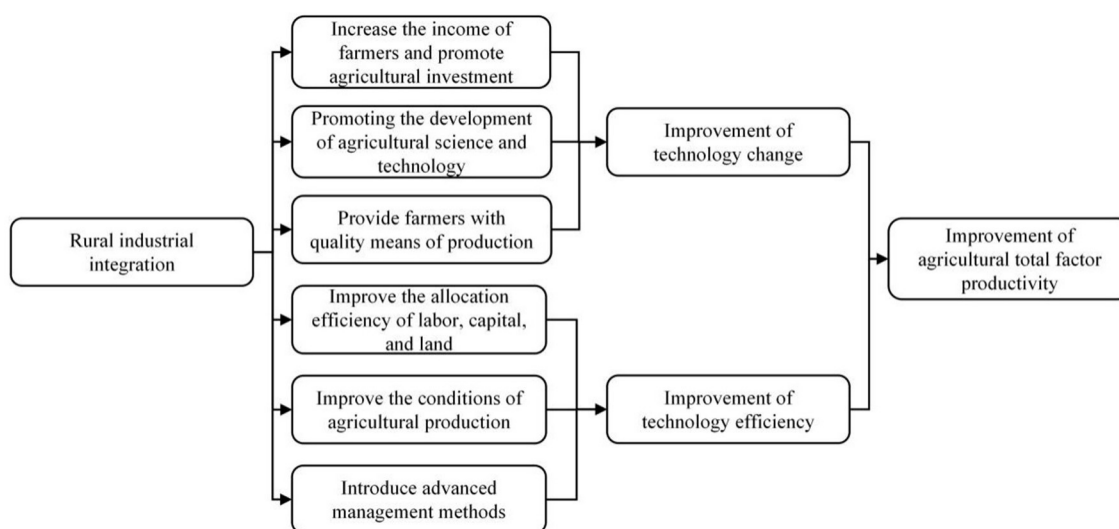


FIGURE 1
Impact mechanism diagram.

fosters agricultural technology progress by facilitating research and development of agricultural science and technology, and by linking the interests of large agricultural companies and small farmers, who provide quality means of production and contribute to technological change (Zhang et al., 2020).

The second impact mechanism suggests that rural industrial integration enhances agricultural technical efficiency, leading to increased ATFP. The integration of rural industries reduces the cost of agricultural information dissemination and breaks down barriers of information asymmetry, increasing land, labor, and capital utilization efficiency (Gambardella and Torrisi, 1998; Xing et al., 2011; Zhou et al., 2022). Additionally, rural industrial integration improves agricultural production conditions and introduces advanced management methods from other industries, such as digital management, further improving technical efficiency.

Based on this analysis, we propose the following hypotheses and illustrate them in Figure 2:

Hypothesis 1-1: Rural industrial integration can increase ATFP growth.

Hypothesis 1-2: The impact mechanisms of rural industry integration on ATFP are technological change and technological efficiency improvement.

2.2. Heterogeneity analysis: impact of rural industrial integration on ATFP growth

The impact of rural industrial integration on ATFP can be influenced by factors such as regional human capital, rural infrastructure development, and the degree of marketization (Li and Ran, 2019; Wang and Li, 2019; Zhang et al., 2020). Therefore, the impact of rural industrial integration on ATFP shows regional differences. In regions with higher human capital, technological innovations brought about by rural industrial integration can be applied to agricultural production more rapidly (Tian et al.,

2020; Ye et al., 2020), increasing ATFP more effectively. Good infrastructure, such as roads, networks, and water resources, can better leverage the role of rural industrial integration on ATFP growth (Pocol et al., 2021; Zhou et al., 2022). The impact of rural industrial integration on ATFP is more pronounced in areas with a higher degree of marketization, mainly due to the role of resource allocation (Lăzăroiu et al., 2020).

Based on this analysis, we propose the following hypotheses:

Hypothesis 2-1: There is regional heterogeneity in the impact of rural industrial integration on ATFP.

Hypothesis 2-2: The impact of rural industrial integration on ATFP is more significant in areas with higher ATFP.

2.3. Spatial spillover effect of rural industrial integration on ATFP growth

Spatial economics posits that there is a siphon effect in the early stages of economic agglomeration (Ahluwalia et al., 2001). The siphon effect refers to an economy attracting capital, human, and material resources from neighboring regions in the development process, inhibiting economic development in those regions. As a form of economic agglomeration, rural industrial integration may have a siphon effect on ATFP growth, inhibiting growth in surrounding areas. The siphon effect can occur due to rural industrial integration attracting highly qualified labor and capital from neighboring regions (Wang and Li, 2019; Ye et al., 2020), as well as creating a brand effect for agricultural products, which may reduce the competitiveness of agricultural products in surrounding areas, thus inhibiting ATFP growth (Cao et al., 2022).

Based on this analysis, we propose the following hypothesis:

Hypothesis 3: Rural industrial integration has a negative spatial spillover effect, inhibiting ATFP growth in surrounding areas.

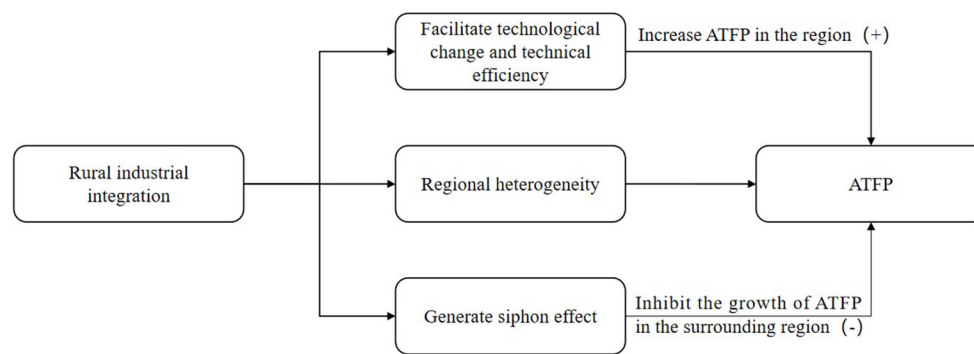


FIGURE 2
Theoretical analysis diagram.

3. Methodology and data sources

3.1. ATFP estimation

We calculate ATFP using the Super-SBM model and Malmquist index. The Super-SBM model is effective in evaluating and sequencing multiple fully effective decision units compared to the traditional DEA model (Tone, 2001; Tao et al., 2016; Zhou et al., 2019). The specific setting of the Super-SBM model is as follows:

$$\rho = \min \frac{\frac{1}{m} \sum_{i=1}^m \frac{\bar{x}_i}{x_{i0}}}{\frac{1}{s_1 + s_2} \left(\sum_{r=1}^{s_1} \frac{\bar{y}_r^g}{y_{r0}^g} + \sum_{j=1}^{s_2} \frac{\bar{y}_j^b}{y_{j0}^b} \right)}$$

$$s.t. \begin{cases} x_0 = X\lambda + S^-, y_0^g = Y^g\lambda - S^g, y_0^b = Y^b\lambda - S^b \\ \bar{x} \geq \sum_{j=1, \neq 0}^n \lambda_j x_j, \bar{y}^g \leq \sum_{j=1, \neq 0}^n \lambda_j y_j^g, \bar{y}^b \leq \sum_{j=1, \neq 0}^n \lambda_j y_j^b \\ \bar{x} \geq x_0, \bar{y}^g \leq y_0^g, \bar{y}^b \geq y_0^b \\ \sum_{j=1, \neq 0}^n \lambda_j = 1, S^- \geq 0, S^g \geq 0, S^b = 0, \bar{y}^g \geq 0, \lambda \geq 0 \end{cases} \quad (1)$$

In equation (1), m and s_1 represent the number of input and output variables, respectively. λ represents the weight vector. x_0 represents the initial input, x represents the input variable, g and b represent the ordinal number of the output variable, and y_0 represents the initial output. The above method can be combined with the Malmquist index to calculate ATFP. We select the global Malmquist index to construct the production frontier, widely used in TFP calculation, as it solves the problem of infeasible solutions in TFP. In addition, the index is able to decompose the ATFP. We can seek the source of ATFP growth by decomposing the index. We use Max DEA to calculate ATFP, which is a software that specializes in calculating productivity.

Calculating ATFP requires selecting input and output variables. Referencing to existing research (Ye et al., 2020), we selected the following agricultural input variables: (1) Land input (LANDI), the sum of agricultural sown area and aquaculture area (thousand square kilometers). (2) Labor input (LI), the number of employees in the primary sector (10,000 people). (3) Machinery input (MI), the total power of agricultural machinery (million kilowatts). (4) Fertilizer input (FI), the number of fertilizer applications (thousand tons). (5) Irrigation input (II), the effective irrigated area

(thousand square kilometers). The output variable selected is the total agricultural production value (TAPV), expressed as the total agricultural, forestry, animal husbandry, and fishery output value (100 million yuan).

3.2. Rural industry integration index calculation

The process of measuring rural industry integration in various studies typically involves four steps: indicator selection, indicator normalization, weight measurement, and index formation. In this paper, we develop a concise and scientifically sound index system to measure rural industry integration levels. We accomplish this by analyzing the concept of rural industry integration, incorporating current policy documents, and referencing existing research results (Li and Ran, 2019). The outcomes are displayed in Table 1.

Specifically, we assess rural industry integration across four dimensions: multi-functionality of agriculture, extension of the agricultural industry chain, integration of agricultural service industry, and benefit linkage mechanism. The corresponding secondary indicators include the level of facility agriculture, the proportion of rural non-farm employment, the scale of agricultural by-product processing industry, the level of agricultural primary processing industry, the development infrastructure of rural service industry, the proportion of agriculture, forestry, animal husbandry, and fishery service industry, and the number of cooperatives.

In this paper, we employ the entropy value method to calculate the level of rural industrial integration, following a series of specific steps (Liu et al., 2017).

First, we use the formula below to normalize the data:

$$S_{ij} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)} \quad (2)$$

Second, we perform a specific gravity transformation on the normalized data using the following formula:

$$M_{ij} = S_{ij} / \sum_{j=1}^m S_{ij} \quad (3)$$

TABLE 1 Evaluation index system of rural industrial integration.

Tier 1 indicators	Secondary indicators	Indicator description	Unit
Agricultural multi-function	Facility agriculture level	Area of facility agriculture/Cultivated land	%
	Proportion of rural non-agricultural employment	Rural secondary and tertiary industry employees/Rural employees	%
Extension of the agricultural industry chain	Scale of agricultural and sideline products processing industry	Business income of agricultural and sideline products processing owners/Total agricultural output value	%
	Primary agricultural processing industry level	Total power of primary processing industrial machinery per 10,000 rural people	kw
Integration of agriculture and service industry	Rural service industry development infrastructure	Social organizations for rural development for every 10,000 rural people	pcs
	Proportion of agriculture, forestry, animal husbandry, and fishery services	Total output value of agriculture, forestry, animal husbandry, and fishery services/Total output value of agriculture	%
Interest linkage mechanism	Farmers' professional cooperatives	Number of farmers' professional cooperatives per 10,000 people in rural areas	pcs

Third, we determine the information entropy value for each index using the following formula:

$$E_j = -(\ln m)^{-1} \sum_{i=1}^m M_{ij} \ln M_{ij} \quad (4)$$

Fourth, we determine the weight of each indicator according to the following equation:

$$W_j = \frac{d_i}{\sum_{j=1}^n d_j}, \quad d_j = 1 - E_j \quad (5)$$

Finally, we determine the level of rural industrial integration in each province for each year using the following equation:

$$RID_{ij} = \sum_{j=1}^n W_{ij} S_{ij} \quad (6)$$

3.3. Research methods

Building on existing research (Hulten et al., 2006), this paper assumes that agricultural production is influenced by capital, labor, land, technology, and other factors, and establishes the following models.

$$Y = A(RID, \gamma, t) f(K, L, M) \quad (7)$$

In the formulas, Y represents agricultural output, RID represents the level of rural industrial integration, γ represents exogenous factors affecting ATFP, and K , L , and M represent physical capital, labor, and land input. $A(RID, \gamma, t)$ represents the standard Hicks neutral function. Rural industrial integration can increase total agricultural output not only by affecting the inputs of capital, labor, and land but also by affecting $A(\cdot)$. This paper primarily discusses the second way of influence. We suppose that the Hicks neutral function is a multivariate function as follows.

$$A(RID, \gamma, t) = A_{i0} e^{\delta RID_{it} + \gamma_{it}} \quad (8)$$

In equation (8), the time variable is t , and i denotes the region. A_{i0} indicates the initial productivity level of region i . δ represents the impact of rural industrial integration on ATFP growth. We incorporate the equation 8 into equation 7 and divide $f(K, L, M)$ to obtain ATFP.

$$R_{TFP_{it}} = \frac{Y_{it}}{f(K_{it}, L_{it}, M_{it})} = A_{i0} e^{\delta RID_{it} + \gamma_{it}} \quad (9)$$

We further simplify the logarithm of the expression and introduce control variables as follows:

$$ATFP_{it} = \beta_0 + \beta_1 RID_{it} + \phi X_{it} + a_i + \mu_{it} \quad (10)$$

ATFP is the cumulative rate of R_{TFP} change. a is the local fixed effect, and μ is the random error term. β and ϕ are the estimated parameters. X is a matrix of the control variables included in the study. Referring to existing studies, we select the following control variables: (1) Infrastructure (ROAD), expressed in terms of road miles per unit area. (2) Human capital (EDU), expressed as the average number of years of education of the regional labor force. (3) Urbanization level (UR), expressed as the ratio of the number of urban population to the total population. (4) Land quality (LAQA), expressed as the ratio of effective irrigated area to sown area. (5) Disaster rate (DR), measured as the ratio of disaster area to total sown area, to control the impact of climate, etc., on ATFP. (6) Agricultural restructuring coefficient (AS), expressed as the ratio of sown area of food crops to total sown area. This indicator can reflect whether the cropping structure of each region evolves toward comparative advantage. (7) Fiscal support to agriculture (AF), expressed as the share of fiscal support to agriculture in total fiscal expenditure.

It is important to note that the dynamic effect of ATFP is not considered in the equation 10. The change of ATFP

in the previous year may affect the change of ATFP in the next year. Therefore, we obtain a dynamic panel data model by adding the lagging expansion of ATFP to the equation 10:

$$ATFP_{it} = \beta_0 + \beta_1 ATFP_{i,t-1} + \beta_2 RID_{it} + \phi X_{it} + a_i + \mu_{it} \quad (11)$$

To investigate the heterogeneity of the impact of rural industrial integration on ATFP, we perform group regressions for different regional samples based on the equation 10. We then conduct unconditional quantile regressions. Next, we investigate the mechanism of the impact of rural industrial integration on ATFP growth using the following equations:

$$TC_{it} = \beta_0 + \beta_1 RID_{it} + \phi X_{it} + a_i + \mu_{it} \quad (12)$$

$$EC_{it} = \beta_0 + \beta_1 RID_{it} + \phi X_{it} + a_i + \mu_{it} \quad (13)$$

The equations 12 and 13 represent the effects of rural industrial integration on technical change and technical efficiency, respectively.

Lastly, this paper constructs a spatial Durbin model (SDM) to study the spatial spillover effect of rural industrial integration on ATFP growth.

$$ATFP_{it} = \beta_0 + \beta_1 w \times ATFP_{it} + \beta_2 RID_{it} + \phi X_{it} + \theta w \times RID_{it} + \tau w \times X_{it} + a_i + \mu_{it} \quad (14)$$

The weight matrix is w , and the influence coefficients are β , θ , and τ . Furthermore, the equation can decompose the total effect of rural industrial integration on ATFP in space, thus solving the direct effect and spatial spillover effect.

3.4. Sample data

This paper examines a sample of 30 Chinese mainland provinces, autonomous regions, and municipalities for the period 2008 to 2018 for the reason that data related to rural industrial integration calculations have only been available since 2008. Due to data availability, our sample does not include Tibet, Hong Kong, Macao, and Taiwan.

Agricultural input-output data comes from the China Rural Statistical Yearbook and China Statistical Yearbook. Data on agricultural products processing industry and service industry are sourced from the China Agricultural Products Processing Industry Statistical Yearbook and China Agricultural Products Processing Industry Development Report. Data on farmers' professional cooperatives are obtained from regional statistical yearbooks and regional market subject development reports in previous years. Data on facility agriculture come from the National Greenhouse System database. Data on rural development social groups are sourced from the China Civil Affairs Statistical

Yearbook in previous years. Data on control variables come from the China Rural Statistical Yearbook and EPS database. Table 2 displays the results of descriptive statistics of the main variables.

4. Empirical results and analysis

4.1. Estimation results of ATFP

Considering potential differences in production frontiers across regions, this paper employs the Malmquist index based on Global, using each province as a Decision Making Unit (DMU) to measure ATFP changes. From 2008 to 2018, ATFP in China exhibited an upward trend with an average annual growth rate of approximately 4.29%, aligning with the findings of other studies (Xu et al., 2019; Sheng et al., 2020; Li et al., 2021). We believe that the improvement in China's ATFP is mainly due to advances in agricultural technology and investments in infrastructure. First, China has continued to innovate in agricultural technology in recent years and has made breakthroughs in the seed industry and other areas. Second, China has promoted infrastructure construction in recent years, mainly high-standard farmland, which has improved agricultural production conditions.

Excluding a few provinces, more than half maintain positive ATFP growth, and growth tends to balance across regions. As the Malmquist index is transitive, this paper converts it into a growth index based on 2008. ATFP results are illustrated in Figure 3. These results demonstrate that ATFP growth in China is determined by both technical change (TC) and technical efficiency (EC). To describe the drivers of ATFP at different time periods, we selected 2012 as the time point because 2012 was the turning point when EC's contribution to ATFP turned from negative to positive. Before 2012, ATFP growth in China was driven by TC. After 2012, both TC and EC contributed to ATFP growth. We believe the likely reason is that China's emphasis on farmer training after 2012 has improved farmers' human capital, which is an important factor contributing to the gradual and rapid growth of EC after 2012.

4.2. Estimation results of rural industrial integration

The average value of rural industrial integration in China between 2008 and 2018 was 0.211, with an overall growth rate of 86.30% and an average annual growth rate of 7.85%. As for specific time trends, the level of rural industrial integration experienced the most rapid increase between 2013 and 2014, growing at a rate of 11.0%. Additionally, there are gradient features in the level of rural industrial integration, with noticeable differences in the development status among the four major regions. The detailed results can be seen in Figure 4. The eastern region consistently maintained a high integration value and led the other regions, with the integration value steadily rising from 0.187 in 2008 to 0.296 in 2018. The northeast region started with a lower integration value, but its growth rate was faster, showing potential to catch up with the eastern region in 2013. However, after 2014, the integration value in the Northeast began to decline. The integration values of the central

TABLE 2 Descriptive statistics of main variables.

Variables	Abbreviation	Obs	Mean	Std.dev.	Min	Max
Total agricultural production value	TAPV	330	2378.469	1728.262	144.991	8284.783
Land input	LANDI	330	5693.400	3828.116	106.400	15204.900
Labor input	LI	330	931.560	659.817	37.090	2847.000
Mechanical input	MI	330	3263.451	2905.645	94.000	13353.000
Fertilizer input	FI	330	191.269	145.835	7.300	716.100
Irrigation inputs	II	330	2111.271	1585.852	109.700	6119.600
ATFP cumulative index	ATFP	330	1.169	0.191	0.771	1.834
Level of rural industrial integration	RID	330	0.211	0.101	0.057	0.538
Infrastructure	ROAD	330	0.925	0.511	0.787	2.297
Human capital	EDU	330	9.676	1.151	6.971	13.617
Urbanization level	UR	330	0.553	0.131	0.291	0.896
Land quality	LAQA	330	0.391	0.169	0.118	0.989
Disaster rate	DR	330	0.188	0.137	0.000	0.695
Agricultural restructuring coefficient	AF	330	0.653	0.133	0.353	0.969
Fiscal support to agriculture	AS	330	0.111	0.031	0.030	0.190

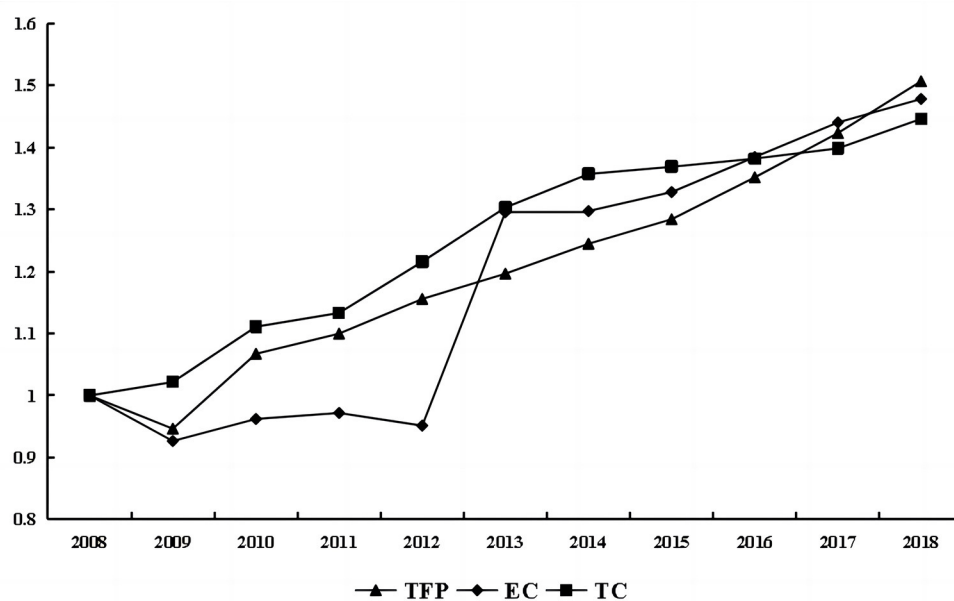


FIGURE 3
Trends of ATFP from 2008 to 2018.

and western regions were relatively similar each year, but generally, the western region was slightly higher than the central region.

4.3. Benchmark regression results

To study the impact of rural industrial integration on ATFP, this paper employs the fixed effect model in panel data for regression. Furthermore, the lag(1) of ATFP is included in the regression

equation, and the System Generalized Method of Moments (GMM) is conducted for the regression equation. The results of the Sargan test, AR (1), and AR (2) in Table 3 show that selecting the GMM is reasonable.

This paper primarily focuses on the impact of rural industrial integration on ATFP growth. The estimated results of both Model 1 and Model 2 have significantly positive coefficients for agricultural industry integration, indicating that rural industry integration development will increase ATFP, thus verifying Hypothesis 1-1. This is consistent with the findings of existing research

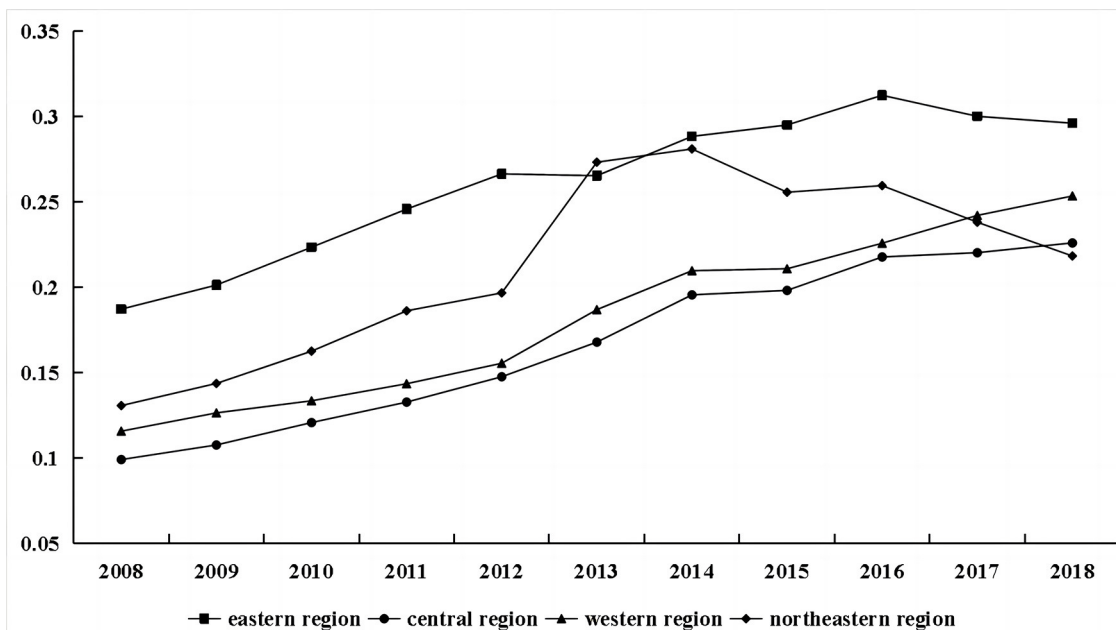


FIGURE 4

Trends of rural industrial integration from 2008 to 2018.

TABLE 3 Results of baseline regression.

Variables	Model 1	Model 2
L.ATFP	–	0.904*** (0.457)
RID	1.085*** (0.239)	0.558*** (0.174)
ROAD	0.147 (0.322)	–0.044 (0.035)
EDU	0.0435* (0.023)	0.075*** (0.007)
UR	0.689*** (0.238)	0.024 (0.071)
LAQA	0.165** (0.070)	0.003 (0.014)
AS	0.410 (0.322)	0.015 (0.023)
AF	–0.263 (0.862)	1.574*** (0.395)
DR	–0.039 (0.050)	–0.066*** (0.029)
Cons_	–2.658*** (0.768)	–0.201 (0.273)
R ²	0.794	–
Hausmann test	261.010(0.000)	–
AR(1)	–	–4.377(0.000)
AR(2)	–	0.930(0.352)
Sargan test	–	29.330(1.000)
N	330	300

***, **, and * are significant at the significance level of 1%, 5% and 10% respectively. Standard deviations are given in parentheses.

(Ye et al., 2020). On one hand, continuous promotion of rural industrial integration optimizes the allocation of agricultural production factors, such as urban and rural labor and land reconfiguration, improving ATFP. On the other hand, rural industrial integration can promote farmers' income, which, in

turn, eases financial constraints in agricultural production. Farmers can use this income to purchase more means of production, significantly increasing ATFP.

Model 1 also reveals the effects of other control variables on ATFP. Rural human capital increases agricultural total factor productivity, consistent with existing studies (Liu et al., 2021). Enhanced human capital raises the likelihood of adopting new agricultural technologies. Urbanization has a significant positive effect on agricultural total factor productivity growth, aligning with existing literature (Li et al., 2021), indicating that urbanization can improve agricultural labor allocation between urban and rural areas and promote ATFP. Land quality enhances agricultural total factor productivity, which is in line with existing studies (Ye et al., 2020). In recent years, the Chinese government has invested significantly in improving land quality through projects like high-standard farmland construction, medium- and low-yield agricultural improvement, farmland water conservancy infrastructure, deep plowing and deep pine technology, and farmland fallowing. The implementation of these projects has enhanced land quality in China, increased agricultural ATFP, and ultimately promoted sustainable agricultural development (Gong, 2018). Furthermore, we have not discovered empirical evidence suggesting that infrastructure, agricultural restructuring coefficients, fiscal support to agriculture, or disaster rates have an impact on ATFP.

4.4. Analysis of impact mechanisms

Referring to existing research (Färe et al., 1994), this paper divides the growth of agricultural TFP into technical change (TC)

TABLE 4 Impact of rural industrial integration on TC and EC.

Variables	Model 1	Model 2
RID	0.440* (0.237)	0.533* (0.300)
Cons_	−1.551** (0.702)	0.004 (0.532)
Control variables	Yes	Yes
R ²	0.639	0.300
N	330	330

***, ** and * are significant at the significance level of 1%, 5% and 10% respectively. Standard deviations are given in parentheses.

and technical efficiency improvement (EC), and further examines the mechanism of rural industrial integration development on ATFP growth. The results are shown in Table 4. The estimated results of Model 1 and Model 2 represent the impact of rural industrial integration on TC and EC respectively. The coefficients of both model 1 and model 2 in Table 4 are positive and significant, which indicates that the integrated development of rural industries can promote TC and EC. The rural industrial integration accelerates the agglomeration of agriculture-related industries, which is more likely to form agricultural technology innovation and thus promote agricultural technology progress. In addition, the rural industrial integration development can improve the technical efficiency in agricultural production by attracting high-quality capital to the countryside, revitalizing rural land resources, and improving the quality of agricultural labor. In summary, this paper verifies hypotheses 1-2.

4.5. Heterogeneity analysis

4.5.1. Regional heterogeneity analysis

The impact of rural industrial integration development on ATFP always depends on external factors such as resource endowment, economic development and agricultural policy bias. Affected by these factors, the impact of rural industrial integration on ATFP in western, central and eastern China may be significant differences. The fixed effect model is used to estimate the parameters. The results are shown in Table 5. Model 1, Model 2, and Model 3 are the regression results for the eastern, central, and western regions, respectively. As can be seen from Table 5, the regression coefficients for the eastern, central and western regions are significantly 0.785, 1.162 and 1.363, respectively. The coefficients for the eastern, central and western regions gradually increase, which indicates that there are significant regional differences in rural industrial integration on ATFP growth. The growth effect of rural industrial integration on ATFP mainly relies on the natural resource endowment of each region, and the western region can use its abundant natural resources and landmark agricultural product brands to develop leisure and tourism agriculture and agricultural product processing industry, which makes the ATFP growth effect of rural industrial integration in the western region higher than that in the eastern region. In summary, we test hypothesis 2-1.

TABLE 5 Regression results of regional heterogeneity.

Variables	Model 1	Model 2	Model 3
RID	0.785*** (0.238)	1.162* (0.589)	1.363*** (0.275)
Cons_	−4.939*** (1.235)	−4.274** (1.364)	0.730 (1.116)
Control variables	Yes	Yes	Yes
R ²	0.853	0.830	0.841
N	132	99	99

***, ** and * are significant at the significance level of 1%, 5% and 10% respectively. Standard deviations are given in parentheses.

4.5.2. Productivity heterogeneity analysis

To further explore the heterogeneity of the impact of integrated rural industry development on agricultural TFP growth, we conducted quantile analysis based on the previous empirical evidence. In this paper, the unconditional quantile regression is chosen for estimation, and the results are presented in Table 6. compared with the conditional quantile regression, the unconditional quantile regression does not depend on other variables in the model, and the estimation results can be more reliable (Agyire-Tettey et al., 2018). Models 1-model 5 in Table 6 represent the estimation results for quintiles 10, 26, 50, 75, and 90, respectively. The results show that the regression results are insignificant at quintile 10 and quintile 25, and significant and progressively increasing coefficients at quintile 50, quintile 75, and quintile 90. The results suggest that the effect of rural industrial integration on ATFP is greater in regions with higher ATFP growth. In summary, we tested hypotheses 2-2.

4.6. Spatial spillover effect of rural industrial integration on ATFP growth

The accelerating integration of rural industries will accelerate the cross-regional flow of production factors such as labor and capital, and often bring about spatial spillover effect. Therefore, this paper uses spatial econometric model to further explore the spatial effect between rural industrial integration and ATFP.

4.6.1. Spatial correlation analysis

Before constructing the spatial model, we need to test the spatial correlation of the core variables. This paper chooses global Moran's I index and Geary's C index to test the spatial relevance of ATFP and rural industrial integration. The results are shown in Table 7. As can be seen from Table 7, the values of the global Moran's I index and Geary's C index of the rural industry integration development level and ATFP of China are significantly larger than 0, which indicates that the rural industrial integration and ATFP showed significant positive correlation during the inspection period.

TABLE 6 Unconditional quantile regression results.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5
RID	0.111 (0.248)	0.051 (0.260)	1.155*** (0.402)	1.756*** (0.409)	2.146** (0.987)
Cons_	−0.791 (0.868)	−1.375** (0.548)	−2.726*** (0.919)	−3.894** (1.574)	−5.477** (2.468)
Control variables	Yes	Yes	Yes	Yes	Yes
R2	0.150	0.627	0.616	0.505	0.308
N	330	330	330	330	330

***, ** and * are significant at the significance level of 1%, 5% and 10% respectively. Standard deviations are given in parentheses.

TABLE 7 Spatial auto-correlation test results.

Variables year	Moran's I index		Geary's C index	
	ATFP	Rural industrial integration	ATFP	Rural industrial integration
2008	–	0.320***	–	0.464***
2009	0.221***	0.322***	0.387***	0.427***
2010	0.176**	0.347***	0.606**	0.401***
2011	0.200***	0.386***	0.629***	0.336***
2012	0.261***	0.401***	0.544***	0.302***
2013	0.242***	0.324***	0.571***	0.421***
2014	0.276***	0.331***	0.515***	0.424***
2015	0.281***	0.336***	0.504***	0.398***
2016	0.273***	0.346***	0.597***	0.401***
2017	0.175**	0.281***	0.549***	0.504***
2018	0.167**	0.232***	0.592***	0.590***

***, ** and * are significant at the significance level of 1%, 5% and 10% respectively.

4.6.2. Analysis of SDM results

Before spatial regression, it is necessary to test the rationality of the model. Referring to the existing literature (Wang et al., 2021; Bai et al., 2022), this paper sets three models of SAR, SEM, and SDM respectively, and selects the optimal model by parameters. Firstly, the spatial correlation coefficient is used to test whether there is spatial effect. Secondly, through LR test and Wald test to determine the rationality of SDM model selection. Wald and LR test results show that SDM model is better. Model 1 and model 2 are the results of adjacency matrix and economic distance matrix respectively. From the regression results of SDM in Table 8, we can see that the coefficient of RID is positive, which indicates that the integration of rural industries in this region will promote the upgrading of ATFP. The spatial coefficient of rural industrial integration is negative, which indicates that the rural industrial integration has negative spillover at the provincial level. Based on the above analysis, hypothesis 3 is verified.

4.6.3. Decomposition of spatial effects

The process of rural industrial integration and development will inevitably bring radiation effect, demonstration effect or resource plunder effect in space. In order to further explore the above effects, we will further analyze the effects of rural industry

TABLE 8 SDM model regression results.

Variables	Model 1	Model 2
RID	0.929*** (0.101)	0.585*** (0.090)
W × RID	−0.397** (0.195)	−0.589*** (0.144)
R ²	0.022	0.011
Control variables	Yes	Yes
Wald test	38.770***	67.320***
LR test spatial lag	37.960***	64.730***
LR test spatial error	38.320***	95.910***
Likelihood	507.141	542.867
N	330	330

***, ** and * are significant at the significance level of 1%, 5% and 10% respectively. Standard deviations are given in parentheses.

integration on agricultural TFP in the SDM model, including direct effects and indirect effects. In Table 9, the direct effects of Model 1 and Model 2 are positive, which indicates that industrial integration will have a positive impact on local ATFP, which further confirms Hypothesis 3. The negative coefficients of the indirect effects of model 1 and model 2 indicate that the rural industrial integration has a negative spatial spillover effect on ATFP.

TABLE 9 Decomposition results of SDM.

Model	Type of effect	Variable	Coefficient	t-statistic value
Model 1	Direct effect	RID	0.851***	9.380
	Spatial spillover effect	RID	−0.289**	−2.020
	Total effect	RID	0.562***	3.520
Model 2	Direct effect	RID	0.668***	7.780
	Spatial spillover effect	RID	−0.659***	−6.000
	Total effect	RID	0.008	0.060

***, ** and * are significant at the significance level of 1%, 5% and 10% respectively.

5. Discussion

This paper primarily aims to accurately measure the growth of ATFP and the level of rural industrial integration development in China. Furthermore, it investigates the impact, heterogeneity, and spatial effects of rural industrial integration development on ATFP using a suitable model, providing new insights for sustainable agricultural development. The empirical evidence discussed above has led to some intriguing findings.

Firstly, despite fluctuations in China's ATFP from 2008 to 2018, the overall trend was upward, with an average annual growth rate of 4.29%. These findings are consistent with existing literature (Liu et al., 2020; Ye et al., 2020; Li and Lin, 2022) and other studies using DEA to measure trends in ATFP growth. The growth of ATFP can be a good measure of the sustainability of national food production and is widely used as an evaluation indicator of sustainable development. To achieve food sustainability, Chinese agriculture must prioritize improving agricultural economic growth and efficiency while transitioning from a previous growth model to a more intensive one. ATFP, as a central aspect of intensive growth, reflects not only the efficiency of traditional production factor inputs to output but also the contributions and roles of factors like technological progress, technical efficiency improvement, and institutional changes in output growth (Binswanger, 1974; Chavas et al., 2018). In developed countries, agricultural sustainability is primarily achieved through ATFP enhancement. The rapid ATFP growth in China can be attributed to the contributions of agricultural science and technology progress, such as the widespread promotion of quality seeds, organic fertilizers, and biological pesticides. By relying on ATFP growth, China can maximize output with minimal input, given resource constraints—an essential tool for sustainable agricultural development.

Moreover, our study indicates that rural industrial integration effectively contributes to ATFP growth, thus achieving sustainable food production. This finding aligns with existing research (Ye et al., 2020). The results suggest that the government can promote food production specialization by promoting rural industrial integration to ensure food security. As agricultural development faces challenges like overexploitation of resources, overuse of inputs, and groundwater over-extraction, sustainable development becomes increasingly difficult (Razzaq et al., 2022). These issues can be alleviated through rural industrial integration. China's success in this area provides a new path for promoting sustainable agricultural development. In developing countries,

breaking the boundaries of rural primary, secondary, and tertiary industries and promoting rural industrial integration are crucial for sustainable agricultural development (Tian et al., 2020). Our study extends existing literature by exploring the mechanisms of action concerning agricultural technological change and improvements in agricultural technical efficiency. We found that rural industrial integration contributes to the enhancement of agricultural technological progress and agricultural technical efficiency. The continuous promotion of rural industrial integration accelerates the agglomeration of agriculture-related industries, which is more likely to foster agricultural technological innovation and promote agricultural technological progress (Zhao, 2019). Additionally, the improvement of agricultural technical efficiency relies on the combined allocation of production factors, and the integrated development of rural industries can optimize the allocation of factors. Specifically, rural industrial integration can improve technical efficiency in agricultural production through paths such as absorbing high-quality capital into the countryside, revitalizing rural land resources, and improving the quality of agricultural labor (Meng et al., 2018).

Furthermore, our study reveals that the impact of rural industrial integration on ATFP has significant regional heterogeneity in China. This effect is largest in the western region, followed by the central region, and smallest in the eastern region. Previous research (Zhang et al., 2020) analyzed the heterogeneity of rural industrial integration's effect but did not elaborate on possible causes. We offer an explanation for these causes. First, the growth effect of rural industrial integration on ATFP relies primarily on each region's natural resource endowment, with the western region utilizing its abundant natural resources and unique agricultural product brands to develop leisure, tourism agriculture, and agricultural product processing industries. This development results in a higher growth effect of rural industrial integration on ATFP in the western region compared to the eastern region (Ye et al., 2020). Second, human capital serves as a bridge for rural industrial integration to promote ATFP. In recent years, China has invested significant funds and policies to aid western development and the accumulation of human capital in western rural areas, such as professional farmer training and family farm recognition. For regions with low ATFP, such as the less developed western regions, the stock of human capital tends to be low. However, increasing its input tends to have a greater incentive effect (Zhang and Hu, 2020). The rural industrial integration for sustainable agricultural development exhibits regional heterogeneity. Therefore, it is

essential to develop a heterogeneous model of rural industrial integration for different regions to fully exploit its policy effects.

Lastly, our study found that rural industrial integration inhibits ATFP development in surrounding areas. The essence of rural industrial integration is economic agglomeration, which produces spatial effects. Existing research has begun to focus on the spatial spillover effect of rural industrial integration on farm household income (Abbas et al., 2016; Chen and Yu, 2022). However, few studies have concentrated on the spatial spillover effects of rural industrial integration on agricultural development. We attempt to fill this gap in the literature. We argue that rural integration promotes ATFP development in the region while inhibiting ATFP growth in surrounding areas, which may have a negative impact on food sustainability. Rural industrial integration absorbs talent, materials, and capital from neighboring areas through the agglomeration effect, promoting ATFP growth in the region. However, the loss of high-quality talent and capital from surrounding areas leads to a decline in ATFP, negatively affecting sustainable agricultural development. To promote sustainable agricultural development, appropriate protection policies should be formulated at the early stage of rural industrial integration to prevent the loss of quality resources. We believe that the negative impact of rural industrial integration on ATFP in surrounding areas is temporary, an inevitable occurrence in the early stages of economic development (Li and Ran, 2019; Ye et al., 2020). As rural industrial integration continues to advance, its impact on the periphery will shift from negative to positive. In the process of promoting rural industrial integration, developing countries should implement measures to reduce the initial siphon effect. Through these policy initiatives, we can effectively reduce the negative impact on the sustainable development of food in the surrounding areas during the initial phase of rural industrial integration.

6. Conclusions and recommendations

6.1. Conclusion

Rural industrial integration is a crucial approach to agricultural development and sustainable agricultural production. Studying whether rural industrial integration can enhance ATFP and achieve sustainable agricultural development is an important proposition. This paper measures the level of rural industrial integration by constructing a scientific and concise index system and examines the impact of rural industrial integration on ATFP from two perspectives: heterogeneity and spatial spillover effects. The research results are as follows.

- (1) The level of rural industrial integration and the growth rate of agricultural total factor productivity in China are gradually increasing, with average annual growth rates of 7.85% and 4.29%, respectively.
- (2) Rural industrial integration can increase ATFP growth. The impact mechanisms of rural industry integration on ATFP are technological change and technological efficiency improvement.
- (3) Due to differences in internal and external conditions and resource endowments, there is regional heterogeneity in the

impact of rural industrial integration on ATFP, with the most pronounced effects in the western region, followed by the central region and the smallest in the east.

- (4) The impact of rural industrial integration on ATFP has a marginal incremental effect. The impact of rural industrial integration on ATFP is more significant in areas with higher ATFP.
- (5) Rural industrial integration has a negative spatial spillover effect, inhibiting ATFP growth in surrounding areas.

6.2. Recommendations

Based on the above findings, this paper suggests that promoting sustainable agricultural development should not only rely on the development of rural industrial integration but also develop differentiated rural industrial integration initiatives according to regional heterogeneity and spatial spillover effects. The specific policy recommendations are as follows.

- (1) Each region should promote rural industrial integration according to local conditions. Regions should develop specialized industries based on actual local conditions, support regional specialty agricultural products, and improve regional ATFP by combining regional special industries and industrial integration in a reformative and innovative way.
- (2) The government should consider the heterogeneity of the impact of rural industrial integration on ATFP and optimize the spatial layout of rural industrial integration development. For China's central and western regions, policies should be implemented to accelerate rural industrial integration development and achieve ATFP growth to catch up with the east. For the eastern regions, the focus should be on the efficiency of integrated rural industry development and enhancing its impact on ATFP growth.
- (3) The government should improve and implement policies on talent introduction and investment. As China's rural industrial integration development is still in its initial stage, each region should attract high-quality agricultural producers and capital investment based on their comprehensive conditions to minimize the "siphon effect".

6.3. Limitations and prospects of the study

Our study provides new evidence to promote food sustainability in China. However, there are some limitations of the article. Limited by the availability of data, the data of our study is only updated to 2018. In future studies, we need updated data to examine the long-term effects of rural industrial integration on ATFP growth. Second, limited by the length of the article, we did not explore the impact mechanism in depth, which is a future research direction.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

Conceptualization, methodology, and data curation: FY and SQ. Software and investigation: FY. Validation: FY, QZ, and TT. Formal analysis: FY, NN, and QZ. Resources: FY and LW. Writing original draft preparation: FY, SQ, and TT. Writing, review, and editing: FY, SQ, NN, QZ, TT, and LW. Visualization: FY and TT. Supervision: SQ and QZ. Project administration: SQ, QZ, and NN. Funding acquisition: SQ. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Estimation of greenhouse gas emissions from Japanese healthy meals with different protein sources

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Introduction: Diets that promote people's health and environment-friendly are essential for achieving a sustainable society. Protein sources are the main contributors of greenhouse gas emissions (GHGE), and lower intakes of livestock meat and more intakes of poultry meat and legumes are recommended. Although Japanese consume less meat than other countries, it is unclear whether the GHGE of healthy Japanese meals is sufficient to solve climate change. In addition, most previous studies have focused on general household meals, not necessarily healthy meals. Therefore, we explored recommended food choices of protein sources in both healthy and environment-friendly meals.

Methods: We used data on healthy meals provided by retailers certified under the "Healthy Meal and Food Environment" Certification System. We first examined the number of main ingredients in the staple, main, and side dishes. We then compared the GHGE of meals with different combinations of main ingredients of main dishes (protein sources). To estimate the GHGE, we developed a database of GHGE per food weight for each food in the Standard Tables of Food Composition in Japan.

Results: Data on a total of 509 meals were considered in the analysis. The mean \pm standard deviation of the total GHGE of one meal was 1044.7 ± 614.9 g-CO₂ eq/650 kcal. The minimum and maximum values were 412.5 and 4268.5 g-CO₂ eq/650 kcal, respectively. Regarding meat, chicken was more likely to be used in meals with low GHGE.

Discussion: The healthy meals with the lowest GHGE in this study had the potential to contribute to solving climate change. Although healthy meals in this study were created with the same nutrient level criteria, a large difference existed between the minimum and maximum GHGE and it depends on the choice of protein ingredients. The findings may be useful to develop food guide for Japanese taking environmental perspectives into account.

KEYWORDS

climate, sustainable diet, healthy diet, greenhouse gas emission, food group

1. Introduction

In future food choices, it is essential to consider not only people's health, but also the global environment. Incorporating global environmental perspectives, the EAT-Lancet Committee has published guidelines for sustainable diets (Willett et al., 2019). They suggest a shift from an

animal-based to a plant-based diet. For example, the guideline recommends 14g of beef per day (Willett et al., 2019); this is a daily guideline, not for one meal, but per day. In addition, the EAT-Lancet guidelines are a uniform global policy, so each country needs to develop its own guidelines that take into account the health status and cultural background of the country (Willett et al., 2019). The Japanese Ministry of Agriculture, Forestry, and Fisheries (2022) has started to discuss the direction of future food guides based on the situation in other countries. The proposal was to add to the existing food guide “information that provides hints on specific food and ingredient choices in daily diets,” and to “quantitatively present such information using environmental indicators (Japanese Ministry of Agriculture, Forestry, and Fisheries, 2022).

One way to promote environmentally friendly food choices is to show the volume of greenhouse gas emissions (GHGE) contained in one meal (Japanese Ministry of Agriculture, Forestry, and Fisheries, 2022). The GHGE burden has been shown to vary widely among foods (Clune et al., 2017): vegetables, fruits, cereals (except rice), and pulses (including soybeans) have the lowest GHGE; eggs and non-ruminant livestock (fish, chicken, and pork) have medium GHGE; and ruminant livestock (sheep, cattle) have the highest GHGE. Meat has been shown to be the major source of GHGE emissions in the Japanese diet (Akenji et al., 2019; Sugimoto et al., 2021) and the factor that causes differences in GHGE emissions among household consumption (Koide et al., 2019; Li et al., 2022). Therefore, attention to the selection of protein sources may be important for reducing dietary GHGE.

A systematic review (Hallström et al., 2015) of the environmental impact reduction potential of dietary transformation included 12 studies that used GHGE as an environmental indicator and showed the GHGE reduction potential for each scenario compared with the reference diets in each study (the reference diets in most of the studies were estimated by using the average food intake in each country): vegan diet (no animal products, reduction potential: 25–55%), vegetarian diet (no meat products, 20–35%), ruminant replaced by non-ruminant (sheep and beef replaced by pork and chicken, 20–35%), and healthy diet (0–35%). Also, in examining meal levels, a meat-free diet reduced GHGE by up to 77% compared with the meat-containing diet (Ernststoff et al., 2019).

Previous studies in Japan have shown that the GHGE of diet or meals varied depending on the choice of protein source food groups (Ita et al., 2011; Sugimoto et al., 2021; Nakamura and Itsubo, 2022). However, the subjects of these previous studies were the average intake and model menus of the general population, not necessarily healthy meals. The average amount of protein source foods may differ between a typical family meal and a healthy meal. Therefore, understanding the environmentally desirable food choices and amounts of foods that serve as protein sources in healthy meals would enable us to propose both healthy and environmentally beneficial meals. However, to the best of our knowledge, no study has estimated GHGE in the Japanese healthy meals, and it is unclear whether the same food choices are recommended in healthy meals as in general household meals. The results of the comparison could also be applied to the development of food guidelines that incorporate environmental perspectives in Asian countries where rice is the staple food. This study follows the article that emphasizes the need to consider both health and environmental perspectives (Heller et al., 2013; Willett et al., 2019).

In Japan, the “Healthy Meal and Food Environment” Certification System was launched in 2018 to develop a healthy food environment

(“Healthy Meal and Food Environment” Certification System, 2023a). It certifies retailers that continuously provide healthy meals in a healthy environment through restaurants, takeouts (*bento*), and office meal services. The meals provided by certified retailers are nutritionally balanced meals that meet certification standards (“Healthy Meal and Food Environment” Certification System, 2023b); therefore, the meals could serve as a model for Japanese healthy meals. Also, the meals include a staple, main, and side (SMS) dish (in this study, “dish” referred to a cuisine as part of a meal. For example, salad, grilled fish, omelet, and so on). SMS meals are a traditional style of Japanese cuisine. A higher frequency of SMS meals has been associated with a better intake of nutrients (Kurotani et al., 2018), and higher adherence to Japanese food guidelines that recommend SMS meals is associated with a lower risk of total mortality (Oba et al., 2009; Kurotani et al., 2016). Therefore, examining specific characteristics of these healthy Japanese SMS meals may provide useful insights for other countries. SMS dishes each have a main ingredient: for example, the main ingredient of main dishes are meat, fish, soybeans, and eggs (Yoshiike et al., 2007). The number of main ingredients per meal and the amount of each main ingredient serve as specific characteristics of a meal.

To promote diets that improve people’s health and are sustainable from the global environment perspective, we need to know what ingredients to choose in a meal. This study was conducted to provide basic data for developing food guidelines of a healthy meal with low environmental impact. We used data for healthy Japanese meals and (i) estimate GHGE of Japanese healthy meals and (ii) explored the main ingredients of main dishes (protein sources) in low-GHGE meals.

2. Materials and methods

2.1. Data collection

We used the dietary data for healthy meals provided by retailers certified under the “Healthy Meal and Food Environment” Certification System between 2018 and 2020 in Japan. The meals provided by certified retailers met certification standards. An English translation of the certification criteria is shown in Supplementary Table 1. The certification standards for the two patterns’ energy category are set as “More than 450 kcal and less than 650 kcal” and “More than 650 kcal and equal to or less than 850 kcal,” respectively. Each retailer registers more than one menu item. Certification is conducted by the Healthy Meal and Food Environment Consortium, which comprises multiple academic associations related to nutrition and disease.

We included all retailers certified by 2020 and collected dietary data from all businesses that provided consent to use the data. We collected data from application documents submitted by retailers. We obtained data for 602 meals (368 restaurant meals and 234 takeout meals) from 136 retailers (91 restaurants and 45 takeouts).

Prior to data collection, we asked the retailers through the certification system management office to indicate whether they approved the following condition related to the research data: “The contents of the application documents will be compiled and analyzed as a whole by the consortium or the secretariat, and presented publicly or at conferences, etc.” Those retailers who agreed to the same were included in the analysis. The Healthy Meal and Food Environment

Consortium was informed of the use of the data from this survey and permission was obtained from them. Anonymous and statistical data collection was performed to ensure that individual retailers could not be identified, and efforts were made to protect personal information. As this study handled only dietary data, it was not subject to the Ethics Special Review Board of Ochanomizu University Biomedical Research.

2.2. Features of the meals: basic characteristics, nutrition quantity, and amount of food

The application documents submitted by the retailers included the retail sector, price, nutrition quantity, name of ingredients, and weight of ingredients in each meal. Because the nutrient calculation software differed among retailers, the researchers conducted nutrient calculations to unify them (Excel Eiyo-Kun ver. 8, Kenpakusha, Tokyo). The calculations were based on the food weight (g) of the ingredients reported by the retailers. Two researchers performed the nutritional calculations, and one researcher checked all the input data for any discrepancies with the data in the application documents of the retailers. After the nutritional calculations, the researchers confirmed that these nutritional quantities met the certification criteria.

In this study, the amount of food was calculated for each main ingredient of the SMS dishes. The definition of the main ingredients was based on the Japanese Food Guide Spinning Top (Japanese Ministry of Health Labour and Welfare, and Ministry of Agriculture, Forestry, and Fisheries, 2005; Yoshiike et al., 2007): main ingredients of staple dish (cereals); main ingredients of main dish [meat, fish and seafood (fish), soybeans, and eggs]; main ingredients of side dishes (vegetables, potatoes, mushrooms, and seaweed); and others (sugar, other beans, nuts, fat and oils, confectionary, beverage, and seasoning). In general, the main ingredients of these food groups were consistent with those in the Standard Tables of Food Composition in Japan (STFCJ; Japanese Ministry of Education, Culture, Sports, Science and Technology, 2015). As an exception, pulses were divided into soybeans and other beans because only soybeans are considered a main ingredient of main dishes.

In the data regarding the weight of ingredients submitted by the retailers, some of the same foods had different forms such as “raw” or “boiled.” Therefore, we unified the food weights before calculating the amount of food, using the method described in the National Health and Nutrition Survey (Japanese Ministry of Health, Labour and Welfare, 2019). Briefly, food weights were standardized to the steamed weight for rice, boiled weight for noodles, soaked weight for dried foods, and raw weight for all other ingredients.

2.3. The number of main ingredients of the SMS dishes

The main ingredients of the SMS dishes were defined based on the Japanese food guide. The main ingredients of each dish were as follows: staple dish—cereal; main dish—meat, fish, soybeans, eggs; and side dish—vegetables, potatoes, mushrooms, and seaweed. Of these food groups, we counted the number of main ingredients in the

SMS dishes. According to a previous study (Torheim et al., 2003) that counted the number of foods, the criterion was to use at least 0.1 g of each food group per meal.

2.4. Main ingredients for main dishes (protein sources)

The main ingredients of the main dishes were further classified into the following eight protein sources: beef, pork, chicken, other livestock meat (other meat), processed meat products (ham), fish, soybeans, and eggs. Meat was divided into subcategories (beef, pork, chicken, other meat, and ham) because of the differences in the GHGE burden of this food group (Clune et al., 2017; Sugimoto et al., 2021).

2.5. Calculation of dietary GHGE

To estimate the GHGE of meals, we developed a database of GHGE per food weight (g-CO₂ eq/g) for each of the foods in the STFCJ.

The method for creating the database was similar to the method described by Sugimoto et al. (2021) for creating the database for the production price-based Global Link Input–Output (GLIO) model. In their study, Sugimoto et al. (2021) created databases using three methods and compared them, and stated that the production price-based GLIO model method might be more valid than the other methods (literature-based method and consumption price-based GLIO model method).

Given the use of retailers’ meals in this study, many processed foods were not included in the STFCJ, and it was not possible to distinguish between cultured and natural fish. Therefore, we developed a new database with the aim of creating data for foods not listed in the STFCJ and data that take the production ratio of cultured and natural fish into account.

The method for creating the database has been described in detail by Sugimoto et al. (2021). Briefly, the database was developed through the following steps:

Step 1—Collection of unit production cost data: Collect unit production cost data for food commodities from the Table of Domestic Products (TDP) by Sector and Commodity 2005 (Japanese Ministry of Internal Affairs and Communications, 2005a).

Step 2—Supplementation of unit production cost data: For commodities for which unit production costs could not be collected in Step 1, data on production volume and production value were collected from national statistical data to calculate unit production costs. The statistical data used in this study are listed in Supplementary Table 2. For commodities for which unit production costs could not be collected in Step 1, data on production volume and production value were collected from national statistical data to calculate unit production costs (Japanese Ministry of Internal Affairs and Communications, 2005b; Japanese Ministry of Agriculture, Forestry and Fisheries, 2005a,b,c,d,e,f).

Step 3—Linking foods in the STFCJ to commodities in the TDP: For all foods in the STFCJ and all foods used in meals in this study, the food commodities in the TDP were linked. The rules for this link are based on those of Sugimoto et al. (2021).

Step 4—Calculation of unadjusted GHGE: The unit cost of the linked commodities was multiplied by the emission intensity of the commodities to obtain the GHGE (g-CO₂ eq/g) per food weight for each food product. The emission intensity was obtained by downloading the GLIO model values from the website of the Embodied Energy and Emission Intensity Data for Japan Using Input–Output Tables (National Institute for Environmental Studies, 2012). Nansai et al. (2012) have described a method for setting emission intensity.

Step 5—Calculation of the adjusted GHGE: The GHGE obtained in Step 4 was adjusted according to the food disposal and weight change rates. The disposal rate and weight change rates were obtained from the STFCJ.

In particular, the following special measures were used for foods in the STFCJ tied to multiple commodities:

- Chestnuts: For the two commodities tied to fruit and forestry specialties, the average GHGE was used.
- Leachate (tea, coffee): Adjusted GHGE values based on the ingredients (e.g., tea leaves) and water content in the STFCJ were used. For example, according to the STFCJ, green tea leachate can be prepared using 10 g of tea leaves in 430 mL of hot water. Therefore, the GHGE value of “green tea leachate” was determined by taking the average GHGE of “green tea (TDP commodity code 1129011101)” multiplied by 10/440 and the GHGE of “green tea beverage (TDP commodity code 1129021301).” Sugimoto et al. (2021) applied this method for tea and coffee, and it was also used for dashi (Japanese soup stock) in this study.
- Processed food: The GHGE was calculated assuming that the food was made from the ingredients. In this study, the recipes for processed foods in the STFCJ were used as a reference. Based on the total weight of the processed food, the GHGE per unit weight of processed food (g-CO₂ eq/g) was calculated.
- Fish and seaweed: Some fish and seaweed are tied to two or more of the following sectors in Step 3: marine fisheries, inland fisheries, marine aquaculture, and inland aquaculture. Sugimoto et al. (2021) used average GHGE values for multiple commodities. However, several fish species were biased toward one type of fishery. Therefore, in this study, the ratio of production for each type of fishery was determined and used to adjust the GHGE values. For example, “yellowtail” was tied to two commodities: “yellowtail (TDP commodities code 171011112)” for marine fishery and “yellowtail (TDP commodity code 311041102)” for marine aquaculture, with a 3:7 production ratio between these two items (Japanese Ministry of Agriculture, Forestry and Fisheries, 2005d). Therefore, the GHGE value for “yellowtail” was determined as the GHGE of “yellowtail” in marine fishery $\times 0.3$ + the GHGE of “yellowtail” in marine aquaculture $\times 0.7$. Adjustments were made for horse mackerel, ayu, carp, eel, salmon, flounder, pufferfish, yellowtail, bora, scallops, other shellfish, prawn, kelp, wakame seaweed, and other seaweed.

In addition to the GLIO model, the emission intensity of 3EID (Embodied Energy and Emission Intensity Data for Japan Using Input–Output Tables) is available. The most recent update of the GLIO model was in 2005, which is older than the 3EID model, which was

updated in 2015. However, the 3EID assumes that all food is produced domestically, whereas the GLIO model can account for food production systems outside Japan in its calculations. Because Japan relies on imports for food (Japanese Ministry of Agriculture, Forestry and Fisheries, 2021) and it has been reported that the GHGE load of food varies widely by country of production (Clune et al., 2017), the emission intensity of the GLIO model was used in this study.

Although the STFCJ was revised in 2020 in Japan, this study used the revised STFCJ in 2015. This is because the healthy meals used in this study were nutritionally calculated and certified under the STFCJ revised in 2015. Supplementary Table S3 shows the number of foods in the completed database and the representative values of the GHGE by food group.

2.6. Data analysis

All statistical analyses were performed using SPSS ver. 27.0. Categorical variables were described as distribution and continuous variables were described as mean \pm standard deviation. The amount of food in and the GHGE from the meals was adjusted to 650 kcal. Analysis of the GHGE and the amount of food of meals with different protein sources was performed only for the meal that had the greatest number of combinations of the number of main ingredients in each of the SMS dishes.

3. Results

Of the 602 meals for which dietary data were received, meals with missing data on the amount of ingredients and meals with overlapping menus among retailers were excluded; therefore, data on 509 meals were included in the analysis (analysis coverage, 84.6%).

3.1. Basic characteristics of the meals

The basic characteristics of the meals are listed in Table 1. The meals in this study were healthy and met the certification criteria. The criteria values for energy, fat, protein, and carbohydrate are presented as ranges in Supplementary Table 1. The nutritional quantity of meals in this study was approximately equal to the midpoint values of the criteria.

3.2. The number of main ingredients of the SMS dishes

The meals used in this study included SMS dishes and could be used as a model for healthy meals. We examined the number of main ingredient foods used in each of the SMS dishes in the meals. The results are shown in Table 1. There were 508 (99.8%) meals with one main ingredient as the staple food. Meals with one, two, three, or four main ingredients in the main dishes numbered 71 (13.9%), 218 (42.8%), 133 (26.1%), and 87 (17.1%), respectively. Meals with one, two, three, or four main ingredients in the side dishes numbered 41 (8.1%), 147 (28.9%), 210 (41.3%), and 111 (21.8%), respectively.

TABLE 1 Basic characteristics of diets included in this study ($n = 509$).

			All (<i>n</i> = 509)	
			<i>n</i>	%
Energy		450 ≤, < 650 kcal	264	51.9
		650 ≤, < 850 kcal	245	48.1
Business sector		Restaurant	316	62.1
		Takeout (<i>bento</i>)	193	37.9
Number of main ingredients ¹	Staple dishes	Nothing ²	1	0.2
		One ingredient	508	99.8
	Main dishes	One ingredient	71	13.9
		Two ingredients	218	42.8
		Three ingredients	133	26.1
		Four ingredients	87	17.1
		Side dishes	One ingredient	41
	Two ingredients		147	28.9
	Three ingredients		210	41.3
	Four ingredients		111	21.8
			Mean	±SD
Price		(JPY)	940	± 549
Nutrition quantity	Energy	(kcal)	658.2	± 93.0
	Protein	(% Energy)	16.4	± 2.1
	Fat	(% Energy)	25.7	± 2.9
	Carbohydrate	(% Energy)	56.7	± 3.5
	Salt	(g/650 kcal)	2.7	± 0.5

¹Based on the Japanese Food Guide Spinning Top, the main ingredients of dishes were categorized into staple dishes (cereal); main dishes (meat, fish, soybeans, and eggs); and side dishes (vegetables, potatoes, mushrooms, and seaweed).

²A meal consisting of starch noodles (potatoes) as a staple food.

3.3. Mean, minimum, and maximum value of GHGE in all meals in the analysis

In this study, we estimated the GHGE of meals by developing a database of production price-based GLIO models, using a method similar to that of Sugimoto et al. (2021). The mean dietary GHGE in this study was 1044.7 g-CO₂ eq/650 kcal. The minimum and maximum values were 412.5 and 4268.5 g-CO₂ eq/650 kcal, respectively. The protein sources of the meals with the minimum GHGE were “fish, meat (chicken), soybeans” (GHGE: 129.3, 15.8, and 5.7 g-CO₂ eq/650 kcal, respectively). The protein sources of the meals with the maximum GHGE were “meat (beef), fish, eggs” (GHGE: 1833.5, 1159.1, and 10.9 g-CO₂ eq/650 kcal, respectively). Other meals with low GHGE used more chicken, while those with high GHGE used more beef.

3.4. GHGE of meals with different protein sources

Table 2 shows the differences in GHGE among meals with different protein sources. Table 2 lists the number of protein source ingredients in descending order; the GHGE of meals with more than 10% of combinations is shown first, and the GHGE of meals with less combinations is shown below in each number of protein source ingredients group.

The mean GHGE for one, two, three, or four protein sources were 882.0, 1013.3, 1099.2, and 1172.8 g-CO₂ eq/650 kcal, respectively, and the GHGE tended to increase as the number of protein sources increased. Among the most common (more than 10% of each number of protein source ingredients group) meals with one protein source, the protein source was “meat (chicken),” “meat (pork),” and “fish” (GHGE [g-CO₂ eq/650 kcal]: 688.0, 862.6, and 1093.7, respectively), in order from lowest to highest GHGE. In meals with two protein sources, the protein sources were “fish, soybeans” and “fish, eggs” (GHGE: 1072.8 and 1202.5, respectively). In meals with three protein sources, the protein sources were “fish, meat (chicken), soybeans” and “fish, soybeans, eggs” (GHGE: 712.1 and 1272.9, respectively). In meals with four protein sources, the protein sources were “fish, meat (pork), eggs, soybeans” “fish, meat (chicken), soybeans, eggs” and “meat (beef, pork, chicken), fish, soybeans, eggs” (GHGE: 837.8, 941.3, and 1647.7, respectively).

Supplementary Table 4 shows the GHGE for each main ingredient of side dishes, with the mean GHGE for vegetables, potatoes, mushrooms, and seaweed being 145.2, 11.1, 33.7, and 12.8 g-CO₂ eq/650 kcal, respectively.

3.5. Amount of food of meals with different protein sources

Table 3 shows the amount of food used in the same meal as in Table 2: the items are arranged in the same order as those in Table 2.

The mean amount of meat, fish, soybeans, and eggs were 41.4, 29.8, 15.5, and 10.2 g/650 kcal, respectively. “Meat (chicken)” was the meal with the lowest GHGE with one protein source, and the amount of chicken was 86.7 g/650 kcal. “Fish, soybeans” had the lowest GHGE of the meals with two protein sources, with 69.1 and 30.5 g/650 kcal of fish and soybeans used, respectively. “Fish, meat (chicken), soybeans” had the lowest GHGE among the meals with three protein sources, with 25.9, 55.8, and 24.9 g/650 kcal of fish, chicken, and soybeans, respectively. “Fish, meat (pork), eggs, soybeans” had the lowest GHGE among the meals with four protein sources, with fish, pork, eggs, and soybeans used at 29.4, 34.9, 17.7 and 19.0 g/650 kcal, respectively.

As for the main ingredients other than protein sources, the mean amount of cereals was 169.2 g/650 kcal (steamed weight for rice, boiled weight for noodles). Cereals included rice and wheat: 466 meals (91.6%) used rice, and 287 meals (56.4%) used wheat. Vegetables were used in all meals, and the mean amount was 167.1 g/650 kcal (Supplementary Table 5).

TABLE 2 Greenhouse gas emissions (g-CO₂ eq/650 kcal) according to protein sources among Japanese healthy meals (*n* = 509).

Protein sources	n	Total/Meal	Staple ¹	Main dish									Side dish ²	Fruits	Milk	Others ³
				Meat						Fish	Soy-beans	Eggs				
				Total	Beef	Pork	Chicken	Other meat	Ham							
All																
	509	1044.7	152.5	255.9	138.0	77.4	28.1	3.0	9.3	246.9	25.3	18.3	202.9	12.0	22.3	108.5
Number of main ingredients of main dishes (protein sources): 1																
All	71	882.0	140.4	194.1	54.5	75.4	50.0	7.1	7.2	152.2	11.1	0.0	229.8	15.7	47.4	91.3
Meat (chicken)	24	688.0	133.9	129.2	0.0	0.0	129.2	0.0	0.0	0.0	0.0	0.0	248.8	19.7	81.0	75.4
Meat (pork)	11	862.6	162.1	404.7	0.0	404.7	0.0	0.0	0.0	0.0	0.0	0.0	203.2	16.2	0.0	76.5
Fish	19	1093.7	132.9	0.0	0.0	0.0	0.0	0.0	0.0	568.8	0.0	0.0	214.2	13.1	56.1	108.5
Meat (ham, chicken, and pork)	1	501.2	179.1	66.0	0.0	4.8	28.9	0.0	32.3	0.0	0.0	0.0	190.0	0.0	7.3	58.8
Soybeans	6	548.6	122.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	131.3	0.0	208.0	10.8	0.0	76.1
Meat (pork, chicken)	1	770.6	157.7	384.9	0.0	372.5	12.4	0.0	0.0	0.0	0.0	0.0	185.9	0.0	0.0	42.1
Meat (ham, chicken)	3	811.4	219.7	235.2	0.0	0.0	108.1	0.0	127.0	0.0	0.0	0.0	220.5	36.9	3.8	95.4
Meat (beef, pork)	1	1326.1	107.7	797.4	576.8	220.5	0.0	0.0	0.0	0.0	0.0	0.0	314.4	39.8	0.0	66.9
Meat (other meat, chicken)	1	1385.4	220.8	298.5	0.0	0.0	81.4	217.1	0.0	0.0	0.0	0.0	153.5	0.9	102.6	609.2
Meat (beef, pork, other meat, and ham)	2	1516.6	96.7	1022.6	825.6	76.1	0.0	71.5	49.4	0.0	0.0	0.0	309.5	0.0	26.7	61.0
Meat (beef, pork, and other meat)	2	1548.1	95.9	965.7	819.3	75.5	0.0	71.0	0.0	0.0	0.0	0.0	331.8	0.0	90.7	64.0
Number of main ingredients of main dishes (protein sources): 2																
All	218	1013.3	158.1	222.5	106.6	81.5	25.0	0.0	9.5	269.4	20.4	17.7	193.4	12.9	19.1	99.7
Fish, soybeans	34	1072.8	140.4	0.0	0.0	0.0	0.0	0.0	0.0	540.1	52.1	0.0	240.3	12.9	8.2	78.8
Fish, eggs	37	1202.5	167.0	0.0	0.0	0.0	0.0	0.0	0.0	712.7	0.0	38.5	157.0	26.1	6.2	95.0
Meat (chicken, ham), soybeans	1	502.9	163.0	146.6	0.0	0.0	117.4	0.0	29.1	0.0	15.7	0.0	133.7	0.0	0.0	43.9
Meat (chicken), eggs	19	562.3	153.8	89.2	0.0	0.0	89.2	0.0	0.0	0.0	0.0	66.1	157.9	9.5	15.0	70.8
Meat (chicken, pork), fish	2	651.1	173.7	183.6	0.0	43.7	139.9	0.0	0.0	8.5	0.0	0.0	231.9	0.0	0.0	53.5
Meat (pork, chicken), eggs	1	658.8	166.1	318.6	0.0	288.5	30.1	0.0	0.0	0.0	0.0	7.3	78.0	16.7	0.0	72.3
Meat (chicken), soybeans	14	680.4	156.4	101.0	0.0	0.0	101.0	0.0	0.0	0.0	70.4	0.0	276.5	2.7	4.4	69.0
Meat (ham, chicken), fish	4	695.0	129.8	112.9	0.0	0.0	45.9	0.0	67.0	98.4	0.0	0.0	249.2	0.0	67.5	37.2
Meat (pork, chicken), soybeans	4	715.2	144.3	246.4	0.0	196.9	49.5	0.0	0.0	0.0	67.3	0.0	158.9	0.2	37.0	61.1
Soybeans, eggs	4	728.2	139.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	130.0	33.6	291.6	12.3	35.1	86.1

(Continued)

TABLE 2 (Continued)

Protein sources	n	Total/Meal	Staple ¹	Main dish									Side dish ²	Fruits	Milk	Others ³
				Meat						Fish	Soy-beans	Eggs				
				Total	Beef	Pork	Chicken	Other meat	Ham							
Fish, meat (chicken)	15	776.4	162.9	94.3	0.0	0.0	94.3	0.0	0.0	126.6	0.0	0.0	233.3	14.5	61.2	83.7
Meat (pork), eggs	6	829.5	184.5	372.8	0.0	372.9	0.0	0.0	0.0	0.0	0.0	23.3	132.7	40.7	0.0	75.5
Meat (pork), soybeans	18	863.3	169.9	356.1	0.0	356.1	0.0	0.0	0.0	0.0	35.7	0.0	175.2	12.7	0.0	113.7
Meat (pork, ham), eggs	6	884.2	151.4	469.3	0.0	373.0	0.0	0.0	96.2	0.0	0.0	21.8	153.9	2.1	12.9	72.9
Meat (ham), soybeans	1	914.5	80.0	236.9	0.0	0.0	0.0	0.0	236.9	0.0	164.7	0.0	226.3	0.0	79.9	126.6
Fish, meat (pork)	19	929.8	175.7	196.0	0.0	196.0	0.0	0.0	0.0	234.4	0.0	0.0	179.0	1.8	11.7	131.3
Meat (beef, ham, pork), eggs	1	971.3	140.5	431.6	301.2	0.0	55.1	0.0	75.3	0.0	0.0	24.4	249.9	20.8	2.7	101.4
Meat (pork, ham), soybeans	1	1021.9	144.2	491.3	0.0	476.8	0.0	0.0	14.5	0.0	53.1	0.0	86.1	12.3	77.7	157.3
Meat (beef, ham, chicken, pork), fish	2	1059.5	151.2	373.9	261.7	24.3	30.7	0.0	57.2	165.3	0.0	0.0	239.3	0.7	2.0	127.0
Meat (ham), eggs	1	1181.8	311.7	87.4	0.0	0.0	0.0	0.0	87.4	0.0	0.0	56.3	207.1	101.0	306.6	111.8
Fish, meat (ham)	5	1241.2	155.2	82.2	0.0	0.0	0.0	0.0	82.2	691.3	0.0	0.0	206.0	8.0	20.7	77.8
Meat (beef, ham), eggs	1	1302.8	77.2	794.3	733.9	0.0	0.0	0.0	60.4	0.0	0.0	34.3	204.2	0.0	41.6	151.2
Meat (beef, pork), egg	11	1359.3	159.3	834.2	740.4	93.9	0.0	0.0	0.0	0.0	0.0	59.0	152.6	12.7	57.4	84.1
Fish, meat (pork, ham)	2	1389.9	195.2	311.4	0.0	215.8	0.0	0.0	95.6	660.6	0.0	0.0	196.9	0.0	0.0	25.9
Meat (beef, pork), fish	2	1454.0	127.1	665.8	664.9	1.0	0.0	0.0	0.0	294.3	0.0	0.0	193.1	7.8	69.3	96.5
Meat (beef), fish	4	1996.0	131.4	1215.1	1215.1	0.0	0.0	0.0	0.0	382.9	0.0	0.0	189.1	9.7	0.0	67.9
Meat (beef), eggs	1	2988.8	156.4	2645.5	2645.5	0.0	0.0	0.0	0.0	0.0	0.0	10.7	109.8	0.4	16.5	49.6
Meat (beef), soybeans	2	4114.5	153.0	2348.9	2348.9	0.0	0.0	0.0	0.0	0.0	6.8	0.0	133.1	8.0	63.5	1401.2
Number of main ingredients of main dishes (protein sources): 3																
All	133	1099.2	153.3	253.9	123.6	86.9	28.8	7.8	6.9	258.9	34.7	22.7	215.9	10.4	22.5	127.0
Fish, meat (chicken), and soybeans ⁴	18	712.1	147.1	83.1	0.0	0.0	83.1	0.0	0.0	175.1	43.3	0.0	177.3	9.6	0.4	76.4
Fish, soybeans, and eggs	18	1272.9	145.7	0.0	0.0	0.0	0.0	0.0	0.0	728.3	54.1	28.2	189.0	10.4	44.7	72.6
Fish, meat (ham, chicken), and soybeans	4	577.3	146.4	85.4	0.0	0.0	20.8	0.0	64.7	117.8	40.4	0.0	110.1	0.0	22.4	54.8
Meat (pork, chicken), fish, and eggs	1	591.8	152.5	110.8	0.0	58.3	52.5	0.0	0.0	68.9	0.0	15.5	142.1	1.4	46.0	54.5
Meat (chicken, ham), fish, and eggs	4	621.9	146.2	157.6	0.0	0.0	113.5	0.0	44.1	72.9	0.0	16.0	157.4	0.0	12.5	59.4
Meat (pork, chicken), eggs, and soybeans	2	663.1	152.5	244.8	0.0	181.1	63.7	0.0	0.0	0.0	20.3	34.3	165.3	0.0	0.0	46.1

(Continued)

TABLE 2 (Continued)

Protein sources	n	Total/Meal	Staple ¹	Main dish									Side dish ²	Fruits	Milk	Others ³
				Meat						Fish	Soy-beans	Eggs				
				Total	Beef	Pork	Chicken	Other meat	Ham							
Meat (other meat), soybeans, and eggs ⁵	4	669.2	155.3	257.7	0.0	0.0	0.0	257.7	0.0	0.0	49.3	8.7	152.4	0.0	0.0	45.8
Fish, meat (chicken), and eggs	9	674.5	168.9	68.5	0.0	0.0	68.5	0.0	0.0	137.8	0.0	24.5	190.4	2.9	16.1	65.4
Meat (chicken), soybeans, and eggs	7	702.1	149.5	110.1	0.0	0.0	110.1	0.0	0.0	0.0	50.8	24.8	225.3	10.7	73.6	57.4
Meat (beef, pork), fish, and eggs	3	753.5	180.2	292.8	224.6	68.2	0.0	0.0	0.0	54.1	0.0	37.6	123.3	0.0	2.7	62.6
Meat (pork), soybeans, and eggs	11	797.3	148.3	311.7	0.0	311.7	0.0	0.0	0.0	0.0	48.8	28.6	148.0	5.6	18.1	88.2
Meat (pork, chicken), fish, and soybeans	3	897.4	174.0	272.3	0.0	247.9	24.5	0.0	0.0	157.4	58.6	0.0	167.4	11.9	0.0	55.8
Meat (pork, ham), soybeans, and eggs ⁵	2	907.0	153.3	271.1	0.0	203.4	0.0	0.0	67.7	0.0	25.9	17.6	373.1	25.1	0.0	40.9
Fish, meat (pork), and eggs	12	954.9	136.5	202.4	0.0	202.4	0.0	0.0	0.0	220.4	0.0	54.8	193.6	12.6	20.8	113.9
Meat (beef, pork, and chicken), fish, and eggs	1	1143.7	108.3	624.1	388.0	214.6	21.5	0.0	0.0	62.3	0.0	2.8	240.8	0.0	34.9	70.6
Meat (beef, pork, and chicken), eggs, and soybeans	7	1204.9	192.4	577.9	476.6	82.9	18.4	0.0	0.0	0.0	23.3	29.7	254.5	0.0	16.3	110.8
Meat (beef), eggs, and soybeans	1	1424.9	183.7	915.4	915.4	0.0	0.0	0.0	0.0	0.0	4.1	85.4	145.2	0.0	0.0	91.1
Fish, meat (ham, pork), and eggs	2	1479.4	145.1	102.0	0.0	42.6	0.0	0.0	59.3	803.5	0.0	69.1	99.5	13.2	19.3	227.7
Fish, soybeans, and meat (ham)	1	1504.2	160.9	16.2	0.0	0.0	0.0	0.0	16.2	923.4	59.2	0.0	113.4	13.8	86.6	130.8
Fish, meat (pork), and soybeans	8	1539.2	146.8	197.8	0.0	197.8	0.0	0.0	0.0	471.1	100.1	0.0	530.2	0.3	0.0	92.8
Fish, eggs, and meat (ham)	4	1860.5	140.4	52.3	0.0	0.0	0.0	0.0	52.3	1232.0	0.0	58.1	226.0	13.0	58.8	79.8
Meat (beef, chicken), fish, and eggs	1	2295.5	143.5	1366.2	1361.6	0.0	4.5	0.0	0.0	371.5	0.0	47.0	322.2	1.3	0.0	43.8
Meat (beef, pork), soybeans, and egg	9	2367.6	159.1	1043.2	880.8	162.4	0.0	0.0	0.0	0.0	35.5	9.3	311.8	48.6	33.8	726.2
Meat (beef), fish, and eggs ⁵	1	4268.5	264.4	1833.5	1833.5	0.0	0.0	0.0	0.0	1159.1	0.0	10.9	349.9	94.2	60.5	496.0
Number of main ingredients of main dishes (protein sources): 4																
All	87	1172.8	147.3	392.9	307.1	54.3	17.1	0.0	14.5	249.4	35.0	28.2	184.7	9.0	9.8	116.5
Fish, meat (pork), eggs, and soybeans	15	837.8	148.1	172.8	0.0	172.8	0.0	0.0	0.0	176.5	32.5	33.1	167.5	13.0	7.7	86.4
Fish, meat (chicken), soybeans, and eggs ⁵	17	941.3	136.5	38.1	0.0	0.0	38.1	0.0	0.0	351.1	35.9	33.1	218.7	11.2	15.4	101.3

(Continued)

TABLE 2 (Continued)

Protein sources	n	Total/Meal	Staple ¹	Main dish									Side dish ²	Fruits	Milk	Others ³
				Meat						Fish	Soy-beans	Eggs				
				Total	Beef	Pork	Chicken	Other meat	Ham							
Meat (beef, pork, and chicken), fish, soybeans, and eggs	17	1647.7	134.7	848.6	818.0	19.4	11.1	0.0	0.0	277.3	21.9	16.2	205.7	7.3	3.1	132.9
Eggs, fish, meat (ham), and soybeans	2	711.4	110.1	90.5	0.0	0.0	0.0	0.0	90.4	119.2	16.0	136.6	122.6	12.5	34.6	69.3
Meat (pork, ham), soybeans, fish, and eggs	1	720.0	132.7	142.3	0.0	86.1	0.0	0.0	56.2	40.5	64.5	16.3	181.0	44.7	21.0	77.0
Meat (ham, beef, pork, and chicken), fish, soybeans, and eggs	2	721.9	158.3	179.5	49.2	28.1	21.2	0.0	81.1	147.5	10.4	7.6	171.4	0.7	6.8	39.8
Fish, meat (chicken, ham), soybeans, and eggs	6	735.5	175.1	100.4	0.0	0.0	56.1	0.0	44.3	221.6	28.9	25.3	112.3	1.8	0.0	70.1
Meat (pork, ham, and chicken), fish, soybeans, and eggs	5	804.4	144.9	283.6	0.0	146.9	27.0	0.0	109.7	36.0	27.1	23.5	194.6	14.3	0.0	80.3
Fish, meat (pork, chicken), eggs, and soybeans	8	899.2	161.1	53.2	0.0	39.2	14.0	0.0	0.0	461.2	7.5	18.8	109.5	1.4	5.3	81.1
Meat (beef, chicken), fish, eggs, and soybeans	2	1507.2	191.6	637.9	626.9	0.0	11.0	0.0	0.0	488.1	25.7	26.5	76.7	10.6	0.0	50.2
Meat (beef), fish, soybeans, and eggs	6	1786.2	166.2	948.6	948.6	0.0	0.0	0.0	0.0	143.5	115.4	48.2	261.6	10.9	40.7	51.1
Meat (beef, pork), fish, soybeans, and eggs	5	2020.2	145.0	888.7	766.8	121.9	0.0	0.0	0.0	148.7	67.5	7.2	225.0	4.5	5.3	528.3
Meat (beef, ham), fish, eggs, and soybeans	1	2409.9	140.1	1974.7	1930.5	0.0	0.0	0.0	44.2	17.1	9.3	15.0	199.3	0.0	9.8	44.6

The names of the combinations of protein sources describe from left to right the used foods with the highest average greenhouse gas emissions. Although this study included diets ranging from 450 to 850 kcal, GHGE was adjusted to 650 kcal for the analysis.

¹Cereals.

²Vegetables, potatoes, mushrooms, and seaweed.

³Sugar, other beans, nuts, fat and oils, confectionary, beverages, and seasoning.

⁴Includes meals with the minimum GHGE per meal (412.5 g-CO₂ eq/650 kcal) in all meals in the analysis (GHGE of each food: 129.3, 15.8, and 5.7 g-CO₂ eq/650 kcal, respectively).

⁵The meal with the maximum GHGE per meal (4268.5 g-CO₂ eq/650 kcal) in all meals in the analysis (GHGE of each food: 1833.5, 1159.1, and 10.9 g-CO₂ eq/650 kcal, respectively).

TABLE 3 Amount of food (g/650 kcal) according to protein sources among Japanese healthy meals ($n = 509$).

Protein sources	n	Total/Meal	Staple ¹	Main dish									Side dish ²	Fruits	Milk	Others ³
				Meat						Fish	Soy-beans	Eggs				
				Total	Beef	Pork	Chicken	Other meat	Ham							
All																
	509	569.9	169.2	41.4	5.3	15.8	18.8	0.6	0.9	29.8	15.5	10.2	199.9	10.5	7.8	85.6
Number of main ingredients of main dishes (protein sources): 1																
All	71	588.0	167.4	52.9	2.0	15.2	33.5	1.5	0.6	25.1	7.6	0.0	221.3	14.5	16.3	82.9
Meat (chicken)	24	649.9	173.8	86.7	0.0	0.0	86.7	0.0	0.0	0.0	0.0	0.0	235.4	12.4	31.1	110.5
Meat (pork)	11	527.9	180.5	81.6	0.0	81.6	0.0	0.0	0.0	0.0	0.0	0.0	204.1	15.9	0.0	45.8
Fish	19	577.3	165.0	0.0	0.0	0.0	0.0	0.0	0.0	93.8	0.0	0.0	203.8	16.6	11.9	86.2
Meat (ham, chicken, and pork)	1	501.3	212.2	23.3	0.0	1.0	19.4	0.0	2.9	0.0	0.0	0.0	235.6	0.0	1.0	29.2
Soybeans	6	571.8	169.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	90.0	0.0	220.2	9.3	0.0	82.9
Meat (pork, chicken)	1	478.5	168.6	83.5	0.0	75.1	8.3	0.0	0.0	0.0	0.0	0.0	202.2	0.0	0.0	24.1
Meat (ham, chicken)	3	542.3	150.8	83.1	0.0	0.0	72.7	0.0	10.4	0.0	0.0	0.0	190.5	45.0	0.7	72.3
Meat (beef, pork)	1	576.0	128.7	65.4	21.5	44.0	0.0	0.0	0.0	0.0	0.0	0.0	305.7	53.6	0.0	22.5
Meat (other meat, chicken)	1	720.3	163.8	100.3	0.0	0.0	54.7	45.6	0.0	0.0	0.0	0.0	203.2	0.3	74.3	178.4
Meat (beef, pork, other meat, and ham)	2	500.5	113.9	65.9	30.7	15.3	0.0	15.3	4.5	0.0	0.0	0.0	286.9	0.0	3.6	30.4
Meat (beef, pork, and other meat)	2	521.3	113.0	60.9	30.5	15.2	0.0	15.2	0.0	0.0	0.0	0.0	267.1	0.0	49.7	30.7
Number of main ingredients of main dishes (protein sources): 2																
All	218	572.6	171.5	37.9	4.0	16.4	16.6	0.0	0.8	33.3	12.2	9.8	202.8	11.0	6.9	87.2
Fish, soybeans	34	649.1	166.8	0.0	0.0	0.0	0.0	0.0	0.0	69.1	30.5	0.0	241.3	14.8	2.0	124.6
Fish, eggs	37	526.9	168.0	0.0	0.0	0.0	0.0	0.0	0.0	78.2	0.0	21.4	173.5	22.5	1.6	61.5
Meat (chicken, ham), soybeans	1	423.0	180.3	81.6	0.0	0.0	78.9	0.0	2.6	0.0	8.8	0.0	124.7	0.0	0.0	27.6
Meat (chicken), eggs	19	509.8	168.3	58.3	0.0	0.0	58.3	0.0	0.0	0.0	0.0	37.1	177.8	6.7	6.5	55.1
Meat (chicken, pork), fish	2	528.4	193.1	102.8	0.0	8.8	94.0	0.0	0.0	0.8	0.0	0.0	200.8	0.0	0.0	30.8
Meat (pork, chicken), eggs	1	595.1	179.4	78.4	0.0	58.2	20.2	0.0	0.0	0.0	0.0	3.9	142.8	18.6	0.0	171.9
Meat (chicken), soybeans	14	600.7	190.1	67.9	0.0	0.0	67.9	0.0	0.0	0.0	40.0	0.0	219.8	2.1	0.6	80.3
Meat (ham, chicken), fish	4	502.7	147.4	36.5	0.0	0.0	30.8	0.0	5.7	32.4	0.0	0.0	254.4	0.0	9.0	22.9
Meat (pork, chicken), soybeans	4	540.6	174.5	73.0	0.0	39.7	33.3	0.0	0.0	0.0	37.6	0.0	161.2	0.4	9.2	84.9
Soybeans, eggs	4	595.2	161.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	74.1	17.7	228.3	17.4	26.9	69.0
Fish, meat (chicken)	15	583.7	175.4	63.1	0.0	0.0	63.1	0.0	0.0	25.5	0.0	0.0	214.9	12.2	18.6	74.0

(Continued)

TABLE 3 (Continued)

Protein sources	n	Total/Meal	Staple ¹	Main dish									Side dish ²	Fruits	Milk	Others ³
				Meat												
				Total	Beef	Pork	Chicken	Other meat	Ham	Fish	Soy-beans	Eggs				
Meat (pork), eggs	6	624.5	178.0	75.2	0.0	75.2	0.0	0.0	0.0	0.0	0.0	12.4	214.0	12.9	0.0	132.0
Meat (pork), soybeans	18	612.3	173.5	71.8	0.0	71.8	0.0	0.0	0.0	0.0	22.6	0.0	202.1	14.7	0.0	127.6
Meat (pork, ham), eggs	6	517.3	168.1	82.7	0.0	75.3	0.0	0.0	7.4	0.0	0.0	11.9	191.0	0.7	5.3	57.7
Meat (ham), soybeans	1	597.4	194.7	21.4	0.0	0.0	0.0	0.0	21.4	0.0	149.8	0.0	184.5	0.0	10.7	36.4
Fish, meat (pork)	19	622.5	169.0	39.5	0.0	39.5	0.0	0.0	0.0	34.6	0.0	0.0	220.7	0.7	6.3	151.7
Meat (beef, ham, and pork), eggs	1	429.2	155.2	58.7	11.2	0.0	37.1	0.0	10.4	0.0	0.0	15.2	128.7	21.1	2.2	48.0
Meat (pork, ham), soybeans	1	678.2	160.3	97.3	0.0	96.2	0.0	0.0	1.1	0.0	29.7	0.0	161.3	4.0	32.1	193.6
Meat (beef, ham, chicken, and pork), fish	2	533.9	161.6	42.8	12.0	4.9	20.7	0.0	5.2	32.2	0.0	0.0	198.9	1.1	1.2	96.2
Meat (ham), eggs	1	589.2	80.4	12.1	0.0	0.0	0.0	0.0	12.1	0.0	0.0	35.2	147.5	44.2	195.9	74.0
Fish, meat (ham)	5	539.1	173.9	6.8	0.0	0.0	0.0	0.0	6.8	88.7	0.0	0.0	200.9	2.5	16.8	49.4
Meat (beef, ham), eggs	1	506.9	200.1	32.7	27.3	0.0	0.0	0.0	5.5	0.0	0.0	18.2	186.5	0.0	18.2	51.2
Meat (beef, pork), egg	11	509.4	176.7	46.5	27.5	18.9	0.0	0.0	0.0	0.0	0.0	32.0	189.1	13.1	13.9	38.1
Fish, meat (pork, ham)	2	530.2	196.8	51.6	0.0	43.5	0.0	0.0	8.1	56.6	0.0	0.0	206.9	0.0	0.0	18.3
Meat (beef, pork), fish	2	520.5	156.4	24.9	24.7	0.1	0.0	0.0	0.0	49.4	0.0	0.0	184.3	10.1	33.8	61.6
Meat (beef), fish	4	505.9	200.3	45.2	45.2	0.0	0.0	0.0	0.0	32.4	0.0	0.0	186.5	3.0	0.0	38.5
Meat (beef), eggs	1	498.2	171.9	98.4	98.4	0.0	0.0	0.0	0.0	0.0	0.0	5.7	178.9	0.5	11.8	31.0
Meat (beef), soybeans	2	648.5	158.5	87.3	87.3	0.0	0.0	0.0	0.0	0.0	6.0	0.0	205.3	2.6	26.2	162.5
Number of main ingredients of main dishes (protein sources): 3																
All	133	573.8	169.5	44.4	5.1	17.9	19.1	1.7	0.7	23.3	21.4	12.6	196.4	9.9	7.3	89.0
Fish, meat (chicken), and soybeans	18	570.6	173.9	55.8	0.0	0.0	55.8	0.0	0.0	25.9	24.9	0.0	182.6	11.3	0.1	96.1
Fish, soybeans, and eggs	18	627.0	180.8	0.0	0.0	0.0	0.0	0.0	0.0	59.2	31.0	15.9	201.0	8.7	9.1	121.2
Fish, meat (ham, chicken), and soybeans	4	467.5	165.5	20.3	0.0	0.0	13.6	0.0	6.7	47.5	27.9	0.0	165.0	0.0	7.2	34.1
Meat (pork, chicken), fish, and eggs	1	500.0	191.2	47.1	0.0	11.8	35.3	0.0	0.0	10.6	0.0	8.2	180.3	2.4	31.2	29.1
Meat (chicken, ham), fish, and eggs	4	507.4	168.9	68.4	0.0	0.0	64.3	0.0	4.2	18.5	0.0	9.0	207.0	0.0	2.6	33.0
Meat (pork, chicken), eggs, and soybeans	2	527.6	199.6	79.3	0.0	36.5	42.8	0.0	0.0	0.0	11.8	18.2	164.9	0.0	0.0	53.7
Meat (other meat), soybeans, and eggs	4	488.5	163.4	55.3	0.0	0.0	0.0	55.3	0.0	0.0	41.6	4.7	189.0	0.0	0.0	34.6
Fish, meat (chicken), and eggs	9	485.4	165.6	46.0	0.0	0.0	46.0	0.0	0.0	23.1	0.0	14.2	190.3	1.2	8.5	36.5
Meat (chicken), soybeans, and eggs	7	566.1	166.0	74.0	0.0	0.0	74.0	0.0	0.0	0.0	28.3	14.2	197.3	11.3	8.5	66.6
Meat (beef, pork), fish, and eggs	3	493.7	181.5	22.1	8.3	13.7	0.0	0.0	0.0	36.8	0.0	22.7	162.2	0.0	0.4	67.9

(Continued)

TABLE 3 (Continued)

Protein sources	n	Total/Meal	Staple ¹	Main dish									Side dish ²	Fruits	Milk	Others ³
				Meat												
				Total	Beef	Pork	Chicken	Other meat	Ham	Fish	Soy-beans	Eggs				
Meat (pork), soybeans, and eggs	11	563.1	168.7	62.9	0.0	62.9	0.0	0.0	0.0	0.0	27.6	15.5	186.8	3.8	7.8	90.0
Meat (pork, chicken), fish, and soybeans	3	549.5	177.4	66.2	0.0	50.0	16.2	0.0	0.0	7.0	52.1	0.0	195.9	11.8	0.0	39.1
Meat (pork, ham), soybeans, and eggs	2	590.2	181.2	50.4	0.0	41.0	0.0	0.0	9.3	0.0	9.3	9.3	279.7	25.2	0.0	35.0
Fish, meat (pork), and eggs	12	565.2	154.8	40.8	0.0	40.8	0.0	0.0	0.0	11.5	0.0	29.6	200.8	15.5	16.1	96.0
Meat (beef, pork, and chicken), fish, and eggs	1	473.6	133.3	72.1	14.4	43.3	14.4	0.0	0.0	17.6	0.0	1.4	204.9	0.0	13.7	30.5
Meat (beef, pork, and chicken), eggs, and soybeans	7	594.5	158.9	65.2	27.3	24.1	13.9	0.0	0.0	0.0	22.2	18.2	182.5	0.0	6.2	141.3
Meat (beef), eggs, and soybeans	1	642.7	204.2	34.0	34.0	0.0	0.0	0.0	0.0	0.0	2.3	45.4	158.8	0.0	0.0	198.0
Fish, meat (ham, pork), and eggs	2	574.5	160.4	15.9	0.0	8.6	0.0	0.0	7.3	49.4	0.0	36.7	205.6	4.7	4.3	97.4
Fish, soybeans, and meat (ham)	1	717.4	178.8	1.3	0.0	0.0	0.0	0.0	1.3	85.8	33.1	0.0	155.0	4.5	35.8	223.2
Fish, meat (pork), and soybeans	8	608.9	169.0	39.9	0.0	39.9	0.0	0.0	0.0	32.9	55.9	0.0	194.4	0.2	0.0	116.6
Fish, eggs, and meat (ham)	4	532.4	157.2	4.1	0.0	0.0	0.0	0.0	4.1	67.8	0.0	32.0	151.5	4.1	31.2	84.6
Meat (beef, chicken), fish, and eggs	1	631.2	176.3	54.9	50.7	0.0	4.3	0.0	0.0	59.0	0.0	29.4	262.0	2.5	0.0	47.1
Meat (beef, pork), soybeans, and eggs	9	707.9	176.9	65.5	32.8	32.8	0.0	0.0	0.0	0.0	24.8	5.0	265.2	50.2	6.6	113.7
Meat (beef), fish, and eggs	1	590.6	68.2	68.2	68.2	0.0	0.0	0.0	0.0	17.0	0.0	6.8	256.9	62.5	37.5	73.4
Number of main ingredients of main dishes (protein sources): 4																
All	87	542.1	164.4	36.2	11.5	11.3	11.9	0.0	1.4	34.9	21.1	15.5	180.2	7.2	3.8	78.8
Fish, meat (pork), eggs, and soybeans	15	562.0	161.4	34.9	0.0	34.9	0.0	0.0	0.0	29.4	19.0	17.7	182.0	9.9	3.4	104.3
Fish, meat (chicken), soybeans, and eggs	17	557.7	158.4	25.4	0.0	0.0	25.4	0.0	0.0	43.5	21.0	19.2	177.6	9.0	6.1	97.4
Meat (beef, pork, and chicken), fish, soybeans, and eggs	17	537.8	161.5	45.4	31.0	5.3	9.1	0.0	0.0	33.3	12.0	9.8	195.3	5.1	1.5	74.1
Eggs, fish, meat (ham), and soybeans	2	483.6	141.8	11.5	0.0	0.0	0.0	0.0	11.5	40.4	6.6	63.6	162.4	17.1	7.2	32.9
Meat (pork, ham), soybeans, fish, and eggs	1	562.5	147.6	21.7	0.0	17.4	0.0	0.0	4.3	6.9	47.7	8.7	224.4	43.4	8.7	53.4
Meat (ham, beef, pork, and chicken), fish, soybeans, and eggs	2	463.9	185.2	31.3	1.9	6.3	15.7	0.0	7.3	32.8	6.2	4.1	172.3	1.1	2.8	28.1
Fish, meat (chicken, ham), soybeans, and eggs	6	470.6	179.1	42.8	0.0	0.0	37.6	0.0	5.2	24.3	16.0	13.8	145.5	0.6	0.0	48.5

(Continued)

TABLE 3 (Continued)

Protein sources	n	Total/Meal	Staple ¹	Main dish								Side dish ²	Fruits	Milk	Others	
				Meat						Soy-beans	Eggs					
				Total	Beef	Pork	Chicken	Other meat	Ham							Fish
Meat (pork, ham, and chicken), fish, soybeans, and eggs	5	527.5	162.7	58.6	0.0	30.5	19.5	0.0	8.6	15.2	15.0	13.8	188.0	14.1	0.0	60.1
Fish, meat (pork, chicken), eggs, and soybeans	8	509.4	178.0	18.4	0.0	8.0	10.3	0.0	0.0	70.6	8.4	9.8	151.6	0.9	1.5	70.4
Meat (beef, chicken), fish, eggs, and soybeans	2	429.4	162.3	30.7	23.3	0.0	7.4	0.0	0.0	50.6	12.1	16.2	118.0	5.6	0.0	33.8
Meat (beef), fish, soybeans, and eggs	6	567.8	172.3	35.3	35.3	0.0	0.0	0.0	0.0	15.8	65.6	26.1	189.9	6.8	16.8	39.2
Meat (beef, pork), fish, soybeans, and eggs	5	670.2	161.5	53.1	28.5	24.6	0.0	0.0	0.0	28.7	49.1	3.9	224.1	5.8	1.0	143.0
Meat (beef, ham), fish, eggs, and soybeans	1	499.9	168.3	75.8	71.8	0.0	0.0	0.0	4.0	4.0	16.0	8.0	191.7	0.0	8.0	28.3

The names of the combinations of protein sources describe from left to right the used foods with the highest average greenhouse gas emissions (same order as Table 1). Although this study included diets ranging from 450 to 850 kcal, amount of food was adjusted to 650 kcal for the analysis.

¹Cereals.
²Vegetables, potatoes, mushrooms, and seaweed.
³Sugar, other beans, nuts, fat and oils, confectionary, beverages, and seasoning.

4. Discussion

This study aimed to examine desirable meals from two perspectives, namely, people’s health and the global environment, to develop food guidelines for sustainable diets in Japan. In particular, this study aimed to quantitatively demonstrate the differences in GHGE among different food choices in healthy meals. The results showed that despite using the same nutritional certification criteria, the GHGE of healthy meals varied greatly, depending on food choices. This study indicated that meals containing chicken may be desirable as a healthy meal that contributes to GHGE reduction.

In the present study, the minimum and maximum GHGE of a meal were 412.5 and 4268.5 g-CO₂ eq/650 kcal, respectively, and a wide range of GHGE was observed among the meals. In previous studies, GHGE was compared between model meals of the general population (Ita et al., 2011; Ernstoff et al., 2019; Nakamura and Itsubo, 2022). In these previous studies, the maximum difference in GHGE between meals was about three times (the GHGE of a meatless meal showed a 77% reduction of GHGE compared with a meat-containing meal; Ernstoff et al., 2019). The present study showed a larger difference in GHGE between meals than previous studies. This difference may have been influenced by the fact that the meals used in this study were healthy meals, or due to differences in the comparison conditions (i.e., presence or absence of meat or combinations of protein sources). The type of meat was subdivided as a comparison condition in this study. This study implies that dietary GHGE may be more strongly influenced by the type of meat than by the occurrence of meat.

This study is possibly the first to estimate GHGEs for healthy meals in Japan, and the meals with the lowest GHGE in this study might be recommended for solving climate change; the previous study (Akenji et al., 2019) that examined the target amount of GHGE reduction to achieve the 1.5 degree goal for climate change reported that 67% GHGE reduction is needed for Japanese people from 2017 to 2030. Based on this previous study, the dietary GHGE as of 2017 was 1,400 kg-CO₂ eq/capita/year, then we cloud estimate that Japanese people need to aim for about 462 kg-CO₂ eq/capita/year, 1.3 kg-CO₂ eq/person/day, and 422 g-CO₂ eq/capita/meal. The minimum GHGE value in our study was 412.5 g-CO₂ eq/meal, and approximately equal to the reduction target value. Therefore, the target value could be achieved by changing the food selection of protein sources.

In this study, chicken was found in meals with low GHGE, pork in meals with moderate GHGE, and beef and fish in meals with high GHGE. The results are consistent with previous studies that showed that meat and fish are the major sources of GHGE in the Japanese diet (Akenji et al., 2019; Sugimoto et al., 2021). The results were also consistent with previous studies that reported the GHGE load by food group (Sugimoto et al., 2021). Therefore, this study strengthened the evidence of recommendation of chicken-based meals for GHGE reduction, by the finding that they had the GHGE value that reaches the 1.5 degrees target for climate change. In addition, in this study, fish also appeared in some meals with low GHGE. Previous study has reported that different species of fish have different GHGE loads, for example, bluefish had a relatively low GHGE load (Clune et al., 2017). This may have influenced the result of this study. This study followed the food classification of Sugimoto et al. (2021) and therefore did not subdivide the species of fish, and few previous studies at meal-level have examined fish types separately and there were few references to

fish species in existing food guides from other countries (Japanese Ministry of Agriculture, Forestry, and Fisheries, 2022). Future studies should examine fish species separately.

In this study, the GHGE of a meal tended to increase as the number of protein sources increased. This means that GHGE increased even when soybeans and eggs, which have a low GHGE load, were combined with meat and fish, which have a high GHGE load. Therefore, it may be possible to reduce the GHGE of a meal by reducing the number of protein sources.

The results that show the number of main ingredients in the SMS dishes may be used to support the preparation of healthy meals. For example, the use of three or more main ingredients for side dishes may have contributed to meeting the certification criterion which was used for the meals examined in this study (at least 140 g of vegetables including potatoes, mushrooms, and seaweed). In previous studies, although potatoes, mushrooms, and seaweed were excluded, young children with a high vegetable intake consumed five or more types of vegetables in one meal, indicating that the number of foods may be used as an indicator of high vegetable intake (Yoshii et al., 2021).

This study created a database of GHGE and calculated dietary GHGE in roughly the same manner as Sugimoto et al. (2021). As a result, the GHGE of meals in our study was lower than the daily GHGE of healthy Japanese adults reported by Sugimoto et al. (2021, 2022). The difference in the GHGE values may have been influenced by differences in the completed databases. Also, compared to the average food intake of the Japanese population reported in the National Health and Nutrition Survey (Japanese Ministry of Health, Labour and Welfare, 2019), the meals in this study had more cereals and vegetables. For example, the percentage of the weight of cereals in the total weight of one meal was 29.7% in this study and 20.1% for Japanese aged 20 years and older (Japanese Ministry of Health, Labour and Welfare, 2019). So, it is assumed that the meals considered in this study were more plant-based than those of the general household, and this may have caused the difference between the GHGE values.

In conclusion, the healthy meals with the lowest GHGE in this study reached the target value for solving climate change. Meals with low GHGE were characterized by the use of chicken, consistent with previous studies. Since the study suggested that fish may contribute to GHGE reduction depending on the species, future studies of meals with low GHGE should subdivide the species of fish.

4.1. Limitations

Despite the importance of its findings, this study has some limitations. First, the number of meals of some combinations of protein sources was small. Therefore, only common combinations were focused on, and the number of combinations treated was limited. Moreover, the meals were served by restaurants and takeout (*bento*) retailers. Therefore, the results of this study may not be generalizable to meals of the general public. In addition, only one environmental indicator, GHGE, was used in this study. However, this study used an indicator of climate change, which is a typical environmental issue. Moreover, in previous studies using nitrogen footprints, healthy meals with a high nitrogen footprint used more pork and beef (Sameshima

et al., 2022), which was consistent with the characteristics of meals with high GHGE obtained in this study. Importantly, this study quantitatively showed that GHGE differed considerably among meals with different protein sources to include environmental perspectives in the food guidelines. Future studies should undertake similar investigations with larger sample sizes, consider food use in average households, and examine other environmental indicators.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RA and HS: research conception and design and writing of the manuscript. HS: statistical analysis of the data. HS, RA, FH, and YT: interpretation of the data and manuscript review and revision. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2023.1232198/full#supplementary-material>

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Assessing green total factor productivity and spatial spillover effect in China's maize industry for sustainable food production: a carbon emissions perspective

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Although Enhancing green total factor productivity (GTFP) within the agricultural sector is crucial for fostering sustainable development. In this paper, the GTFP of China's maize industry is analyzed using the SBM-GML index method, considering data from the primary maize-producing provinces from 2004 to 2020. This analysis incorporates carbon emissions as undesirable outputs. The spatial Durbin model aids in investigating the factors influencing maize GTFP. Our findings reveal a positive trajectory for China's maize GTFP over the designated period, featuring an average yearly increase of 0.8%. This ascension is primarily attributed to advancements in green maize technology. In the key cultivation regions of the Yellow and Huaihai areas, the Northern region, and the Southwest region, the average annual growth rates were 1.5%, 0.87%, and 0.09%, respectively. Among the direct influences, variables such as regional human capital, the extent of maize cultivation area, financial assistance towards agriculture, and the degree of agricultural mechanization considerably bolster the optimization of maize GTFP. Conversely, urbanization and the prevalence of natural disasters in the agricultural sector pose substantial challenges to enhancing maize GTFP. Furthermore, the spatial spillover effects reveal that natural agricultural disasters in a particular region inadvertently contribute to the improvement of maize GTFP in adjacent regions. Additionally, the regional human capital levels can significantly impede the progress of maize GTFP in neighboring regions. Therefore, to ensure food security, it is imperative to actively advocate for green development within the maize industry to Enhancing green total factor productivity (GTFP) in agriculture is crucial for agriculture to promote sustainable development. In this paper, using data from 2004–2020 from China's main maize-producing provinces, the SBM-GML index method is used to measure China's maize GTFP, and the spatial Durbin model is applied to examine the influencing factors and spatial spillover effects of China's maize GTFP growth. The results of the study revealed a positive trajectory of Chinese maize GTFP over the specified period, with an average annual growth of 0.8%. This enhancement is mainly attributed to the progress of green maize technology. The average annual growth rates were 1.5%, 0.87%, and 0.09% in the major cultivation areas of the Yellow and Huaihai regions, the northern and southwestern regions, respectively. The analysis of influencing factors showed that among the direct influencing factors, variables such as regional human capital, extent of maize cultivation area, financial assistance to agriculture and degree of agricultural mechanisation contributed significantly to the optimization of maize GTFP. Conversely, urbanisation and the prevalence of natural disasters in the agricultural sector pose significant challenges to improving

maize GTFP. Furthermore, spatial spillovers reveal that natural agricultural disasters in a given region unintentionally contribute to the improvement of maize GTFP in neighbouring regions. Furthermore, regional human capital levels can significantly hinder progress in maize GTFP in neighbouring regions. Therefore, in order to ensure food security, the greening of maize production must be actively promoted.

KEYWORDS

maize GTFP, spatial and temporal differences, food security, carbon emissions, spatial measurement

1. Introduction

As global climate change and resource shortages intensify, food production is slowing down, and the world's food supply is getting tighter. Maize is the world's most widely planted and most productive cereal crop, topping the list of the three major grains (maize, wheat, and rice). China is the world's second-largest producer and consumer of maize, with the second-largest sown area, total production, and consumption behind the USA (Kong et al., 2002; Olubunmi et al., 2022). In the last few years of the new century, China's maize production and consumption have grown quickly. In 2021, 43.32 million ha were planted, which is 44.75% of the total area of the three major staple foods and makes maize the largest grain crop currently planted in China at the moment. But, the negative externalities associated with the rapid growth of maize production have caused serious damage to the ecological environment. GTFP of maize refers to the inclusion of undesirable output such as carbon emission and non-point source pollution in the measurement of TFP of maize. The improvement of maize's GTFP has become an important tool to overcome the dilemma of "resource-environment-sustainable growth" in agriculture (Fu et al., 2022; Ye et al., 2023).

Currently, research on GTFP in agriculture has focused on these three areas (Song et al., 2022; Wang X. et al., 2022; Wang Y. et al., 2022). First is the definition of the concept of GTFP and the construction of the indicator system. GTFP refers to the inclusion of undesirable output indicators based on the traditional total factor productivity calculation that treats environmental pollution in the production process as a factor input or as a by-product of economic development and generally measures undesirable outputs around agricultural fertilizers, pesticides, surface pollution, and carbon emissions to make the study more scientific (Reinhard et al., 1999; Hailu and Veeman, 2001; Sun, 2022; Yu D. et al., 2022; Yu et al., 2022a,b).

The second aspect is about the methodology for measuring agricultural GTFP. There are two primary methods for calculating agricultural GTFP, namely the parametric method and the non-parametric method. The parametric method generally uses parametric stochastic frontier analysis (SFA), the SFA model beyond logarithmic functions, and the SFA-Malmquist method to measure and decompose agricultural total factor productivity (Hong et al., 2022; Wang F. et al., 2022; Wang L. et al., 2022). The DEA non-parametric method is the most commonly used method to measure AGTFP (Fang et al., 2021; Yang et al., 2022). The DEA method was first used to measure efficiency based on the traditional distance function (DF), but Faere et al. (1989) incorporated undesirable output into the efficiency measurement system and proposed a directional distance function (DDF) based on the output perspective. Chung et al. (1997) further

developed the Malmquist-Luenberger (ML) indicator based on the DDF to measure total factor productivity with undesired output. Based on Chung et al. (1997)'s research, Oh (2010) further proposed the Global-Malmquist-Luenberger (GML) index to address the problem that the ML index is not circularly transferable and cannot be solved by linear programming. Tone (2001) proposed a slack-based efficiency measure, the SBM method, for the "slack" problem.

The third aspect is about the search for factors influencing the optimization or deterioration of GTFP. In the relevant studies analyzing the factors influencing GTFP in agriculture, the influencing factors that are more recognized by most scholars include agricultural disaster rate, crop sowing area, mechanization level, production labor, irrigation facility level, economic development level, industrial structure, urbanization level, environmental regulation, and other aspects. The study showed that economic level, financial investment, wheat disaster area, and wheat sown area *per capita* all had a negative impact on the GTFP of wheat (Dai and Xu, 2022); five factors, such as grain production machinery and labor, had a significant positive or negative impact on the GTFP of grain in Henan Province; three factors, such as diesel used in grain production, had a significant negative impact on technological progress; and four factors, including financial input, had a significant positive or negative effect on technical efficiency (Deng, 2019). Furthermore, Sang et al. (2023) found that agricultural mechanization services help to narrow the income gap between rural households and alleviate income inequality in rural areas.

The above review reveals that previous studies have rarely included carbon emissions in the GTFP measurement system and have neglected the spatial effects of agricultural GTFP, resulting in biased conclusions. Given this, this paper attempts to make a marginal contribution to the research in this area through the following three aspects: First, the SBM-GML index method is used to measure maize GTFP from the perspective of carbon emissions and reveal its spatial and temporal evolution patterns. Secondly, in terms of research methodology, the spatial Durbin model is applied to explore the significant influencing factors of maize GTFP. Finally, spatial decomposition effects are applied to analyze the direct and indirect effects on maize GTFP.

The overall objective of this study is to determine the GTFP of maize in China based on a carbon emissions perspective and to identify its influencing factors for the sustainable development of the maize industry. Improving the green total factor productivity of corn is one of the ways to realize the sustainable development of corn production. More specifically, this study will: (1) establish a maize GTFP measurement system, SBM-GML, for measuring GTFP in China's major maize production areas and analyze its causes in both temporal and spatial dimensions; (2) identify the key causes affecting maize GTFP and spatial spillover effects; explore new pathways for achieving



green and high-quality maize development in China; help identify the main drivers of maize development and explore its intrinsic influence mechanism; and help the connotation and extension of maize green development; and (3) at the same time, using maize as the research object makes up for the lack of GTFP measurement research objects, and aims to explore a new way to achieve green and high-quality development of maize in China, reduce carbon emissions from maize production through agricultural technology progress and agricultural technology efficiency improvement, and explore its intrinsic influence mechanism by identifying the main driving forces of maize development, which has certain theoretical and practical significance.

The plan for the research is as follows: first, to measure China's maize GTFP and explain its endogenous sources of growth in both time and space; second, to analyze the important factors affecting China's maize GTFP and spatial spillover effects; and finally, to draw conclusions and make corresponding policy recommendations.

2. Materials and methods

2.1. Study area

China's major maize producing regions are divided into three agricultural zones due to their geographical location and resource endowments (Figure 1): the Northern Region, comprising six provinces (Heilongjiang, Jilin, Liaoning, Inner Mongolia, Gansu, and Xinjiang);

the Huaihai Region, comprising six provinces (Henan, Shandong, Hebei, Shanxi, Shaanxi, and Anhui); and the Southwest Region, comprising five provinces (Sichuan, Yunnan, Guizhou, Guangxi, and Hubei).

All seventeen of China's major maize-producing provinces were selected for this study. These provinces are leading the nation in maize sown area and total maize production (Figure 2), while the total maize production of the 17 provinces studied accounts for 95.08% of China's total maize production in 2022. They were chosen to be more representative of the study and reflect the changes in maize production in China (Kuo et al., 2022; Liu S. et al., 2022; Shuo et al., 2022).

Figure 3 shows that China's total maize production increased from 130,287,100 tons in 2004 to 27,255,06 tons in 2021, an increase of 1.09 times in production during the period; the sown area of maize expanded from 254,456,700 hectares to 433,242,400 hectares during the same period, an increase of 70.26%, and maize has become the largest sown area and most productive crop in China (Chen et al., 2022). China's maize production has been growing consistently since 2004, but the study period was set at 2004–2020 based on data availability.

2.2. Research methodology

2.2.1. Calculation of carbon emissions

In this study, carbon emissions are considered undesirable outputs. Based on the findings of previous scholars (Li et al., 2011; Xu T. et al., 2022), carbon emissions are calculated to include

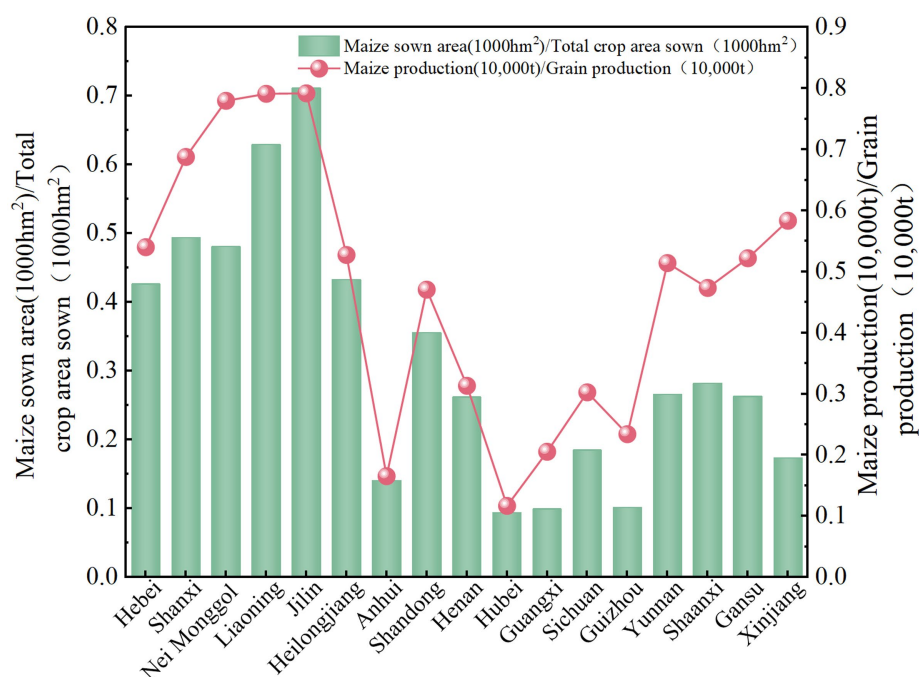


FIGURE 2

Total sown area and total production in China's 17 major maize-producing provinces, 2021.

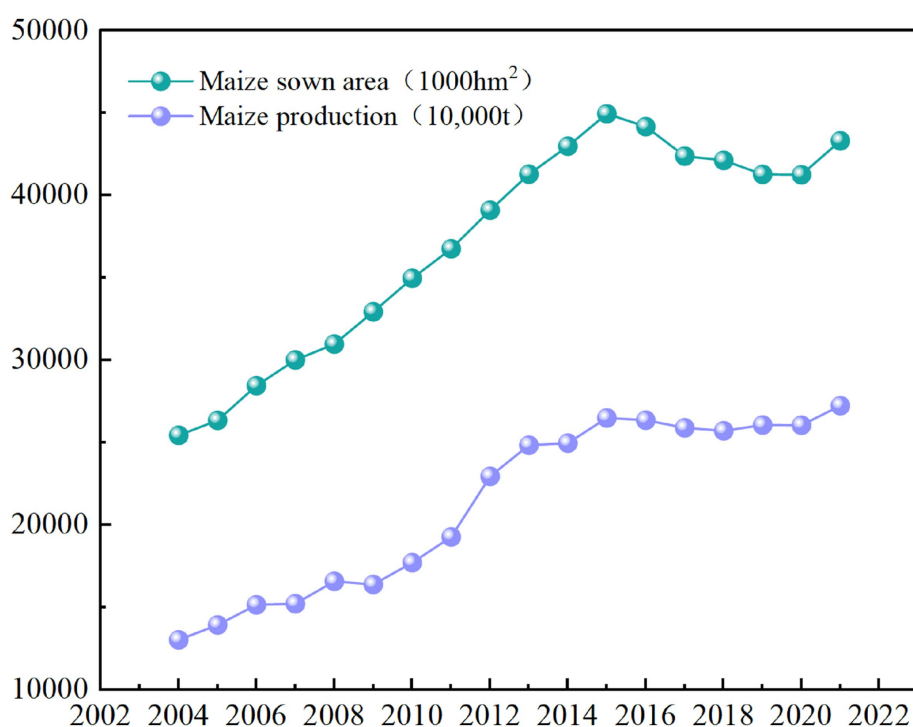


FIGURE 3

The change of maize sown area and production in China, 2004–2020.

emission factors for five sources of carbon emissions, namely, pesticide use, converted fertilizer use, agricultural film, agricultural diesel use, and maize sown area (Table 1), calculated as:

$$E = \sum E_i = \sum T_i \cdot \delta \quad (1)$$

Where, E represents the total carbon emissions in maize production, E_i represents the emissions of various carbon emission

TABLE 1 Carbon emissions' influencing factors and coefficients.

Carbon emissions source	Carbon emissions coefficient	Source of coefficient
Chemical fertilizer	0.8956 kg.kg ⁻¹	Oak Ridge National Laboratory, ORNL
Pesticides	4.9341 kg.kg ⁻¹	Oak Ridge National Laboratory, ORNL
Agricultural film	5.18 kg.kg ⁻¹	Institute of Resources, Ecosystems, and Environment of Agriculture, IREEA
Diesel oil	0.5927 kg.kg ⁻¹	IPCC
Plowing	312.6 kg.km ⁻²	Institute of Agriculture and Biotechnology of China Agricultural University, IABCAU

sources, T_i is the number of each carbon source, and δ is the carbon emission coefficient of each carbon emission source. The carbon emissions coefficient is derived from the existing literature. Based on the existing literature, this paper gives a summary of the carbon emission coefficient for growing (Table 1).

2.2.2. Measurement of green total factor productivity (GTFP) in maize

In this study, MATLAB software combined with SBM-GML index was used to measure. The SBM model solves the slackness problem and productivity evaluation problem (Kumar et al., 2021; Shi et al., 2022). The basic form of the model is as follows:

$$\left\{ \begin{array}{l} \rho^* = \min \frac{1 - \frac{1}{\rho} \sum_{p=1}^P \frac{S_p^x}{X_p^k}}{1 + \frac{1}{Q+1} \left(\sum_{Q=1}^Q \frac{S_Q^k}{Y_Q^k} + \sum_{R=1}^R \frac{S_R^u}{U_R^k} \right)} \\ Y_Q^k = \sum_{\lambda_k} \lambda_k Y_Q^k - S_Q^y \\ U_R^k = \sum_{\lambda_k} \lambda_k U_R^k - S_R^u \\ S_p^x \geq 0, S_Q^y \geq 0, S_R^u \geq 0, \lambda_k \geq 0, \sum_z \lambda_k = 1 \end{array} \right. \quad (2)$$

where, x_p^k, y_q^k , and u_r^k denote inputs, desired outputs, and undesirable outputs, respectively; P, Q , and R represent the numbers of the three vectors, respectively; s_p^x, s_q^y , and s_r^u represent slack variables for inputs, desired outputs, and undesirable outputs (carbon emissions), respectively; λ_k is the weighting percentage; $\sum_{k=1}^k = 1$ denotes constant returns to scale, or variable returns to scale if this constraint is removed. The objective function of SBM represents the ratio of input-output efficiency, and the SBM model measures only static productivity. This study uses the GML to measure the change in GTFP in Chinese maize agriculture by referring to Tone and Oh's research findings. The GML index can be expressed as:

$$GML_t^{t+1} = \frac{1 + D^G(P^t, Q^t, u^t)}{1 + D^G(P^{t+1}, Q^{t+1}, u^{t+1})} = \text{GEC} * \text{GTC} \quad (3)$$

GTFP in agriculture rises when $\text{GML} > 1$ and falls when $\text{GML} < 1$. The GML index is decomposed into technical efficiency and technical progress, with GEC denoting the technical efficiency index and GTC representing the technical progress index.

2.2.3. Spatial empirical methods

2.2.3.1. Estimation of Moran's I index

The global spatial correlation reflects the overall characteristics of the spatial association of variables and is often measured by the global Moran's I index (Chen and Shen, 2020; Pinto et al., 2021), which can be written as Equation 4.

$$\text{Moran's } I = \frac{\sum_{i=1}^n \sum_{j=1}^n \omega_{ij} (x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i=1}^n \sum_{j=1}^n \omega_{ij}} \quad (4)$$

where, S^2 is the variance of the sample and ω_{ij} is the (i, j) element of the spatial weight matrix. Moran's I index ranges from -1 to 1 , where a value greater than 0 indicates a positive correlation between regions, and the closer the value is to 1 , the greater the correlation; similarly, a value less than 0 indicates a negative correlation between regions. When $I = 0$, the variable is not spatially correlated, and the variables are not spatially correlated when $I = 0$. In the selection of the spatial weight matrix ω_{ij} , the geographical distance weight matrix is chosen in this study. The geographical distance between the capital cities of the two provinces is calculated by latitude and longitude, and the reciprocal of the distance is used as the weight setting, i.e., $w_{ij} = 1/d_{ij}$, if $i \neq j$; and $w_{ij} = 0$, if $i = j$.

2.2.3.2. Spatial Durbin model

It has been shown that agricultural GTFP exhibits a strong spatial correlation. Therefore, to examine the spatial autocorrelation of maize GTFP, traditional econometric regression models are no longer applicable, and this paper chooses to use spatial econometric models to analyze the intrinsic relationships. The more commonly used spatial econometric models include the spatial lag model (SLM), also known as the spatial autoregressive model (SAR), the spatial error model (SEM), and the spatial Durbin model (SDM), which under certain conditions can be formed into a spatial lag model and a spatial error model (Pan et al., 2021; Gu et al., 2022). In this paper, we construct a spatial econometric model to investigate the factors influencing GTFP in the main maize-producing areas of China. This will be followed by an LR test to verify whether the spatial Durbin model (SDM) degenerates into a spatial lag model and a spatial error model.

$$GTFP_{it} = \alpha_0 + \rho W GTFP_{it} + \alpha_i V_{it} + \theta_i W V_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (5)$$

Where, i denotes the i th maize-growing province and city, t denotes the year of observation, ρ is the spatial autoregressive coefficient of the explanatory variable (maize GTFP), α_i is the

coefficient of the influencing factor variable, μ_i is a regional fixed effect, δ_t is a time fixed effect, and ε_{it} is the residual term.

2.3. Description of variables

2.3.1. Input–output indicator selection

The accounting system for maize GTFP includes both input and output components. Choosing the right input and output variables is the key to measuring maize GTFP (Xu Q. et al., 2022). The three main types of input indicators are labor, agricultural materials, and land resources (Hlahla, 2022). Output indicators are divided into two main categories (Liu et al., 2023): desired output and undesired output. Drawing on the existing literature (Ma et al., 2022) combined with the characteristics of maize production, the input–output variables in this study were selected as shown in Table 2.

2.3.2. Selection of indicators for influencing factors

When carbon emissions are taken into account, the GTFP of maize mostly reflects how much the existing inputs of production materials contribute to the output. Based on the current maize production situation in China and the research results of other scholars (Zhang et al., 2021; Xing et al., 2023; Yao et al., 2023), the following indicators were chosen as the factors that affect maize's GTFP.

2.3.2.1. Explanatory variables

In this paper, maize GTFP is used as the explanatory variable, while maize GTFP is calculated from the SBM-GML index, which includes non-desired outputs. However, maize GTFP, as measured directly by the SBM-GML index, is a dynamic indicator. Therefore, it must be transformed by it. The year 2004 is set as the base period, and the GTFP for that year is specified as 1. The GTFP for other years is obtained by multiplying it cumulatively.

2.3.2.2. Explanatory variables

The key factors affecting GTFP include infrastructure, business conditions, and natural climate change. With reference to studies on the factors impacting GTFP in agriculture (Li et al., 2022), the following explanatory variables are selected in this paper: (1) The level of economic development (GDP), expressed using regional GDP *per capita*. (2) The level of urbanization (URB), expressed using the share of the non-farm population in the total population. (3) The level of agricultural natural disasters (ADR), as measured by the ratio of the area affected to the total area sown by crops in the region. (4) Regional human capital (HC), expressed using the average number

of years of schooling of the regional labor force. (5) Maize cultivation structure level (CPS), expressed as a share of the maize-sown area in the crop-sown area. (6) The level of financial support to agriculture (FSA), as measured by the expenditure on agriculture, forestry, and water in each province in a calendar year. (7) The level of agricultural mechanization (MACH), is measured by the ratio of total regional agricultural machinery power to total crop sown area.

2.4. Data sources and descriptive statistics

This paper uses 17 major maize-producing provinces in China as the study area, and the study spans the period 2004–2020. Data on inputs and outputs in the maize GTFP accounting were obtained from the 2005–2021 National Compilation of Agricultural Costs and Returns and the China Rural Statistical Yearbook. The National Compilation of Agricultural Costs and Returns, the China Agricultural Statistical Yearbook, regional yearbooks, and the EPS database were used to get information about other variables. Table 3 shows the results of the descriptive statistical analysis of the research data. In addition, the measurement results of this paper were mainly realized through Stata 17 software.

3. Results

3.1. Measurement of GTFP in maize in China

3.1.1. Chinese maize GTFP in a time-series perspective

The dynamic maize green total factor productivity (GTFP), maize green technical efficiency (GEC), and maize green technical progress (GTC) in the main maize-producing areas of China from 2004 to 2020 were measured using Matlab software based on the SBM-GML method, as shown in Figure 4. As can be seen in Figure 4, China's maize GTFP showed an overall “M”-shaped fluctuation during the study period, with sustained growth over a longer period from 2013 to 2018. From 2004 to 2014, China's maize GEC was higher than China's maize GTC for many years; from 2015 to 2020, China's maize GTC outpaced maize GEC, with an overall upward trend in maize GTFP driven by technological progress; and from 2013 to 2020, maize GTC was basically the same as maize GTC. In 2013–2020, maize GTC largely kept pace with maize GTFP, suggesting that the source of growth in maize GTFP was mainly maize green technological progress (Gao et al., 2022; Liu S. et al., 2022). The possible reason is that maize,

TABLE 2 Selection of input–output variables.

Indicators	Quantitative indicators	unit
Land input	Corn sown area	Ten thousand hectares
Labor input	Corn practitioners	Thousands of people
Mechanical input	Total power of corn production machinery	Ten thousand kilowatts
Pesticide input	Pesticide amount used in corn production	Ten thousand tons
Fertilizer input	Corn production of chemical fertilizer discount purity volume	Ten thousand tons
Expect output	Total corn production	Ten thousand tons
Non-expected outputs	Total carbon emissions from corn	Ten thousand tons

TABLE 3 Descriptive statistics for all variables.

Variables	Abbrev.	Unit	Mean	S.D.	Min.	Max.
Corn GTFP index	GTFP	–	1.008	0.158	0.532	1.577
Economic development level	GDP	RMB 10,000/person	3.121	1.673	0.424	7.671
Urbanization level	URB	%	0.481	0.098	0.263	0.721
Agricultural disaster area	ADR	–	0.217	0.141	0.016	0.689
Regional human capital	HR	Year	8.616	0.811	6.378	10.450
Plant structure level	CPS	–	0.271	0.160	0.050	0.697
Financial support for agriculture	FSA	–	43.079	30.947	3.381	133.936
Level of agricultural mechanization	MACH	–	0.544	0.229	0.170	1.270
Total corn production	OUTPUT1	10,000 tons	1105.750	857.507	176.100	3982.156
Corn carbon emissions	OUTPUT2	10,000 tons	6052.828	4072.977	1135.540	19914.860
Mechanical input	INPUT1	10,000 kw	1130.951	1016.264	88.106	4126.257
Land input	INPUT2	10,000 hectares	190.678	128.491	35.750	631.780
Labor input	INPUT3	10,000 people	150.631	83.714	30.945	407.579
Fertilizer input	INPUT4	10,000 tons	62.223	1.253	7.218	191.742
Pesticide input	INPUT5	10,000 tons	1.575	44.569	0.077	5.066
Diesel input	INPUT6	10,000 tons	82.478	71.511	4.8	487

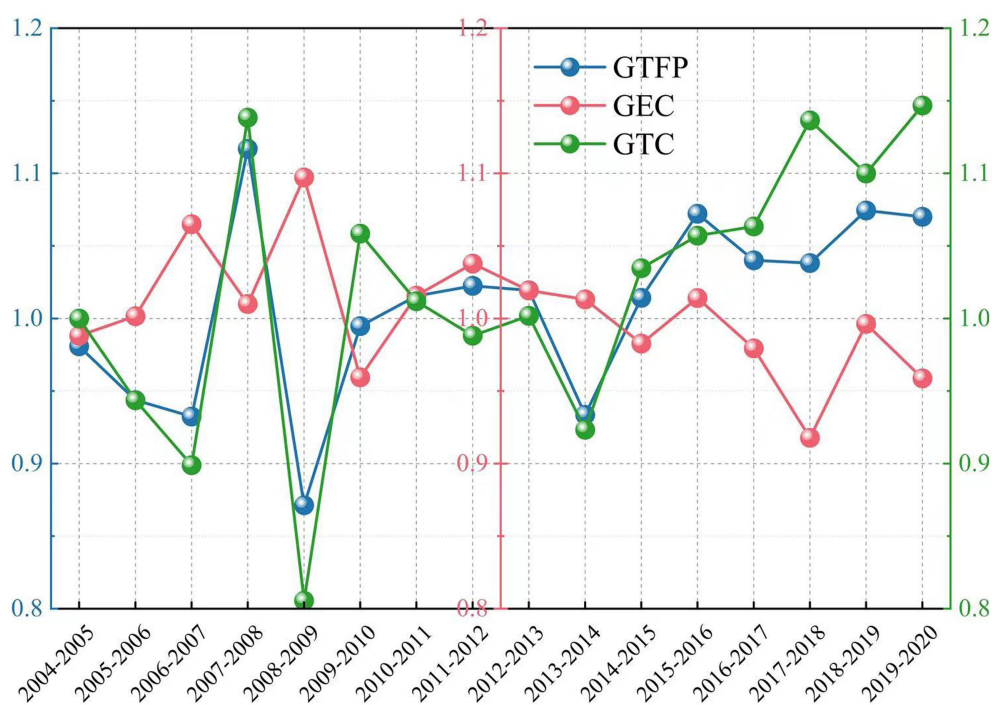


FIGURE 4
GTFP and its decomposition for maize production in China, 2004–2020.

as one of the three main grains in China, is easy to popularize agricultural technology in the process of maize production, which is conducive to the growth of GTFP of maize.

Table 4 shows the change in GTFP and its decomposition index for the main maize-producing areas from 2004 to 2020. There has been a long-standing and unavoidable pattern of unrefined agricultural growth that depletes resources and pollutes the environment, and the maize GTFP that reflects this reality is closer to the actual efficiency of maize production. Overall, the average value of GTFP in China's major maize-producing areas from 2004 to 2020

is 1.008. Even though there is a general trend toward more efficiency, the growth of maize GTFP is weak, mainly due to the large decline in maize GTFP in the early years, which slowed down the growth dynamics.

The dynamics of agricultural GTFP in the major grain-producing regions in 2002–2019 can be broadly discussed in the following three phases: (1) From 2004 through 2009, it can be seen that GEC drove GTFP, while GTC hindered its enhancement, and the impact of GTC on GTFP was more significant. Therefore, the drive of GEC failed to compensate for the negative effect of GTC, thus preventing GTFP from

TABLE 4 Values of GTFP, GEC, and GTC for maize production in China, 2004–2020.

Year	GTFP	GEC	GTC
2004–2005	0.981	0.988	1.000
2005–2006	0.944	1.002	0.944
2006–2007	0.932	1.065	0.899
2007–2008	1.117	1.010	1.138
2008–2009	0.871	1.097	0.806
2009–2010	0.995	0.959	1.059
2010–2011	1.016	1.016	1.012
2011–2012	1.022	1.038	0.988
2012–2013	1.019	1.019	1.002
2013–2014	0.934	1.013	0.923
2014–2015	1.014	0.983	1.035
2015–2016	1.072	1.014	1.057
2016–2017	1.040	0.979	1.063
2017–2018	1.038	0.918	1.137
2018–2019	1.074	0.996	1.100
2019–2020	1.070	0.959	1.147
Average	1.008	1.003	1.019

MATLAB software results collated.

improving. (2) Between 2010 and 2016, GEC remained dominant, showing significant fluctuating growth with a significant positive effect on the change of GTFP, and the improvement of GTC had a significant impact on GTFP when the two-way driving effect of GEC and GTC enabled GTFP to improve effectively. (3) Between 2016 and 2020, the development of green technology in China significantly improved, in which the change in GTC is the main one and has a significant positive effect on the change in GTFP, while the effect of GEC on GTFP is negative. The improvement in GTC can compensate for the negative effect caused by the decline in GEC, which in turn promotes the improvement in GTFP. During this period, the development of green technology was an important factor contributing to the increase in GTFP, which could be attributed to the introduction of government policies on non-point source pollution, which increased investment in new technologies, thus promoting the development of green technology and thus the increase in GTFP (Huang et al., 2022).

3.1.2. The spatial perspective of Chinese maize GTFP

The annual average GTFP change indices and decomposition indices for the 17 provinces in China's major maize-producing regions and the northern region, the Yellow and Huaihai Sea region, and the southwest region from 2004 to 2020 are shown in Table 5. At the provincial level, from 2004 to 2020, 15 provinces (Heilongjiang, Jilin, Liaoning, Neimenggu, Xinjiang, Henan, Shandong, Hebei, Shanxi, Shaanxi, Anhui, Sichuan, Yunnan, Guizhou, and Guangxi) have an agricultural GTFP change index greater than 1, and only two provinces (Gansu and Hubei) have a maize GTFP change index less than 1.

The majority of provinces were able to keep making progress toward being green and efficient. Among them, Heilongjiang ranks first in the GTFP for maize with a GTFP change index of 1.050, while Hubei ranks last with a GTFP change index of 0.967, making

the difference in maize GTFP between provinces more obvious. According to the indices of GTFP, GEC, and GTC in the major maize-producing provinces, they are divided into the following three types: (1) The high-efficiency zone of maize green production (Heilongjiang, Henan, Hebei, Shandong, Guizhou, and Liaoning). The difference between GEC and GTC in these provinces is small, suggesting that both GEC and GTC are driving maize GTFP growth. The balance between economic growth and environmental friendliness in maize production is well achieved. (2) The medium maize green production efficiency zones (Yunnan, Shaanxi, Sichuan, Guangxi, Neimenggu, and Xinjiang), where the degree of improvement in agricultural green production is relatively small. This can be explained by the immaturity of early agricultural production systems, the relatively weak awareness of environmental protection and resource conservation among farmers, and the frequent occurrence of natural disasters, which eventually resulted in a slightly declining GTFP. (3) Maize green production efficiency zones (Jilin, Shanxi, Anhui, Gansu, and Hubei), which had an average annual maize GTFP index of less than 1 in these provinces from 2004 to 2020 and whose overall production efficiency was in retreat due to their primitive agricultural production practices.

At the regional level, the best result in green maize production is in the Yellow and Huaihai regions, with a maize GTFP variation index of 1.015, it may be caused by the different level of economic development, technological innovation strength and technological improvement efficiency among different regions, and the maize GTFP of three provinces, Henan, Hebei, and Shandong, is greater than the average of all provinces. Lastly, the southwest region has a maize GTFP index of 1.001, but the overall agricultural GTFP is still on the rise between 2004 and 2020, with Sichuan, Guangxi, and Hubei provinces all ranking lower. Therefore, it is necessary to improve the green production status of maize in the southwest region.

Table 5. Comparative analysis of maize GTFP, GEC, and GTC by major maize-producing areas in China, 2004–2020.

3.2. Spatial correlation test

Before establishing a spatial measure, a pre-test for spatial autocorrelation must generally be conducted. The most famous ones are the Moran's I index, the Geary's C index, and the Getis-Ord index, while the Moran's I index is now preferred for testing among most studies (Maya et al., 2019). From the results of the global Moran's I index test, it was observed that maize GTFP was significant and positive in the majority of years, indicating a strong spatial autocorrelation of agricultural GTFP. The global Moran's I test shows that maize GTFP in China shows a strong spatial dependence in all years. The global Moran's I test (Table 6) shows that the maize GTFPs in China all exhibited strong spatial dependence.

3.3. Spatial regression results

The Hausman test was used to determine whether fixed effects or random effects were used for the spatial regressions, and the results were significant at the 1% level, rejecting the original hypothesis that fixed effects were better than random effects. In the selection of the spatial econometric model, the spatial lag model (SAR), the spatial error model (SEM), and the spatial Durbin model (SDM) were regressed under the selected geographic distance weight matrix, and the LR test was applied to verify whether the spatial Durbin model (SDM) would degenerate into the spatial lag model (SAR) and the spatial error model (SEM), and the statistical value results were significantly positive at the 1% level. Significantly positive; therefore, the final regression results of the Durbin spatio-temporal stationary model were selected for analysis as follows (Table 7).

In the spatial Durbin model, the coefficients of the direct effects of the level of urbanization and the level of financial support to agriculture were both significantly positive, which indicates that these variables helped increase maize GTFP. On the other hand, the level of agricultural disaster and the level of agricultural mechanization, both of which were significantly negative at the 5% level, slowed the growth of maize GTFP. However, the regression coefficients of economic development level, regional human capital, and maize planting structure level were not significant, but the coefficient of the spatially lagged term of regional human capital was significantly negative at the 1% level and the coefficient of the spatially lagged term of maize planting structure level was significantly positive at the 5% level, indicating that the effect of high or low regional human capital and a reasonable maize planting structure level on maize GTFP in the province was not significant. The coefficient of the spatially lagged term is positive at the 5% level. In addition, the coefficient of the spatially lagged term of the degree of agricultural disaster is significantly negative at the 10% level, showing a negative spatial spillover effect on the GTFP of agriculture in neighboring provinces, while the coefficient of the spatially lagged term of the level of financial support to agriculture is significantly positive at the 5% level, showing a positive spatial spillover effect on the GTFP of agriculture in neighboring provinces.

3.4. Decomposition of spatial effects

Table 8 shows the results of the effect decomposition of the spatial Durbin model. The significant influences are explained in this study as follows:

- (1) The regression coefficient for the level of urbanization (URB) is significantly negative at the 10% level, with each unit of elevation reducing the maize GTFP by 1.550 units, and its direct and indirect effects are both negative, indicating that the rural population moves to a certain extent into the urban, it not only inhibits the elevation of the maize GTFP in the region but also hinders the development of the maize GTFP in neighboring areas.
- (2) In terms of direct effects, the coefficient of the impact of the level of agricultural natural disasters (ADR) on the GTFP of maize in the region was negative and passed the 1% significance test. This indicates that the level of agricultural natural disasters had a negative, hindering effect on the GTFP of maize in the region. In the indirect effect, the coefficient of the effect of the level of agricultural natural disasters on GTFP in the surrounding area was positive and passed the significance test at the 10% level. This indicates that the level of agricultural disaster has a positive effect on the GTFP of maize in geographically adjacent areas.
- (3) For every additional unit of regional human capital (HC), maize GTFP goes down by 0.229, which is not statistically significant. The effects of direct and spatial spillover are 0.156 (significant at the 1% level) and -0.385 (significant at the 5% level), respectively. The results indicate there is a certain offsetting effect between the direct and indirect effects, which ultimately makes the total effect insignificant, so it is necessary to reasonably guide the flow of talents between provinces to bring into play the positive externalities of human capital.
- (4) For every 1 unit increase in cropping structure (CPS), maize GTFP increases by 1.145, which mainly comes from the direct effect. The indirect effect is not statistically significant, which indicates that the adjustment of crop structure only positively affects maize GTFP in the province and does not significantly affect the optimization or deterioration of maize GTFP in the surrounding areas.
- (5) For every 1 unit increase in financial support to agriculture (FSA), maize's GTFP goes up by 0.00936. Its growth contribution is primarily attributable to its direct effect (0.00752). The effect of its spatial spillover is insignificant, which implies the need to improve policies to support agricultural development as well as increase financial investment to promote sustainable agricultural development.
- (6) Using mechanization (MACH) can help make the best use of production resources, bring in more advanced technologies for agricultural production, and help the province's maize GTFP grow by making technological progress. But China's level of mechanization in agriculture is not yet at the same level as that of developed countries. So, creating an imbalance between supply and demand, which always leads to fierce competition on the domestic market and the province's aggressive development of agricultural mechanization will lead to a situation where supply and demand are not in balance. The vigorous development of agricultural mechanization in the province will hinder the development of mechanization levels in neighboring provinces, inhibiting the growth of agricultural GTFP in neighboring provinces.

TABLE 5 Comparative analysis of maize GTFP, GEC, and GTC by major maize-producing areas in China, 2004–2020.

Provinces or regions	GEC	Rank	GTC	Rank	GTFP	Rank
Heilongjiang	1.008	7	1.034	3	1.050	1
Jilin	0.979	15	1.033	4	1.004	13
Liaoning	0.976	16	1.040	2	1.012	6
NeiMonggol	0.994	12	1.013	10	1.006	11
Gansu	0.993	14	1.013	9	0.976	16
Xinjiang	1.002	10	1.002	16	1.005	12
Thenorthernregion	0.992		1.023		1.009	
Henan	1.021	3	1.018	7	1.033	2
Shandong	1.045	1	1.072	1	1.016	4
Hebei	1.015	4	1.022	6	1.032	3
Shanxi	0.993	13	1.011	11	1.002	14
Shaanxi	1.014	5	1.007	13	1.008	8
Anhui	1.008	8	1.000	17	1.001	15
Yellow and Huaihai region	1.016		1.022		1.015	
Sichuan	1.005	9	1.007	12	1.007	9
Yunnan	1.012	6	1.005	15	1.012	7
Guizhou	0.996	11	1.014	8	1.012	5
Guangxi	1.029	2	1.007	14	1.007	10
Hubei	0.970	17	1.028	5	0.967	17
The southwest region	1.003		1.014		1.001	

MATLAB software results collated.

TABLE 6 Global Moran’s I test in 2004–2020.

Year	Moran’s I	p-value
2004–2005	−0.051	0.427
2005–2006	−0.041	0.372
2006–2007	0.150	0.000
2007–2008	0.046	0.016
2008–2009	0.131	0.001
2009–2010	0.119	0.002
2010–2011	0.110	0.002
2011–2012	−0.200	0.015
2012–2013	−0.060	0.482
2013–2014	0.016	0.095
2014–2015	−0.094	0.300
2015–2016	−0.002	0.176
2016–2017	0.118	0.001
2017–2018	0.089	0.004
2018–2019	0.013	0.116
2019–2020	0.204	0.000

Stata 17 software results collated.

(7) In terms of the level of economic development (PGDP), as the economy continues to develop, it will hinder the growth of maize GTFP in the region, but will promote the growth of maize GTFP in the surrounding areas, but none of it is significant.

3.5. Robustness test

The neighborhood space weight matrix was used to validate the results to make sure they were accurate. The results were generally in

TABLE 7 Empirical regression results.

Models	SAR	SEM	SDM
Variable	GTFP	GTFP	GTFP
Main			
GDP (Economic development level)	−0.0230 (0.0527)	−0.0241 (0.0524)	−0.0627 (0.0449)
URB (Urbanization level)	−0.248 (0.597)	−0.303 (0.614)	1.165** (0.569)
ADR (Agricultural natural disaster level)	−0.145* (0.0757)	−0.151** (0.0694)	−0.156** (0.0651)
HC (Regional human capital)	−0.0905 (0.0776)	−0.102 (0.0798)	−0.0674 (0.0599)
CPS (Cultivation structure level)	−0.190 (0.435)	−0.108 (0.497)	−0.273 (0.369)
FSA (Financial support level)	0.00483*** (0.00122)	0.00493*** (0.00128)	0.00624*** (0.00105)
MACH (Agricultural mechanization level)	−0.513*** (0.131)	−0.495*** (0.126)	−0.361** (0.167)
Spatial			
Rho	−0.229* (0.127)		−0.442** (0.176)
Lambda		−0.319 (0.268)	
Variance			
Sigma2_e	0.00879*** (0.00126)	0.00871*** (0.00116)	0.00703*** (0.00113)
Wx			
GDP (Economic development level)			−0.290 (0.230)
URB (Urbanization level)			0.106 (2.575)
ADR (Agricultural natural disaster level)			−0.557* (0.332)
HC (Regional human capital)			−0.890*** (0.319)
CPS (Cultivation structure level)			5.075** (1.994)
FSA (Financial support level)			0.0105** (0.00479)
MACH (Agricultural mechanization level)			−0.264 (0.826)
Individual fixation	YES	YES	YES
Fixed time	YES	YES	YES

Stata 17 software results collated.

*, **, and *** indicate that the results are significant at 10%, 5%, and 1% levels, respectively. The numbers in the table represent regression coefficients, standard deviations are given in parentheses.

TABLE 8 Decomposition of effects for the spatial Durbin model.

	Total	Direct	Indirect
GDP (Economic development level)	0.0370 (0.0758)	−0.0184 (0.0187)	0.0554 (0.0729)
URB (Urbanization level)	−1.550* (0.904)	−1.115*** (0.269)	−0.435 (0.926)
ADR (Agricultural natural disaster level)	0.0371 (0.237)	−0.464*** (0.0935)	0.501* (0.262)
HC (Regional human capital)	−0.229 (0.155)	0.156*** (0.0303)	−0.385** (0.150)
CPS (Cultivation structure level)	1.145*** (0.384)	0.515*** (0.118)	0.630 (0.405)
FSA (Financial support level)	0.00936** (0.00425)	0.00752*** (0.000784)	0.00184 (0.00417)
MACH (Agricultural mechanization level)	0.253 (0.197)	0.370*** (0.0606)	−0.117 (0.221)

Data source: Stata 17 software results collated.

*, **, and *** indicate that the results are significant at 10%, 5%, and 1% levels, respectively. The numbers in the table represent regression coefficients, standard deviations are given in parentheses.

line with the signs of the coefficients of the above variables, which showed that the model results were reliable (Table 9).

4. Discussion

Striving for green development in agriculture is closely tied to the healthy expansion of our agricultural economy, and is also fundamental for sustainable food production and food security. It plays a crucial role in the balanced growth of our economy, society,

and environment. As a result, studying the Green Total Factor Productivity (GTFP) of maize is of utmost importance. In recent times, research into the green development of maize has gained traction, attracting attention from scholars both locally and globally (Xu X. et al., 2019; Xu X. et al., 2020; Edison, 2022; Gupta et al., 2022; Liu S. et al., 2022; Liu W. et al., 2022).

Following the same trajectory, this study evaluates the productivity of maize in China's main maize production regions by integrating carbon emissions into the measurement of maize GTFP. This approach provides a more comprehensive understanding of maize production

TABLE 9 Robustness test results.

	Total	Direct	Indirect
GDP (Economic development level)	−0.0265 (0.0370)	−0.0128 (0.0200)	−0.0137 (0.0308)
URB (Urbanization level)	−0.599 (0.556)	−1.533*** (0.299)	0.935* (0.515)
ADR (Agricultural natural disaster level)	−0.223 (0.142)	−0.341*** (0.0912)	0.118 (0.142)
HC (Regional human capital)	−0.152* (0.0784)	0.124*** (0.0315)	−0.276*** (0.0702)
CPS (Cultivation structure level)	1.008*** (0.250)	0.391*** (0.127)	0.617** (0.281)
FSA (Financial support level)	0.00961*** (0.00274)	0.00683*** (0.000814)	0.00279 (0.00252)
MACH (Agricultural mechanization level)	0.602*** (0.124)	0.247*** (0.0684)	0.355** (0.150)

Data source: Stata 17 software results collated.

*, **, and *** indicate that the results are significant at the 10%, 5%, and 1% levels, respectively. The numbers in the table represent regression coefficients, standard deviations are given in parentheses.

efficiency. Our findings show that the growth of China's maize GTFP is primarily fueled by the country's strong commitment to green agriculture. In the delicate balance between agricultural development and environmental protection, the government has stepped up its promotion of green agricultural policies. This move has sparked a shift in farmers' mindset, encouraging them to adopt more eco-friendly production methods. The subsequent decrease in pollutants and undesirable output is a promising initial accomplishment towards the green development of maize.

These findings hold significant practical and theoretical implications. They contribute to ensuring national food security, promoting sustainable agricultural growth, modernizing the agriculture sector, supporting economic growth, and protecting the environment. Moreover, these findings offer insights into solving the "three rural issues." As such, this trend towards greener maize production practices is a vital step in promoting sustainable food production.

In this paper, by combing through the research on the spatial correlation of GTFP, most previous studies have assumed that the variables are independent for each province. However, in reality, because agriculture has the attribute of a public good, there will inevitably be some correlation among provinces, and whether and what kind of impact the influencing factors in the home province will have on the green total factor productivity of maize in neighboring provinces is one of the pressing questions in this paper. Some research (Liu, 2019; Hu J. et al., 2022; Hu Q. et al., 2022; Xiao et al., 2022; Zhao et al., 2022) argues that while spatial correlations and maize GTFP are considered together, the interactions between different regions are neglected, and the traditional regression model analysis fails to reflect the role of each influencing factor well. To better study the trends of GTFP changes in China's major maize-producing regions, this study further examined the spatial characteristics of agricultural GTFP in the major maize-producing regions using the Moran index, based on which an empirical study was conducted on the factors affecting the green development of maize in China using the spatial Durbin model. The results show that regional human capital, maize planting structure, level of agricultural financial support and level of agricultural mechanisation all have significant effects on maize GTFP growth, indicating that higher regional human capital, more optimised maize planting structure, higher level of agricultural financial support and higher level of agricultural mechanisation are conducive to promoting maize green total factor productivity growth; the degree of regional natural disasters has a driving effect on maize GTFP growth in the surrounding areas growth is driven, possibly because more severe agricultural disasters

reduce the region's total maize production, thus hindering the growth of local maize green factor productivity, but instead promoting the growth of surrounding maize green factor productivity; regional human capital has a significant inhibitory effect on the increase of maize total factor productivity in the surrounding region, possibly because the inflow of talent from the surrounding area leads to the growth of surrounding maize GTFP decreased. The level of economic development in the region had no significant effect on maize GTFP growth in the region and adjacent areas. Through systematic and in-depth analysis, it will help to understand the current situation and influencing factors of maize GTFP in China and gain insight into the differences in maize development among different regions, etc., to achieve sustainable development among regions and ensure regional food security and even the food security of the whole country.

5. Conclusions and policy implications

5.1. Conclusion

To address the problems of traditional maize TFP measurement, this paper incorporates undesirable output (carbon emissions) into the research framework of maize TFP from the perspective of green development and uses the SBM-GML indicator to measure the dynamic evolution of China's maize GTFP in 2004–2020 and analyze its influencing factors.

- (1) From the perspective of time evolution, China's maize GTFP showed an upward trend during 2004–2020, with an average annual growth rate of 0.8%, gradually changing from being driven by a combination of technological progress and technical efficiency, but the contribution of technological progress was greater than that of technical efficiency.
- (2) From the perspective of spatial partitioning, the growth of China's maize GTFP is dominated by the Yellow and Huaihai Sea region and the northern region, with mean values of 1.015 and 1.009, respectively, during the study period, while the southwest region lags behind the northern region and the Yellow and Huaihai Sea region, with a mean value of 1.001, but is still greater than 1 and is in the optimization stage.

- (3) In terms of influencing factors, the region's regional human capital, maize cultivation structure, level of financial support for agriculture, and level of agricultural mechanization have significant promoting effects on the growth of maize GTFP, while the level of urbanization and the frequency of natural disasters significantly inhibit the growth of maize GTFP. The level of natural disasters in the region plays a driving role in the growth of maize GTFP in neighboring regions, and the regional human capital had a significant inhibitory effect on the increase in maize total factor productivity in the neighboring region. The level of economic development in the region had no significant effect on maize GTFP growth in the region and adjacent areas.

5.2. Policy recommendations

The following recommendations are made based on the findings of the research:

- (1) Farmers should improve their scientific quality and focus on transforming their development methods to improve agro-ecological efficiency, while focusing on cultivating new agricultural business entities, such as training highly qualified farmers, establishing rural cooperatives, and supporting leading agricultural enterprises, as well as prioritizing ecology, the need to vigorously develop the agricultural machinery industry, and more importantly, making breakthroughs in green agricultural production technologies to promote high-quality agricultural economic development (Gesche et al., 2022).
- (2) To improve the technical efficiency of maize production and reduce pollution, farmers should strengthen technical training and rationalize the planting structure so as to reduce the agricultural disaster rate. This would provide a theoretical reference and policy basis for further improving maize GTFP (Zhu L. et al., 2022; Zhu Y. et al., 2022).
- (3) Technological progress plays an important role in boosting GTFP in Chinese agriculture, both temporally and regionally. However, technical efficiency can often be a constraint on the growth of this productivity. At the same time, the farther the distance of technology diffusion, the weaker the technology, and the farther the distance, the lower the level of agricultural technology. This means China needs to be able to innovate in science and technology, establish an agricultural technology extension system, increase extension services, strengthen inter-regional exchanges and cooperation, and close the gap in technology levels (Wang et al., 2020; Guo et al., 2021; Zhang F. et al., 2022; Zhang Y. et al., 2022).

5.3. Limitations of the study and future research

This study uses the SBM-GML index to measure maize GTFP, explores its dynamic evolution, and identifies the important factors affecting the improvement of maize GTFP based on spatial measurement. Due to the limitations of research capacity and conditions, some limitations are worth noting:

Firstly, in the process of data collection and processing, the full range of carbon emission indicators cannot be directly obtained. At present, China's agricultural green total factor productivity non-expected output indicators do not have a complete measurement system, and their measurement results have some deviations from the actual situation. This paper provides a more detailed assessment of China's carbon emissions, based on references to relevant domestic and international research and drawing on the currently accepted calculation methods for various indicators.

Secondly, from the breadth and depth of research, as an important grain crop production base in China, the main maize-producing areas are responsible for the major task of ensuring national food security and the balance between supply and demand of agricultural products. With the rising food consumption level of residents in the new era, the main producing areas, the main marketing areas, and balanced production and marketing areas are working together to enhance the comprehensive grain production capacity (Murrell et al., 2022; Skawińska and Zalewski, 2022; Stavi et al., 2022; Teeuwen et al., 2022). How can the interests of the three regions be balanced? Furthermore, the study of GTFP in China's main maize-producing regions is of great significance in promoting GTFP in China's major maize-producing regions and in formulating green development strategies in a scientific manner. This aspect is yet to be further explored.

Thirdly, the prospect of this study is to find out the factors affecting the growth of GTFP in maize by measuring the GTFP of maize in China's three major maize producing regions and exploring its spatial spillover effects by analysing its temporal and spatial dynamic evolution patterns, so as to contribute to the development of food security. Future research will focus more on the spatial spillover effects of green total factor productivity in agriculture.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

WM, YD, and ZY initiated the study. WM, YD, and MB collected the data, processed the data, and performed analysis. WM, YD, MB, AA, LZ, ZY, QM, and SA wrote and revised the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Developing a new technology for demonstrating environmental sustainability in the Australian grassfed beef industry

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Meeting the increasing consumer and market expectations for sustainably produced beef requires measurement and demonstration of the producers' sustainability practices. Typically, demonstration of sustainable production relies on time consuming and costly on-ground audits. Online tools using combinations of remotely sensed data and other information sources could offer a cost-effective alternative. However, there are also concerns about the merits and risks of such tools. This paper presents a case of the development process of an online platform for Australian beef producers to demonstrate their sustainable production practices, connected with learning opportunities for continual improvement of their sustainability performance. The project is led by an innovative cross-sectoral collaboration of beef industry, non-government organisation and university partners. Our approach combines producer and market perspectives; focusing on the "value proposition" of the proposed technology for producers, and value chains' priorities in sustainability markets and in having the ability to demonstrate sustainability in a cost-effective manner. The development process adopted co-design at three levels: (1) the "Consortium" of project partners (2) collaborative co-design through small online groups with producers and value chain representatives; and (3) consultative co-design through producer testing of the platform as it is built by software developers. The design process focused on five themes: tree cover, ground cover, biodiversity stewardship, carbon balance, and drought resilience. We present the main platform design characteristics sought by the co-design groups, and the indicators and measures they considered important for each of the five themes. We then discuss a set of key issues and their implications for technology development, according to a framework expressing interactions between people and their properties, processes and technology. This case shows the importance of taking a "demand-led" rather than a "supply-driven" approach, for the best possible fit of new technology to its users. Since co-design is more often consultative than treating users as equals or leaders in a technology design process, our case highlights the desirability of a fully collaborative approach to co-design.

KEYWORDS

technology, process, sustainability, environment, red meat, beef, co-design

1. Introduction

Consumer and market demand for sustainably produced agricultural products is increasing (Sánchez-Bravo et al., 2021; Zamuz et al., 2021). Meeting these expectations for sustainable production of foods requires demonstration that environmental expectations are being met, and hence measurement of the sustainability practices and achievements of the producers (Gardner et al., 2019; Meemken et al., 2021). Currently, demonstration of sustainable practices within individual enterprises relies on time consuming and costly on-ground audits (Cosby et al., 2021). However, on-ground auditing by third party specialists is not a realistic proposition for many agricultural businesses. There is also a desire to find methods to credibly demonstrate environmental performance more consistently, economically and inclusively (Meemken et al., 2021). Online tools using combinations of remotely sensed data and other information sources could offer a cost-effective alternative for some circumstances, and a useful complement for others (Sadlier, 2018; Andries et al., 2021). There has been a substantial increase in the use of digital technologies for monitoring, measuring, and reporting environmental change, and verifying environmental practices and outcomes. Remote sensing, drones and smartphone applications (apps) are increasingly used for these purposes, linking local practices on the ground to digital information in the cloud (Urzedo et al., 2023). Despite some limitations in accuracy and user trust in online tools, they have potential to be more affordable to use, and more scalable and inclusive than on-ground audits (Gardner et al., 2019; Sellare et al., 2022).

Internationally, there is increased attention to measuring, monitoring, reporting and verification, also referred to as “measurementality” (Turnhout et al., 2014; Lippert, 2015) as a pathway towards sustainable development. This is intended to produce transparent and objective information which can be used to verify the situation on the ground and assess it against an external standard which defines a desired level of attainment. Incentives such as market access or a price premium are expected to influence production practices towards increasing sustainability. The increase in measurementality has coincided with increased academic attention to the merits and risks of this digital accounting of environmental performance (Turnhout et al., 2016; Turnhout, 2018; Kloppenburg et al., 2022).

Critical scholars give insights into the increasing trend of digital environmental accounting, and its effects (Bakker and Ritts, 2018; Bernards et al., 2020; Dauvergne, 2020; Gabrys, 2020; Gupta et al., 2020; Scoville et al., 2021). Although digital technologies have the capacity to make large amounts of data available in real-time, this does not automatically lead to a better representation of environmental challenges. The remotely sensed data that is used to create digital representations of the environment are not neutral and “objective”. Remote sensing requires satellites, sensors and servers that generate data. Then this data is stored in databases and processed by certain types of software. Finally, it is given comprehensible form in terms of numbers, images or text. The process of collecting and processing digital data is thus underpinned by restrictions of what is technologically possible (e.g., resolution), as well as human selection and interpretation based on the questions asked and purposes for which the data is used. Software developers

and platform builders can tend to emphasise points that can be measured at the expense of those that cannot, and unless developers and users are wary, digital accounting for environmental performance has the potential to privilege some people and marginalize others (Kloppenburg et al., 2022). Accordingly there is a call for research on monitoring, reporting and verification systems that are designed to be responsive to local needs and where local contexts are taken into account (Turnhout et al., 2014).

Recognizing the concerns about the social risks inherent in digital technologies and the need for locally responsive reporting and verification systems, this paper presents a case of design and development of a user-focused online platform by the “Environmental Credentials for Australian Beef” project. This platform will allow Australian beef producers to demonstrate their sustainability performance within specified parameters in order to ensure access to capital and commodity markets and take advantage of the emerging market demand for sustainably produced beef (Faulkner et al., 2022). It builds on earlier insights from, and experiences with, Reflexive Interactive Design (Klerkx et al., 2012; Elzen and Bos, 2019). That approach consists of system and actor analysis, structured design based on collaborative and interactive learning, and anchoring (see Elzen and Bos, 2019). As Eastwood et al. (2022) point out, this is one of the few co-design methods (besides their own) that was created for agricultural contexts. It has been used in the pork industry, laying hen industry, dairy industry, broiler industry, rabbit industry and goat industry (Elzen and Bos, 2019).

The online platform will enable grassfed beef producers to measure and report on environmental performance to their value chains and consumers and will provide supporting resources towards continual improvement. By enabling grassfed beef producers to demonstrate their sustainable practices, the online platform will complement and enhance the industry’s sustainability efforts such as the Australian Beef Sustainability Framework (ABSF) and Carbon Neutral 2030 (CN30) target (explained in Section 2).

The paper documents the background, the approach taken in developing the online platform, the users the platform is intended for, the technology development process (to the time of writing), and the proposed characteristics of the platform. It shares key issues considered during that process and their implications for the evolving platform design. In doing so, we reflect on issues raised in the literature about measurement of sustainability: (1) how the verification approaches incorporated in the digital platform shape visibility (through the technology, indicators and measures chosen), and (2) the influences of those who are creating the platform, i.e., who does the counting, how and for whom (the people and the process). The paper offers guidance for future developers of online platforms. It seeks to contribute to knowledge on use of digital platforms as a tool for demonstrating environmental stewardship; and on development of monitoring, reporting and verification systems by producers, for producers, to document their constructive environmental practices. In so doing it offers an example of technology that seeks to overcome the risks of digital technologies empowering some parties relative to others (Kloppenburg et al., 2022).

The following section presents background on the Australian beef industry and relevant initiatives. Subsequent sections explain the technology development process, including the sequence of project activities and co-design process adopted, then the results, discussion and conclusions.

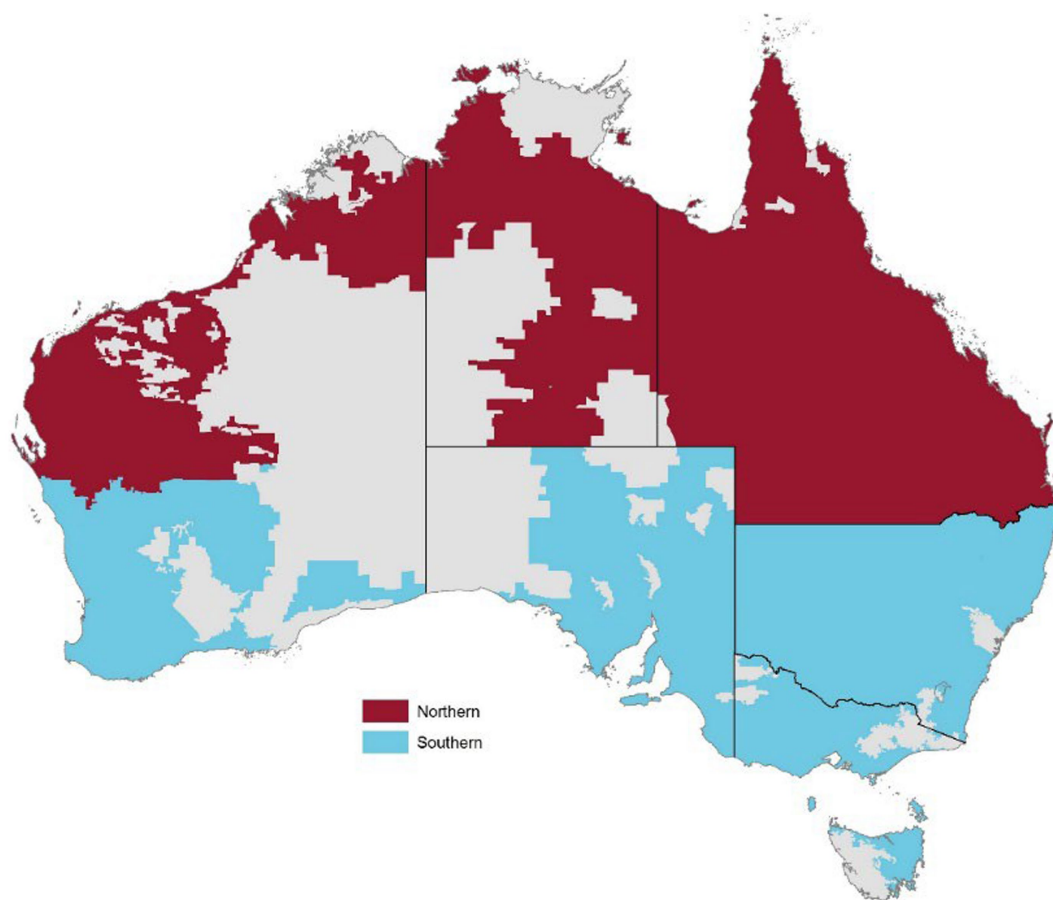


FIGURE 1
The northern and southern beef production systems in Australia (Harper et al., 2019).

2. Background—the Australian beef industry

Beef is a significant agricultural industry for Australia. Over half of the Australian landscape is used for livestock production, employing approximately 428,000 people,¹ with the beef and veal industry worth \$15.9 billion in 2021–2022 (ABS, 2022; MLA, 2022). Australia exports around two-thirds of the beef produced and was the world's fourth largest exporter of beef and veal in 2021 (MLA, 2022). The global demand for beef has increased significantly in recent decades, and the global consumption of beef is projected to increase from 70 million tonnes in 2021 to 76 million tonnes in 2031 (OECD, 2022).

Australia's beef production systems are diverse owing to wide variation in climatic conditions, soil types, different pasture species, genetics of cattle, ownership and scale of cattle enterprises and the management systems adopted by the producers (Bell et al., 2011; Greenwood et al., 2018; Bell and Sangster, 2022). The Australian beef industry can be categorized broadly into the northern and southern production systems (see Figure 1), with sub-systems. Northern Australia has a hotter climate with monsoonal rainfall and relies

largely on natural tropical pastures with lower carrying capacities. This region therefore involves extensive production systems, often on very large land holdings with large herds. The southern region typically has milder temperatures and higher yearly rainfall. The types and quality of pasture available generally allow more intensive production with higher stocking rates than in the north (Harper et al., 2019).

International and Australian beef consumers and value chains are increasingly seeking evidence that the beef they purchase is produced sustainably (Hocquette et al., 2018; Metzger et al., 2018). Thus, demonstrating practices and outcomes to the customers and value chains is becoming increasingly important. There is a similar emerging dynamic within the finance sector, where banks and other investors are seeking assurances about the sustainability of pastoral production systems (Taskforce on Nature-Related Financial Disclosures, 2023).

The Australian beef industry is pioneering a range of sustainability initiatives such as the ABSF and a target to achieve carbon neutrality as an industry by 2030 (CN30). These industry initiatives aim to minimise its environmental impact by adopting sustainable land management practices while maintaining high levels of industry productivity and profitability (ABSF, 2022). The ABSF, launched in 2017, sets out sustainability priorities and the key indicators of performance in sustainability for the beef industry. The framework reflects and encourages the industry's commitment to environmental stewardship through best practices towards improving biodiversity,

¹ The number includes beef cattle and sheep farming, and feedlots.

soil health, groundcover, and reducing greenhouse gases attributable to the industry. The ABSF is also pioneering use of online technology, e.g., an online “balance of tree and grass cover” dashboard, that enables the industry and producers to analyse trends in woody vegetation and seasonal trends in ground cover at a regional level. CN30 is an industry target to achieve carbon neutrality through reducing attributable emissions across the industry, and by increasing carbon storage in soils and vegetation under the custodianship of red meat industry stakeholders.

Beef producers accomplish multiple benefits by improving their environmental stewardship, through enhanced productivity, landscape restoration, and drought resilience. Through the ABSF and other initiatives, the Australian beef industry has shown improvement in its environmental sustainability performance (Witt et al., 2020; ABSE, 2022). Nevertheless, there remain continued challenges in terms of consumer perceptions pertaining to the beef industry’s environmental sustainability (Gerber et al., 2015) and communicating it effectively with the public and within the Australian beef industry (Faulkner et al., 2022). The industry is seeking further opportunities to design and develop practical tools to demonstrate its environmental sustainability to their markets and the value chains, including the online platform documented here.

3. Materials and methods

This section presents an overview of the technology development process, phase by phase, then further details the approach taken to co-design.

3.1. Overview of the technology development process

In 2019 the Australian Government, under its National Landcare Program, sought innovative partnerships to promote environmental sustainability in new ways. This opportunity encouraged three organisations, Meat & Livestock Australia (MLA),² World Wide Fund for Nature Australia (WWF-Australia) and The University of Queensland (UQ) to form a consortium to develop an online platform to simplify measurement and demonstration of environmental performance by “grassfed beef”³ producers seeking to participate in emerging environmental markets. At the same time, the platform is intended to enable greater understanding by, and education of, producers to encourage continual improvement through learning and adaptation that is underpinned by best practice management.

Concurrently, the Australian National University (ANU) was working with the Australian Government on the development of a farm biodiversity certification scheme as part of its Agriculture Biodiversity Stewardship Package. Hence an opportunity was identified to include ANU (from 2021) in the collaboration to

contribute their expertise, and ensure the alignment of approaches and exchange of technical knowledge.

The platform is intended to enable Australian grassfed beef producers to demonstrate their position and pursue continual improvement in five of its sustainability (and resilience) priorities: carbon balance, biodiversity stewardship, maintaining tree cover, maintaining ground cover, and resilience to drought. The platform is being developed through a comprehensive co-design process with beef producers and industry stakeholders. The project was funded from late 2019 to the end of 2023.

The project has four main phases, as illustrated in Figure 2.

1. Scoping phase.
2. Intense co-design phase.
3. Platform development phase.
4. Release and adoption of the platform.

At the time of writing the first two phases are complete, and the third is underway.

3.1.1. Scoping phase

The scoping phase commenced in early 2020 (following pre-project discussions with the funding body before the collaboration could commence work in earnest). At the outset of this project, it was necessary to devote considerable meeting time to forming relationships and developing shared understandings and common language for the project. A lengthy formation period, concurrent with making preliminary decisions about project structures and administrative arrangements, role sharing and approach, helped in developing a smooth collaboration between the three very different Consortium partners, and other contributing organisations. The scoping phase was ramping up just as Australia settled into extended arrangements for managing COVID-19, including lengthy lockdowns and closures of state borders. Therefore, all meetings apart from a single face-to-face team workshop, to strengthen relationships and enable deeper discussion on project direction, had to be held online. This simplified costs and travel, although it made development of relationships more difficult. Since the main project personnel were based in five locations, online meetings were retained throughout the life of the project, even after state borders were opened in early 2022.

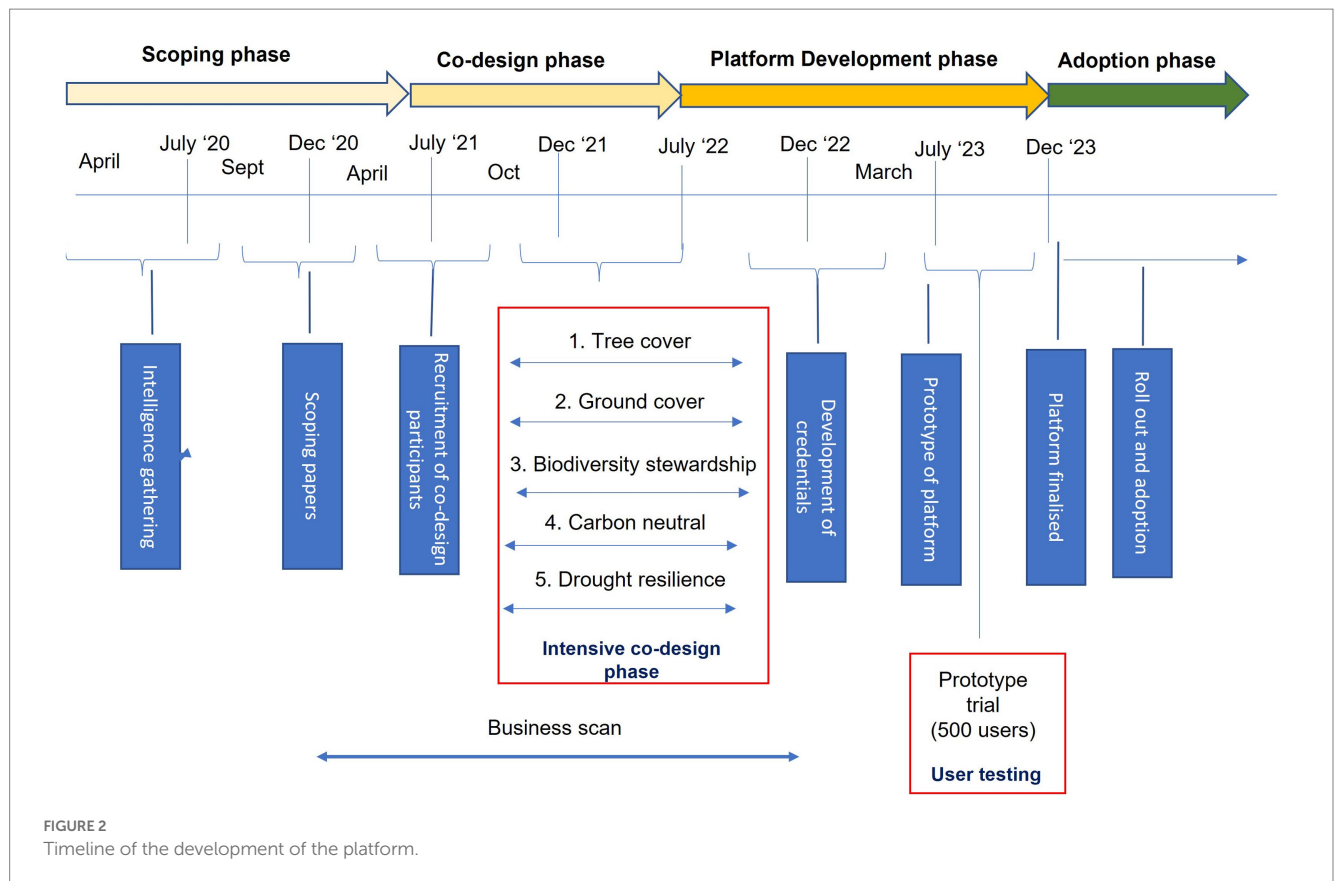
An advisory group was established to provide strategic input and advice to the project team, to ensure the project meets the needs of producers and value chain stakeholders. The advisory group was structured to cover all aspects of the beef value chain, from beef producers, processors, retailers, to food production companies, and included independent stakeholders with relevant expertise.

Background research was essential to inform refinements to the methodology, and the design of the platform itself. A business analysis was conducted during 2021–2022 to gather detailed information on the business context and demand for the proposed platform (Bryceson and Sarwar, 2022). This was conducted through in-depth interviews with value chain actors and producers and explored market interest in sustainable production and an online platform, and the need and opportunity for the industry to demonstrate sustainability. Meanwhile, a literature review on approaches to co-design and online group-based research underpinned decisions about the co-design process.

Once team roles were decided, with each partner choosing one to three themes to specialize in, and one partner (UQ) also specializing

² Australia’s red meat and livestock industry’s service body which invests in research, development and adoption projects.

³ Grainfed producers use feedlots, and are excluded from the work.



in the co-design process, scoping papers were researched and written. These provided essential background information for the choices needed for the co-design approach, and for each of the five themes. They helped to frame discussion priorities for the second phase, intensive co-design. Through a systematic analysis of other relevant initiatives and developments for each of the themes, and the key actors involved, the theme scoping papers sought to avoid any potential for duplication with existing programs or platforms.

3.1.2. Intensive co-design phase

Producers of grassfed beef will be the users of the platform. Where producers are willing to voluntarily share results pertaining to their properties, value chain organisations will be beneficiaries (and “customers”) of the information synthesized on the platform. Accordingly, both producers and value chain organisations were involved in the co-design (and represented in the project’s advisory group).

To ensure relevance to grassfed beef producers and value chains, an intensive, collaborative, co-design approach was adopted (see Section 3.2 below for further detail). Five co-design working groups, one for each project theme, were formed through a combination of open call to producers through MLA’s networks, and invitations to major beef processors. Crucially, this entire process was conducted online. Originally, face to face meetings were considered, but would have presented considerable problems in inclusion given travel distances for many producers and hence time away from their production. The onset of COVID-19 and Australia’s response—involving high uncertainty about interstate travel—made the decision to hold online meetings inevitable. It was reliable, provided groups

were kept small, reduced the time burden on participants and enabled wider geographic inclusion.

Following the series of co-design meetings, the theme leaders edited the deliberations, with some refinements based on their research, into “design briefs” for each theme, for the platform developers. The briefs included the definition of each theme, and its scope, indicators and metrics for measurement, benchmarks appropriate for producers to compare performance, and the types of learning materials preferred to support continual improvement in sustainable production. These documents were peer reviewed by independent technical experts prior to being presented to the platform developers in the next phase.

During this phase a recruitment and contracting process was conducted through MLA’s tender process for technical experts to build the platform. A combination of specialists in overall platform design, remote sensing, and learning materials was appointed.

3.1.3. Platform development phase

Following the recruitment and contracting of software developers, the platform development phase began with orientation of the development team. This included discussions between the project team and platform builders to interpret and synthesise the five theme-based design briefs, and to incorporate the platform builders’ expertise. Close consultation continues between the project team and platform builders.

Conscious that the platform developers had been asked to work mainly from separate design briefs for each theme, the project team created two overarching documents explaining common points across the five themes. These were a list of “design principles” expressed by

all or most of the co-design groups,⁴ and a matrix of interdependencies among the themes, particularly with respect to remotely sensed information. For example, biodiversity stewardship and tree cover have close linkages with the carbon balance theme, and ground cover is an important aspect of drought resilience.

The steps in the design and build phase involve planning and design, system architecture, data ingestion and developing the learning modules. The platform will be refined through user acceptance testing during a pilot testing phase, involving consultative co-design (see Section 3.2 below).

3.1.4. Adoption phase

Before and after the release date, the platform will be promoted through communication and dissemination among members of the Australian beef industry, including grassfed beef producers and wider networks. This will include engagement with various value chain stakeholders to ensure they have a strong understanding of the platform and its capability to drive adoption.

3.2. Detail on approaches to co-design

A co-design approach was vital to the development of the technology. Co-design enabled active involvement of the users in the process of identifying the requirements, so that it would best meet their needs and attain their trust. We elaborate our approach to co-design, given the opportunity to illustrate how different models of co-design can be applied in technology development.

Where new technologies are co-designed with prospective users, there is a range of possibilities, from developers consulting representatives of users about key decisions and actual technology prototypes that the developers have prepared first (which we will call “consultative co-design”) to a much more “bottom-up” approach, led by typical users or created jointly by typical users and a project team (which we will call “collaborative co-design”). These roughly align with the International Association for Public Participation’s spectrum of participation (IAPP, 2018), in the segments from “consult” to “collaborate” and “empower”. Issues for decision concerned the best models of co-design to use at different stages in the project, and the specifics of how to apply them. Under an overarching collaborative approach by the three project collaborators, we chose a sequential approach with producers (see Figure 3), from collaborative (supported by “inform” in the preparatory materials) in the intensive co-design groups in phase 2, to consultative co-design in the platform prototype testing in phase 3.

In principle the project team sought to “empower” producers in the design process (cf IAPP, 2018). However, given expertise was also needed from the theme leads, our approach is best described as collaborative, with the prototype testing phase being consultative. A collaborative co-design process cannot, however, be information free. It is also important to brief participants before discussions, at least on topics they may not already (all) know well, hence aspects of “inform” (IAP2) support collaborative discussions.

The co-design process chosen for this project involves three levels: (1) the cross-sectoral collaboration of Consortium members, explained previously; (2) collaborative online co-design groups consisting of producers, some value chain representatives and content experts; and (3) later consultative co-design through producer testing of the platform as it is built by software developers. Figure 3 illustrates the three levels of the co-design process.

The first level of co-design, which continues throughout the project, is the collaboration between the Consortium members: MLA, WWF-Australia, and UQ. This is more than a management structure: the combination of unusual partners was sought under the grant scheme and enabled combination of different perspectives and expertise to the process and problem solving.

In the second level of the co-design process, collaborative co-design, five co-design groups were formed, one to focus on each theme. To cater for the challenges of online meetings and allow all members plenty of time to participate, each group was kept as close as possible to ten members each: eight to nine producers, and up to two value chain representatives (except in the drought resilience group which comprised only producers; one group had 11 members). The producers, 48 in all, were unique to each group. Given fewer organisations and people available, three individuals represented value chains, participating in two groups each. Each group met online six to eight times, for 90 min to 2 h per meeting. Thus, while there were few participants relative to the size of the industry, each individual participated for 9.5 to 12.5 h online, with some three additional hours in preparation between meetings. This represents unusually intensive input.

Each meeting was convened by the theme lead (a member of the Consortium, or their representative⁵), and jointly facilitated with an independent contractor skilled in online facilitation, and a member of the project’s co-design team. The meetings were supported by background information prepared by the theme leads: the scoping paper at the start of the series and new information (and sometimes tasks for participants) between each meeting. The process followed a “flipped learning” approach (Bergmann and Sams, 2012), in which participants prepared between meetings so that the meetings could concentrate on discussion rather than presentation of information. Through their sequence of meetings, each group developed relationships, and conducted discussions gradually evolving from a broad perspective on what their theme should offer and achieve, to the specifics of definitions, scope, indicators and measures, and other design requirements including the nature of learning materials.

In the third level of the co-design process, using consultative co-design, some 500 grassfed beef producers will test the features and useability of the platform and its layout and design. After further iterations based on the feedback from this testing, the fully functional platform will be widely promoted through communication among grassfed beef producers and the industry networks.

At the time of writing the intensive co-design process (see Section 3.1.2 above) is complete. Technical and educational specialists have begun building the platform’s conceptual prototype (see Sections 3.1.3

⁴ E.g. catering for low internet bandwidth in remote areas, diversity of production systems, data integrity, privacy and confidentiality issues.

⁵ The Australian National University worked with WWF-Australia to coordinate three of the five co-design groups: biodiversity stewardship, tree cover and ground cover.

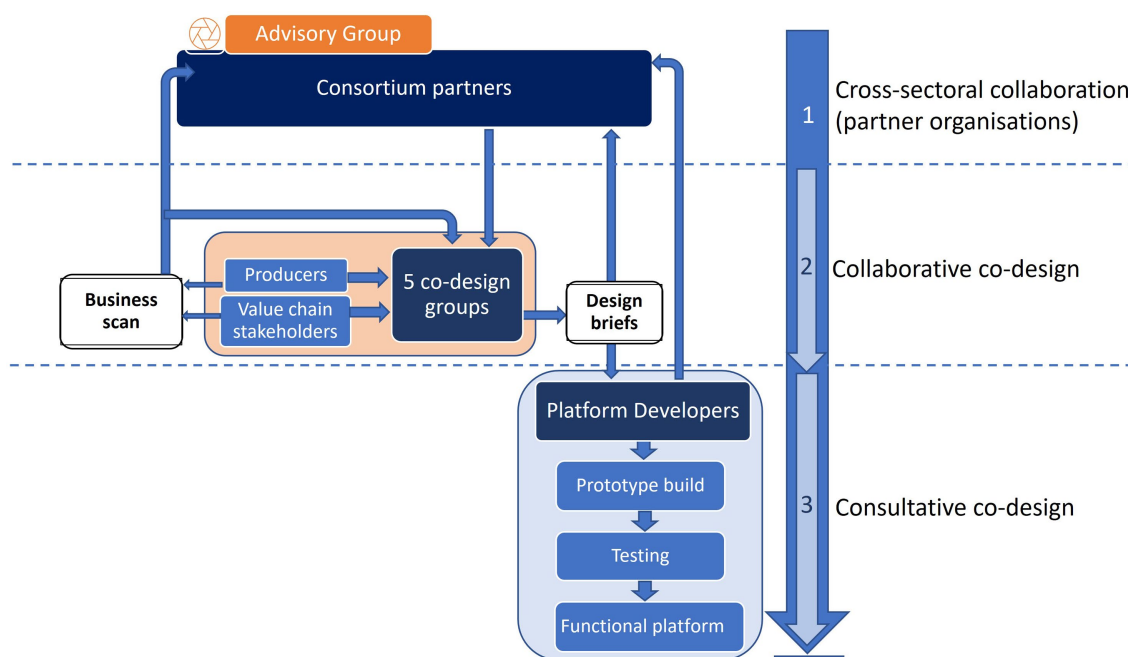


FIGURE 3
The three levels of co-design used in development of the platform.

and 4.1), informed by the design briefs. The prototype testing will commence in late 2023.

4. Results

In this section we share the conceptual design of the platform, and then explain the general design characteristics sought by the co-design working groups, theme by theme, then the indicators they considered important and how to measure them. We then comment on issues faced in the technology development process, and their implications.

4.1. Platform design

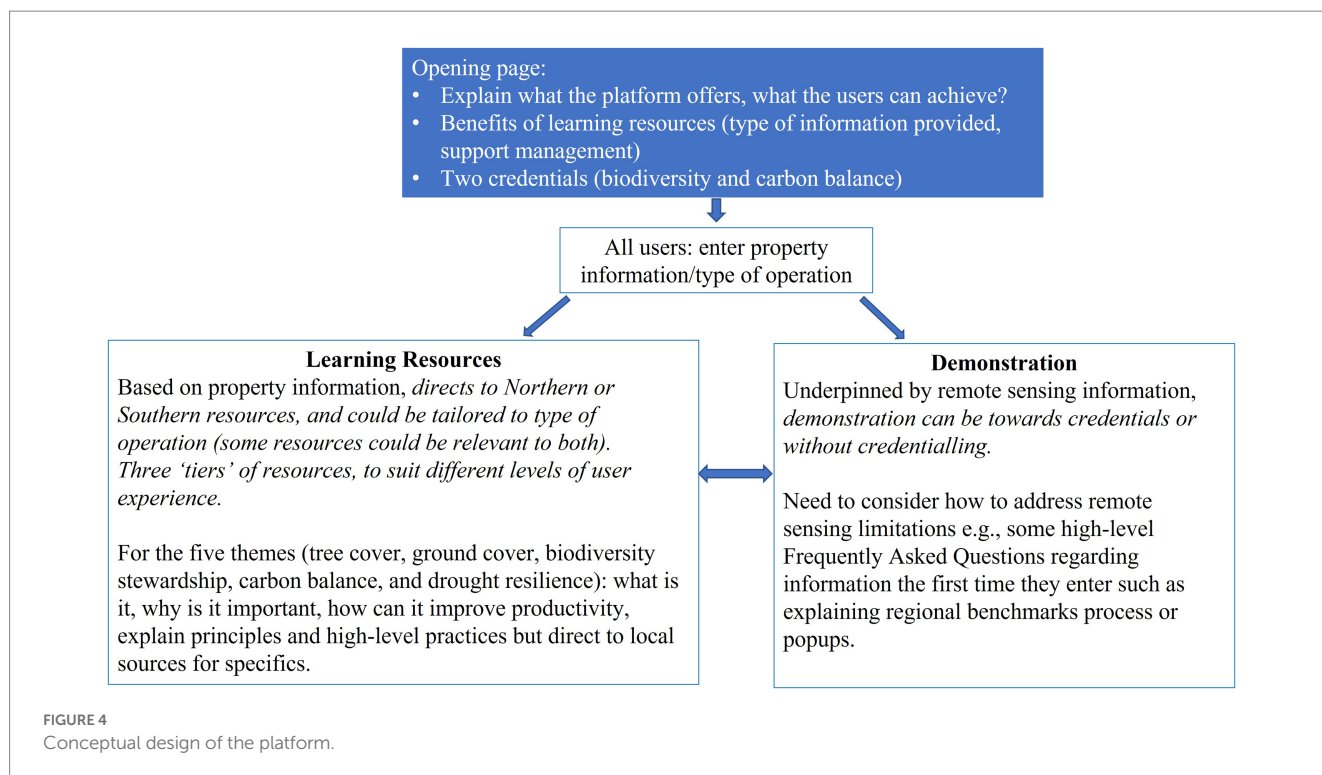
A conceptual design of the platform has been developed based on the design briefs (Figure 4). This will evolve as the platform developers proceed, and user feedback is offered. The main aspects planned are an entry page providing explanations, mechanisms to assure privacy, and then major sections for learning resources, and for demonstration of sustainability performance. Meanwhile work is underway to develop environmental credentials under two of the project's five themes: carbon balance and biodiversity stewardship. This is anticipated to be a further opportunity for landholders to demonstrate their environmental performance under these two themes. Detail about the nature of these environmental credentials and how they will be achieved is yet to be agreed. Based on the business analysis, there is no current market indication to support development of stand-alone tree cover, ground cover or drought resilience credentials. Hence for these three themes, the platform will enable user information and learning opportunities, and sharing of information with value chains should they choose, without being directed towards credentials.

4.1.1. Specific characteristics sought

The producers emphasised that the platform should serve as a *practical tool* for beef producers to measure and demonstrate their sustainability performance and efforts, where applicable, and that reporting and learning through the platform should be *simple and user friendly*.

Equally, *privacy and control of data* about their properties is highly important to the producers. The project team agreed with them from the outset that strict sign-in requirements, associated with delineation of property boundaries, are essential to enable producers to maintain privacy of data synthesized about their own properties. To assure this, users will be required to enter their individual Property Identification Code (PIC) which is a code that is allocated by each state government to ensure each land holding can be referenced to a business. Some primary producers may have several PIC numbers across multiple properties. The use of this code ensures producers are only able to view and provide information relative to their land parcels and businesses. They alone should decide on and control any sharing for market purposes. The platform will thus provide the ability and choice to opt in to share data (or not), to allow a producer to demonstrate to their markets that they are meeting the biodiversity stewardship and/or carbon balance credential sought by that value chain or market (where these exist).

While the platform was originally conceived as an opportunity to demonstrate sustainability performance to markets, the producers were also enthusiastic about the idea of using the platform to *inform their management*, without necessarily sharing information. They were equally keen that the platform provide producers with an information base and learning resources to improve their sustainability practices and gave rich advice as to how to do this. With this in mind, they asked that the self-guided learning modules be both *specific* to a theme (e.g., how to improve ground cover), and *integrative* across themes



(how to improve ground cover in ways that also enhance biodiversity and drought resilience).

Given concerns discussed about the accuracy of remote sensing data, the co-design groups suggested incorporating the capability for *user input* of biophysical data, alongside the primary reliance on remote sensing data. They suggested this feature will be important when remote sensing cannot cover a specific indicator or measure, or when users believe the remote sensed data is incorrect, e.g., vegetation loss after a bushfire. (This feature will not be incorporated in the first version of the platform but may be considered in future).

4.1.2. Indicators and measures chosen

Defining the concept underlying each theme, crystallising the purpose for each theme, then choosing indicators and measures of sustainability were difficult tasks, involving iteration over several meetings for each theme. Table 1 lists the definitions, purpose, and indicators and measures decided by each of the co-design groups. Some were refined by the theme leads.

Remote sensing is preferred as the most widely available and cost-effective basis for measuring and demonstrating sustainability performance, with a focus on outcomes rather than processes. However, the working groups and theme leaders recognised that remote sensing varies in capabilities and limitations for certain themes (discussed in detail in Section 4.2.3.1). For the tree cover and ground cover themes, the desired outcome and use of remote sensing to measure it is relatively straightforward. For biodiversity stewardship, which is conceptually complex, an outcome-based approach focused on the condition of grazing properties to support native biodiversity is recommended. Ecosystem condition has emerged as a central concept in environmental accounting through the United Nation's system of environmental economic accounting and its recommendation as an indicator by the *Taskforce on Nature-Related*

Financial Disclosures (2023). Condition of grazing lands to support biodiversity can be modelled using a range of available data including land use and remotely sensed land cover classes. Spatially explicit estimates of local ecosystem condition can also be compared to regional "benchmarks" to develop a measure that is responsive to the local context. This approach seeks to achieve a balance between scientific rigour and practical limitations, especially where comprehensive on-ground audits are not possible. For some themes, it is difficult to measure and demonstrate sustainability by relying heavily on remote sensing. For example, the carbon balance theme needs to rely largely on carbon calculators for emissions, and indicating carbon sequestration is difficult. For the drought resilience theme, many remote sensed indicators are relevant, but interpretation is necessary to infer *resilience*. Further, remote sensing can contribute to understanding the resilience of the land, but not of the business and the people.

4.2. Key issues faced, and implications

The issues faced in the design process are reported according to a framework expressing interactions among people and their properties, processes and technology. This framework is adapted from a model by Leavitt (1965), originally developed for analysing organisational change according to people, process and technology (PPT). The PPT framework has been applied in different contexts including cyber security organisational management, process improvement, product development, knowledge management, information technology and customer relationship management among others (Chen and Popovich, 2003; Pee and Kankanhalli, 2009; Morgan and Liker, 2020). In this study, involving technology development for the agri-food sector, we necessarily incorporate different considerations under each

TABLE 1 Definitions, purposes, indicators and measures decided for the themes.

	Tree cover	Ground cover	Biodiversity stewardship	Carbon balance	Drought resilience
Definition	Areas containing forests or sparse woody vegetation, including revegetation.	The organic material covering the soil surface.	Conserving and enhancing native plants and animals and ecological communities.	The difference between amount of greenhouse gases emitted when raising beef, and the amount carbon sequestration on-farm.	The ability for land, livestock, enterprise and people to prepare for and adapt successfully when faced with droughts and related challenges.
Purpose	To demonstrate environmental performance in relation to forest and woodland stewardship on-farm, by providing data to help producers better understand the correlation between tree cover and productivity; and support development of carbon balance on farm.	To demonstrate that ground cover is being retained and/or improved in grassfed grazing systems.	To demonstrate that biodiversity is being retained and or improved in grassfed grazing systems.	To lift the collective awareness, understanding and knowledge of beef producers about the opportunities and risks associated with carbon. Enable beef producers to measure on-farm emissions and sequestrations, and to demonstrate actions and benefits in managing carbon balance.	To support awareness and sound management for drought through cycles of before, during and after droughts. Enable demonstration of sound management for drought.
Indicators and measures ^a	Extent (ha) of each class of tree cover (area-based measure) Percentage (%) change in tree cover (change \pm measure) Area cleared or regenerated by type.	Percentage of farm achieving healthy ground cover thresholds (aligns with the ABSF) Percentage of area in groundcover classes, e.g., 0%–30% (low), 30%–70% (medium), >70% high Percentage of groundcover meeting the 3P criteria (palatable, perennial, productive)—would require field verification	Vegetation condition score as a proxy for biodiversity condition, compared to regional benchmarks Land (ha) or % of farm with native vegetation	Total annual emissions (kg CO ₂ e/year emitted) from beef production system. Also presented as emissions per kg liveweight to account for differences in herd size. Carbon stocks (total kg CO ₂ e) and fluxes in soil (kg CO ₂ e/year). Carbon stocks (total kg CO ₂ e) and fluxes in trees (kg CO ₂ e/year). Annual carbon balance (total annual emissions minus total annual sequestrations).	Land management—Stocking rate relative to carrying capacity, LSU/ha/100 mm rainfall Enterprise management—Economic diversity, Farm profit vulnerability, Farm HH income vulnerability Individual/ Family—Stress level, Optimism, Empowerment, Physical health

^aTerminology for indicators and measures can be confusing. For our purposes, an ‘indicator’ indicates something, while a measure gives as precise as possible a measure of it. Indicators are often used as suggestions, e.g., the presence of particular plants may indicate that soil is frequently waterlogged, or the presence of certain species in a soil sample can indicate soil health. Many indicators can be calculated from combinations of data.

main heading. We treat the framework in a “systems” way, emphasizing the interactions and hence mutual influences among people, process and technology (see Section 4.2.4).

People and their properties—This focuses on the types of people the technology is developed for, primarily grassfed beef producers. Since the nature of their properties and business operations is intimately associated, we include their properties.

Process—This covers the processes involved in the development of the platform, including decisions about the forms of collaboration to use, wider participation, and pathways to adoption.

Technology—This focuses on the use of technology, e.g., remote sensing, to produce further technology (the online platform), and ultimately the features of the technology sought.

4.2.1. People and their properties

Any new technology should meet the needs of the types of people for which it is being developed. Several key issues related to the people and their properties are explained below.

4.2.1.1. Remote locations of properties

Beef producers are located throughout much of Australia, from remote savanna areas across Australia’s north, arid regions of central Australia, to higher rainfall areas on the east coast and south. Many properties are very extensive and the majority of the producers are located in rural and regional areas (MLA, 2022) which suffer from unreliable internet connectivity, bandwidth issues, slow speeds, and generally less access to technologies. Hence, a platform with heavy

bandwidth requirements needing high speed internet will be problematic especially for many remote producers. According to the Australian Digital Inclusion Index, which measures digital inclusion across the dimensions of access, affordability and digital ability (Thomas et al., 2021), people living in rural areas and remote locations (including a proportion of Australian beef producers) have low levels of digital inclusion, which can be attributed to lack of infrastructure (Marshall et al., 2020). This has implications for our platform development choices, between catering for those with unreliable internet, and the potential power that could be offered in the platform for users in areas of more reliable internet. Some producers experience unreliable internet even in southern regions where there are pockets of weak service.

Meanwhile, the more remote properties have least access to the existing option for demonstration of an environmental credential, since travel costs for third party audits are higher, and the areas of property to be covered are so much larger.

4.2.1.2. Practical people and diverse user experience

Generally, the producers are “hands on” and busy, with the majority spending most of their time out on their properties rather than at their desks and telephones. They tend to be “time poor”, especially since production costs and profit margins limit capacity for employing others. The users also vary in computer use in their businesses, and range from beginners to advanced users, i.e., those who may not use computers much beyond their business financial recording or may prefer to rely on agronomists for environmental information, to those who are comfortable with looking up information on the web, and are inclined to use some of the complex tools available.

The co-design participants noted several implications for platform design. The technology should be easy to use, intuitive, and avoid complexity for the users. However, it is important to cater for different levels of users, from those who are skilled with information technologies, to those who are less so. Designing for a single skill and interest level risks either not offering value to more advanced users or deterring and confusing beginner users (or both). Further, some producers see returns on their time investments in engaging with technology, while others will not be willing to invest long in learning and using such a tool. While this may or may not be possible, co-design group members also suggested making it possible to use parts of the platform in the field, i.e., on tablets and mobile phones, in addition to desktop computers. Further, to cater for weak internet connectivity, they suggested making offline use possible. The co-design participants preferred the platform to be free to users: ways of achieving this remain under discussion but it may not be feasible to make the entire platform free to users, especially indefinitely.

4.2.1.3. Diverse landscapes and production systems

Australian production systems are extremely diverse and complex, involving interactions among different types of landscapes, climatic conditions, soil types, different pasture species (Greenwood et al., 2018; Bell and Sangster, 2022). The co-design participants across different themes noted that what is desirable and achievable differs regionally, for example ground cover levels in low and high rainfall areas. The possible management practices differ across the production systems. For example, for the carbon balance theme, there are regional

differences in sequestration opportunities and emissions reduction activities. Similarly, levels of tree cover are different due to diverse climates, soil and vegetation types. Drought pressures, and strategies for being resilient, vary by region. The co-design process helped to identify the needs of users in the diverse production systems, across the themes.

The implication is that a “one size fits all” solution is inappropriate. The minimum differentiation needed is between low and high rainfall areas, reflected in the northern and southern production systems. The platform will need to cater for regional differences in setting benchmarks associated with measures, and in learning resources and management practices. The co-design participants suggested that ideally the platform should cater for the wide range of production types, small to large scale, organic and otherwise, land uses and types, breeding versus standard production, at least in benchmarking (if not in all information and learning resources provided).

4.2.1.4. Users’ purposes

Producers will have diverse objectives for using the platform. Some will have a single primary objective, such as carbon balance, biodiversity stewardship or drought resilience. Others manage holistically, across several themes. This will guide the information they require from the platform, and which (if any) objectives they choose to work towards. Therefore, the platform needs to be flexible to cater for these different needs. For instance, if a producer is focused entirely on carbon balance, the species of trees planted may be less important than if they are focused on biodiversity stewardship, in which case locally relevant species would be used. The same applies in ground cover. If the producer’s purpose is solely to prevent erosion many species will do, but for production purposes the producer may seek Perennial, Productive, Palatable (3Ps) and diverse drought resistant species.

4.2.2. Process

Despite much literature over many decades recommending working closely with the prospective users of a new technology (Brhel et al., 2015; Taherdoost, 2018), the reality is that the majority of programs and platforms in the agricultural field have been “supply-driven” by the developers, creating advances in the technical possibilities, often with little consideration for the natures and capacities of the users. The project team recognised a need to be “demand-led”, with focus on the interests of the markets for sustainable beef and the producers seeking to participate in those markets. Market context was explored through business research, and co-design was a natural choice for having producers lead the design process so far as possible.

The next subsections highlight important aspects of the process of developing the technology and discuss their implications.

4.2.2.1. Market analysis

Given that an important aspect of the platform is to facilitate access to sustainability markets, a comprehensive market analysis was conducted to get sustainability context from a business perspective. The analysis explored the current and growing need for sustainability performance from the perspective of beef producers and other value chain players. Those interviewed see value in demonstrating environmental sustainability performance to the market and indicated

that there is significant potential value in doing so in both the domestic and overseas markets. The analysis indicated that all five themes of the project were considered to be important by the participants. The information derived from the analysis provided valuable stakeholder perspectives on the value proposition of the platform.

4.2.2.2. Approaches to co-design

While co-design was the logical choice to ensure that the technology meets the needs of its users, the approaches to co-design required detailed consideration. We explained in Section 3.2 how this project combined collaborative and consultative approaches to co-design. Overall, the approach sought to “empower” users (*cf* IAPP, 2018). The sequenced approach allows strong influence over the design, followed by checking (the consultative co-design aspect) during the platform build phase.

Following initial decisions about the broad approach to co-design (primarily collaborative) a set of design decisions was necessary.

4.2.2.3. Selection of participants

Diversity across Australia’s major beef producing regions and types of property within those was an important issue in selection of participants for online co-design. This raised questions as to whether the co-design group members should be “representative”, especially should they be typical of all producers, or focus on those most interested in sustainable practices and potential use of a technology platform. The co-design participants were not a representative “sample” of all producers but were aware of the nature and concerns of other producers, often providing specific examples.

4.2.2.4. Managing complexity in the co-design discussions

The potentialities for the platform design could have been approached from many possible angles. Some structuring was necessary to simplify discussions and explorations for the project team and for the co-design working groups, when recruited. After much deliberation, the project team decided to focus on the five sustainability and resilience themes, which had been promised in the grant application but not necessarily with the intent of organising the design discussions in that way. This enabled the Consortium members to share out the theme leads roles, and the theme leads and co-design groups to focus in depth on background investigations and discussions towards specific themes. This enabled concentration, but carried the risk of designing five parts, putting the onus on the platform builders to create the “whole” from the parts.

Meanwhile, the technical requirements for building the platform pointed to needing a team that incorporated overall management and platform structure and approach towards a rewarding user experience, remote sensing capabilities, and learning aspects. The organisations and individuals contracted brought their own expertise and experience to interpret the design briefs, and to suggest approaches to fulfil them.

4.2.3. Technology

The success of technology, i.e., the platform being developed, needed consideration of the aspects of remote sensing, to produce technology, data integrity and ultimately the features of the technology sought.

4.2.3.1. Remote sensing

Remote sensing has great power and cost effectiveness, and the platform relies primarily on remote sensing. However, it has stronger potential relevance and accuracy for some themes than others. For example, remote sensing can measure ground cover but can only indicate in terms of green vegetation and non-green vegetation cover etc., and cannot distinguish among the types of cover with certainty. Similarly, the carbon balance theme needs calculators for emissions, as these cannot be remotely sensed. For the drought resilience theme, drought can be indicated, but the aspect of resilience cannot be measured through remote sensing. Also, there are issues for remotely sensed data in terms of resolution, as the larger scale data is generally available for free, while finer scales are more useful for the purposes, but come at a cost.

There are implications for platform design in terms of using remote sensing, so that all themes draw similarly on the remote sensing data to give the platform a coherent information framework. For example, drought resilience will rely on other themes (e.g., ground cover, tree cover). Likewise, biodiversity stewardship draws on sub-indicators involving tree cover, ground cover and land use. Where two themes share indicators, they should ideally also draw on the same data to inform those indicators.

4.2.3.2. Integrity of data sources and calculation processes

Integrity of data sources and the processes used to calculate measures were seen as key issues by the co-design participants. Data integrity is also critical for producer and market confidence. The implication is to ensure data integrity so far as possible by using high-quality and reliable data with transparency about the data sources and the processes used to calculate measures. The trustworthiness of the data sources used and integrity of the calculation process can be shown by providing a “further information” link to enable those who so wish to check the detail. It should be acknowledged that no data source is error free, and that some potential applications may require further verification or refinement of data presented through the platform, rather than building expectations of infallible data sources.

4.2.3.3. User friendliness

The co-design participants emphasized repeatedly that the online platform must be user-friendly, or it would not be used. They made a number of suggestions for achieving this, while catering to varied levels of user experience.

4.2.4. Systemic interactions

We argued earlier that the technology design process should be viewed as systemic. This requires attention to the mutual influences among people, process and technology. Figure 5 summarises the points already raised with respect to each part of the framework and shows the main interactions. At the centre of Figure 5 is the ultimate purpose, development of an online platform that suits producers and their needs to demonstrate the sustainability of their production practices to particular markets, and to have convenient access to learning materials, tailored to their circumstances, to support continual improvement.

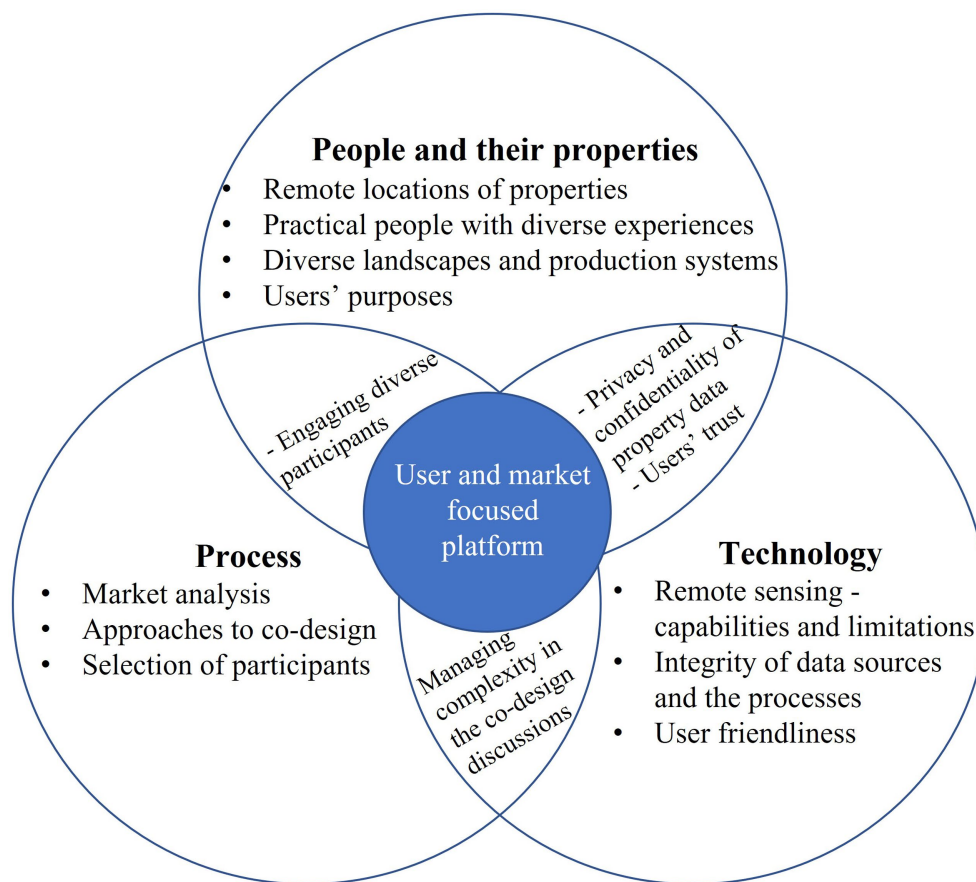


FIGURE 5

Systemic interactions between people, process, and technology.

4.2.4.1. Interactions between people and process

The process needed to suit two sets of people—producers, and value chain participants. A market analysis based on individual interviews and document analysis was best for value chain participants. That analysis could then be supplied into the collaborative co-design process, to inform it. Some value chain members also participated in the collaborative co-design, and some on the advisory group along with some beef producers and other stakeholders. The nature of the people and their properties (including property locations, remote or otherwise, and internet bandwidth in their regions) had a strong influence over the co-design process required. Although COVID-19 travel restrictions and uncertainties originally determined the decision on online co-design, it also made sense in terms of geographical inclusion, and using online methodology for an online platform.

4.2.4.2. Interactions between people and technology

The key issues in the interactions between people and technology, beyond the obvious intention that the technology serve the people's needs, is the very high concern for privacy and control. Producers recognise the widespread availability of remotely sensed data, and how it can be linked and used to support well informed decision making on-farm. However, data privacy is of high importance to producers to ensure sensitive business information is not accessible to those outside of their business, including data such as property locations. Trust in

the privacy controls, so that only producers—and those they choose to share information with—can see the information collated about their property is thus vital. The producers also emphasized that the limitations of the technology, particularly remote sensing, needed to be communicated clearly to users, in ways they could understand readily. Further, they requested the ability to review their data, input additional data and flag errors.

4.2.4.3. Interactions between process and technology

As we have mentioned above, the decision to use online co-design meant that online technology was used to develop further online technology. Less obviously, the collaborating partners were faced with very difficult choices about how to structure the online co-design process (and overall design process) to simplify a complex set of interactions. The choice to separate discussions by themes enabled that simplification and allowed each co-design group to focus intensively on a single topic. The consequence was a challenge in integration across the themes. That was addressed by further information being provided to the platform builders, to point out the synergies and overarching design principles inherent in the separate design briefs. The producers had no such problem with synthesis. In their discussions under their single themes many explained how they managed their properties, often for several theme purposes at once, and hence the information and considerations they took into account.

5. Discussion

Online technologies will be used increasingly, for many purposes that include demonstration of sustainable practices in agricultural production, and assembly of information to improved market access. While every approach to creating a new technology is probably unique, certain points can be learnt and shared.

We have explained our approach to developing an online platform for demonstrating sustainability and learning in an agri-food industry. In doing so we have argued that active participation of the users in the design process helped in identifying their purposes and requirements, to ensure the platform's relevance, and should encourage better trust and adoption by the users after it is developed (Treasure-Jones and Joynes, 2018; Durall et al., 2019; Villatoro Moral and De Benito, 2021).

This section reflects on the findings according to the three dimensions of the framework, and their interactions, to suggest implications and learnings for others. It then returns to points raised in the introduction, to comment on how this project has addressed the critiques about “measurementality” in environmental information systems.

First, while developing new technology, the dimensions of people, process and technology, and their consequences for one another, need to be considered together. Traditionally, the people and process aspects tend to be ignored. In contrast to common approaches in which the potential inherent in technology is used to drive the process of developing it, and people are assumed to want to use it, our procedure puts the people and their requirements first, matched with a suitable process (Meynard et al., 2012; Berthet et al., 2018). Building on earlier work on Reflexive Interactive Design (Bos and Grin, 2012; Elzen and Bos, 2019), we engaged the people as users through a carefully considered, highly collaborative, co-design process which helped to identify their requirements and (subject to feasibility issues that may yet be raised by the platform builders) generate solutions they wanted. This aims to empower Australian grassfed beef producers to move from being reactive recipients of technology designed for them by others, to becoming proactive partners who anticipate market requirements and proactively design the digital tools needed for measuring, reporting and verifying their environmental performance.

Second, the technology we sought to develop was to improve information flow in the producer-market relationship (Ali and Kumar, 2011; Lezoche et al., 2020). The approach thus combined value chain and producer perspectives. Our decision was to research the value chain perspectives, then to feed that information into the co-design process while also incorporating value chain perspectives in that discussion process. Throughout the process, focus remained on the “value proposition” for users, meaning both producers and the value chains which seek verified sustainable produce, with the aim to include the users' perspective and requirements while considering their context (e.g., diversity in producers, their properties and production systems).

Third, the project supports new perspectives on use of co-design in the development of technology in agricultural settings. In Reflexive Interactive Design, co-design originally consisted of a series of three consultative, one off, workshops with different stakeholder groups (farmers, consumers, experts) in which the participants provided information, but it was up to the project team to decide how to incorporate that information into the design. Over time the Reflexive Interactive Design process has become more consultative (Elzen and

Bos, 2019), but there is little reflection on the implications that this has for the roles of the project team (Blackmore et al., 2016). Building on those experiences, our co-design approach consisted of a series of interrelated working group meetings—with the same group of participants—that treated users as full collaborators. By considering our own roles reflexively, we have recognised this user-centered technology development process involved different levels of co-design, involving ourselves as a cross-sectoral collaboration of project partners, as well as the nested collaborative then consultative co-design with producers. Forming and consolidating three project partners as a consortium, then moving through processes to develop the platform (via co-design working groups and design briefs and informed by business research) has been a non-linear process. While the project had clear aims and a general “vision” of what the platform should ultimately offer, much deliberation was required at every stage, starting from quite an open view of what the platform could offer and be, and gradually “funneling” towards greater clarity but with some revisiting of options and ideas. In this process, the project team's views iterated with what we were learning from the co-design group iterations, and no doubt will continue to evolve in interaction with the platform builders and the testers of the technology.

Fourth, as we had expected, technology development to demonstrate sustainability using remote sensing posed several challenges (Bakker and Ritts, 2018; Marshall et al., 2020). While recognising advantages, the producers participating in the co-design process had valid concerns about the visibilities and invisibilities created by remote sensing. The integrity of remotely sensed data was questioned, as well as its varying ability to represent sustainable management practice. Depending on the theme, some argued the need for ground-truthing where possible, to strengthen confidence in the relationship between remote sensing and on-ground actualities (and hence, over time, improve remote sensing and its uses).⁶ This is a separate matter to on-ground audits of performance on properties: it is about validating measures from remotely sensed data to use it within its limitations. The producers also emphasized circumstances in which remotely sensed data should be supplemented by other sources of data. This included carbon calculators, and user input to over-ride remotely sensed data where local knowledge was considered more accurate (but which may not be possible to include in the platform, at least at first). A related issue is how well remote sensing can represent the theme required. In some cases, digital tools and remote imagery can be true substitutes but for many issues—and biodiversity in particular—they should be seen as complementary, providing a way of streamlining and reducing on-ground costs, but not displacing the need for on-ground measurement. A further consideration is that remotely sensed data is geographically comprehensive. This brings in issues of privacy and confidentiality about property management, amidst concerns about information being used against producers by distant policy makers or market actors that may now be able to “read” the properties at a distance and impose control mechanisms in the form of environmental standards or policies.

Fifth, while a strong co-design process can identify and communicate users' requirements, correct interpretation of the design

⁶ This reflects a need for ancillary activity, especially as future research. It is not possible to make it a part of the platform design at this stage.

briefs is critical for translating the co-design process into a practical platform. This depends largely on the level of expertise of the technology developers (Howard and Melles, 2011; Durall et al., 2019) who are stepping up as new intermediaries and knowledge brokers (Bernards et al., 2020). This entails both technical expertise to build the different parts of the platform, and an ability to understand and empathise with what the users are saying, and why, through the design briefs. We note that in our case, three sub-teams of platform builders, each with different expertise, need to develop collaboration to create an integrated platform.

Returning to concerns about measurement raised in the literature, especially about the power differentials that verification practices (and by implication our technology) can create (Bakker and Ritts, 2018; Bernards et al., 2020; Gupta et al., 2020; Kloppenburg et al., 2022), we have sought to produce an alternative that puts producers in stronger positions of control than conventional auditing systems, while making use of potential efficiencies in technology that can be more affordable and hence inclusive. Grassfed beef producers do not actually do the “measuring” as remote sensing provides much of the data, and they need a type of independent verification of their actions and outcomes. Therefore, the producers and the members of value chains, working together in the co-design groups, have selected the indicators and measures that best suit their purposes. In this proposed platform the “how” of doing the measuring may be less accurate than on-ground audits, but is far more accessible, being more cost-effective and less subject to distance. While the project team originally envisaged the platform as providing information to markets to improve market access for producers, the producers decided that “for whom” included themselves: the platform can and should provide valuable management information for their own uses, irrespective of any decisions to share it with their markets. This process of platform development, coupled with producers having the control over what information to share with value chains seeking evidence of sustainability, arguably puts producers in a position of power. It could however introduce new inequalities (Kloppenburg et al., 2022), between those sharing their evidence for market access and those who cannot or choose not to, and so remain in markets which focus on price, or other non-sustainability factors. The growing technology intensiveness of verification of environmental performance may be easier to navigate for larger cattle producers who have the skills and resources to engage with this digital environment. Consequently, smaller and more family-based beef producers, and those with poor internet connections, may be left out, thereby potentially widening existing inequalities in access (Bernards et al., 2020).

5.1. Limitations

This is a unique case study of technology development, in which decisions were taken for specific reasons. As with any study or development process, some limitations are worth highlighting. As this paper presents work in progress, a limitation is that we are not certain that all design characteristics, indicators and measures sought by the co-design groups can necessarily be adopted in the prototype then platform. At this stage we can only say that the platform builders are committed to follow the co-designed specifications as far as is possible and affordable. For example, there is a reliance on remote-sensed data with no current mechanism for user-inputted data on the prototype platform, though such a

capability is being pursued. They may well uncover practical difficulties as they proceed. Further, as experts in technology development and the development of learning materials, they have the right and opportunity to make further suggestions based on their knowledge and experience. The project team will work closely with them to refine the directions the platform build takes.

Another consideration, rather than necessarily a limitation, in the approach to conducting online co-design was that there was a necessary trade-off between the breadth and depth of participation, i.e., the number of people who could be included (with perceptions of having more participants being “more representative”), bandwidth and numbers online limiting the stability of online meetings, and the amount of time each person could contribute within each meeting. In our experience, large face-to-face workshops can appear to include more people, but offer less opportunity for each individual to say much, let alone have their views recorded reliably. A different issue with “representation”, more important to us, is that the producers and value chain members needed to cover (between them) all of Australia’s major beef producing regions, sizes, farming systems and types of property. Participants however needed to be willing and interested, not merely “sampled”. The diversity sought was achieved by purposeful selection among those who responded to the open call for participants, so that they collectively met criteria of property location, size and type of operation, and gender of producers.

5.2. Further research

Further research could take several directions. There is potential to test, adapt, and improve upon the types of approach taken in this project in other agrifood industries, and in other sectors. There is a need to keep testing and refining approaches to co-design, both online (where there are few examples, though there is a growing body of literature on online focus groups) and face-to-face. There is much scope to test the reliability, and market acceptance, of online alternatives to on-ground assessments of sustainable production practices and outcomes, particularly those using remote sensing.

6. Conclusion

In this paper, we have presented a case in which an innovative approach to developing an online platform has involved drawing market analysis and three levels of co-design together to inform development of technology that meets the needs of beef producers seeking to demonstrate and improve their environmental performance. The platform, when built, will draw primarily on remote sensing data, combined with complementary information sources and user inputs where required. The online learning resources on the platform will provide opportunities towards continual improvement of the producers’ sustainability performance. Overall, the platform should offer Australian grassfed beef producers an efficient and cost-effective alternative for demonstrating and informing improvement of their environmental performance. This will assist value chain participants in their purchasing decisions, and ultimately raise consumer confidence and enhance the Australian beef industry’s environmental reputation.

We have shown the importance of taking a “demand-driven” rather than a “supply-driven” approach, for the best possible fit of new

technology to its users. In doing so, we have tested the use and effectiveness of co-design, and in particular online co-design, which is particularly apt for development of an online technology. Our approach shows different approaches to co-design—collaborative and consultative—should be considered and can be combined. It further shows that online co-design, though largely forced by circumstances in this case, is possible.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by the University of Queensland Australia. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

All authors (and some of those acknowledged) contributed to the development of the platform reported here. SS and HR coordinated the drafting and editing of the manuscript. SS, HR, SB, SP, MW, and KL drafted substantial sections and assisted with editing. KB, TC, DB, and AM contributed shorter passages to this manuscript while having substantial roles in the conduct of the project. All authors contributed to the article and approved the submitted version.

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Role of farmers' entrepreneurial orientation, women's participation, and information and communication technology use in responsible farm production: a step towards sustainable food production

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Responsible production is essential for sustainable development and for ensuring global food security. The concept of responsible production has been well studied in other sectors of the economy, but has yet to gain recognition in the agricultural sector. Therefore, this study examined responsible production in the context of agriculture and the factors affecting responsible farm production in the developing country of Pakistan. Face-to-face interviews were conducted to collect data from 196 farmers selected using the multistage random sampling method. An independent sample t-test, chi-square test, and ordered probit model were used to analyze the data. The responsible farm production index was estimated based on the climate change adaptation, resource efficiency, carbon footprints, and economic returns of each farm. The mean value of the responsible farm production index is 0.69. The farmers were divided into low-, moderate-, and highly responsible farm producers using cluster analysis. More than 36% of farms were highly responsible. The results revealed that women's participation in farming activities, extension services, the use of information and communication technologies, and farmer entrepreneurial orientation dimensions significantly affected responsible farm production. Farm producers using the Internet for agriculture had a 1.4% points higher probability of belonging to the highly responsible farm producer category compared to those who did not use the Internet to obtain agricultural information. Farms with women's participation in agricultural activities were 33.5% points more likely to belong to the highly responsible farm producer category than farms where only males perform agricultural operations. Therefore, women's empowerment and farmers' entrepreneurial skills are absolute necessities of responsible farming. This study piques the interests of stakeholders while also adding to the scant body of knowledge on responsible farm production around the world. Furthermore, this study is critical for developing a roadmap for long-term sustainable agricultural development.

KEYWORDS

farmer entrepreneurship, sustainable agriculture, sustainable development goal, sustainable production, natural resource management

1. Introduction

The Sustainable Development Goals (SDGs) provide a shared blueprint for developed and developing nations to pursue sustainable development (United Nations, 2015). SDG 12 emphasizes the significance of responsible production in the development of all goods and services. The purpose of responsible production is to produce more and better with less. It also emphasizes the essence of decoupling economic growth from environmental degradation, increasing resource efficiency, and promoting sustainable lifestyles (Liu et al., 2021). The concept of “responsible production” has appeared in literature such as Huaccho-Huatuco and Ball (2019), Sleiman and Chahine (2019), and Whitson and French (2021), but it has not yet received widespread recognition, especially in the agriculture sector.

Agriculture production is crucial for ensuring global food security and alleviating poverty (Otsuka, 2013; Haq et al., 2021). Moreover, it provides a livelihood to millions of rural households and is critical for economic development, particularly in developing countries. Moreover, agriculture is the largest consumer of scarce natural resources, and competition among sectors for these scarce natural resources is growing due to increasing population pressure (UNEP, 2016). Therefore, the agriculture sector should utilize natural resources efficiently and sustainably in farm production.

An intriguing characteristic of agricultural production that distinguishes it from other sectors is the interdependence between agriculture and climate. Agriculture is entirely dependent on climate, and thus, the utilization of various farm resources is impacted by climate change (Mulwa et al., 2017; Arora, 2019). Climate change is now a reality and poses a serious threat to agricultural productivity. Specifically, agriculture is a major source of greenhouse gas (GHG) emissions, which are the primary driver of global climate change (Blandford and Hassapoyannes, 2018). Climate change has a negative impact on agriculture by reducing farm production. Therefore, agriculture is both a cause and an effect of climate change (Shahbaz et al., 2022a). Furthermore, agriculture production is distinguished by low farm efficiency and economic returns when compared to other sectors (Toma et al., 2017; Kish and Fairbairn, 2018). The aforementioned concerns imply that farming will not be able to sustain itself in the future, and farm producers will need to be more responsible in utilizing various farm resources for production. The importance of this concept in farming comes from the fact that Skouloudis et al. (2015) describe responsible production as a production-oriented obligation that includes the environment, efficiency, and a sustainable way of life.

This study considered Pakistan as a case study for several reasons. Agriculture contributes nearly one-fifth of the national gross domestic product and employs nearly one-third of the

Pakistani population (GoP, 2022). Pakistan also serves as a representative example of developing nations that are very vulnerable to the negative effects of climate change, yet have made little effort to combat those effects. According to Krefit et al. (2016), Pakistan is the 7th most vulnerable country due to climate change in the world. Moreover, Pakistan’s updated national climate change policy in March 2022 aims to make the country more resilient to climate change and lead to a low-carbon society (MOCC, 2022). As a result, supporting responsible consumption and production has become a key priority for decreasing the negative effects of climate change and reducing carbon emissions in the country. One of the crucial policy tools that can assist the Pakistani government in achieving national climate change policy targets for a climate-resilient and low-carbon society is responsible farm production (RFP). Despite the fact that farm production in agriculture is entirely different from the production of goods and services in other sectors, none of the previous studies explicitly focused on responsible production with regard to farming.

Moreover, a plethora of previous studies (Huaccho-Huatuco and Ball, 2019; Sleiman and Chahine, 2019; Whitson and French, 2021) on responsible production have mostly overlooked the agriculture sector in favor of concerns affecting other non-agriculture sectors. Agriculture, as the largest user of natural resources and the driving force of the economy, particularly in developing nations, necessitates greater attention from scholars on the subject of RFP. Therefore, this study bridges the gap by examining the responsible production concept with respect to farm production and addressing three research questions: (1) what is the current status of RFP on farms? (2) What farm and farmer characteristics of farm producers determine RFP status? (3) How does the status of the RFP change in relation to key farm and farmer characteristics?

From a practical standpoint, this study provides a beneficial tool for assessing farm producers’ RFP status. The findings of this study will support policymakers in their on-going attempts to improve farmers’ attitudes toward responsible farm production. In particular, the results point out some of the most important farm and farmer characteristics and key indicators that policymakers all over the world can use to improve RFP.

The rest of study is structured as follows: It begins with the section “Materials and methodology” by defining responsible farm production, introducing the study area and sampling procedure, and discussing the different RFP indicators and techniques for measuring these indicators. In addition, the econometric model utilized to determine the factors influencing RFP has been developed in the same section. The “Results and discussion” section summarizes the study’s findings and discusses the results in light of previous research as well as the county’s ground reality. This study concludes with a summary of results, policy implications, and study limitations in the last section, “Conclusion and policy recommendations.”

2. Materials and methodology

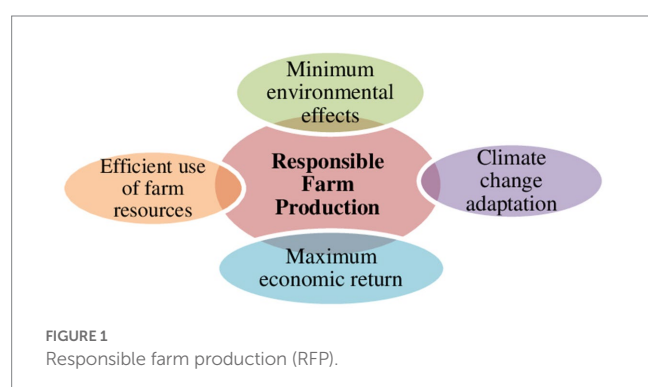
2.1. Responsible farm production

This study uses the literature described in the introduction and the SDG 12.2 target, which outlines sustainable management and the efficient use of natural resources, to develop the definition of RFP: “RFP happens when a farm efficiently integrates its farm resources to optimize economic returns while minimizing negative environmental externalities under changing climate scenarios.”

The RFP definition can be decomposed into four parts: (1) efficient use of farm resources; (2) maximum economic returns; (3) minimum negative ecological degradation; and (4) climate change adaptation (Figure 1). All four parts of the RFP were measured in this study using relevant indicators. The farm’s technical efficiency was used to assess the efficiency of farm resources. Farmers’ economic returns were estimated using their total farm income. The third part is the “minimum negative ecological degradation” of RFP, which was measured in the form of reduced carbon footprints. The fourth part of the RFP description is climate change adaptation, which is estimated by the adoption of climate-smart farming practices (Karimi et al., 2018; Van Meijl et al., 2018; Malhi et al., 2021; Ortiz-Bobea et al., 2021).

2.2. Study area

The study was conducted in the Punjab province of Pakistan, owing to its large share of the country’s rose domestic product (Pasha, 2015). On the agricultural front, the Punjab province alone accounts for more than 60% of the total national agricultural output (Government of the Punjab, 2018). Punjab is also Pakistan’s most populous province, with the majority of its people living in rural areas, and more than one-third of the province’s total population relying on agriculture for a livelihood. Furthermore, Punjab province has an extensive irrigation system, fertile fields, and favorable climate conditions for farming, where crop production covers 10.81 million hectares of its total geographical area (Haq et al., 2021). The agriculture sector of Punjab province plays a crucial role in addressing Pakistan’s food security concerns. In addition, it is worth noting that agriculture serves as a primary means of sustenance for over 45% of the labor force within the province (Ahmad et al., 2019). Between 1980 and 2018, the average minimum and maximum temperatures in Punjab ranged from 16.52 to 21.50°C and 30.09 to 32.75°C, respectively.



During the same period, the average annual precipitation in Punjab was recorded to be 532.5 mm, with a significant portion of 50–75% occurring specifically between June and August (Abbas et al., 2019). Punjab, being the largest province of Pakistan, is susceptible to the impacts of climate change owing to its geographical positioning, limited ability to adapt, and significant reliance on the natural environment (Shahbaz et al., 2021). The year 2010 witnessed the most severe flooding in the history of Punjab, resulting in the displacement of a significant number of individuals, extensive damage to agricultural produce, and loss of animal life (Akbar and Aldrich, 2018).

Punjab province was chosen as the target study area for this research due to its substantial rural population, significance to the national economy, contribution to agricultural output, and substantial cropping area (Figure 2).

The Punjab province is divided into different administrative units. Therefore, a multistage random and purposive sampling technique was used to distribute the determined sample size from the largest administrative unit (districts) to the smallest administrative unit (villages). Punjab was chosen as the study area for this research during the first stage of sampling. The selected province is divided into agro-ecological zones (Ahmad et al., 2019). The mixed cropping, maize-wheat mix cropping, and rice agro-ecological zones were chosen in the second stage of sampling. The mixed cropping zone is characterized by an average annual precipitation of 460 mm. The mean minimum and maximum temperatures within this region exhibit variations ranging from 13°C to 40°C. The maize-wheat mixed cropping zone has a yearly average precipitation of 590 mm. The mean minimum and maximum temperatures within this region exhibits yearly variation, spanning from 11°C to 38°C (Ahmad et al., 2019). In the third stage of sampling, one district from each agro-ecological zone was chosen. In the fourth stage of sampling, two towns (local = tehsil) from each district were chosen. In the fifth stage, two union councils were picked from each town. Two villages were chosen from each union council in the sixth step of sampling. In the last round of sampling, farmers or farm producers were chosen. A team of four experienced enumerators collected data using a well-designed questionnaire and a face-to-face survey.

This study’s representative sample size was estimated using the following equation from Cochran (1963):

$$n_0 = Z^2 \times p \times q / e^2 \quad (1)$$

Where, n is sample size; Z represents the abscissa of the normal curve that cuts off an area α at the tails; e is accuracy level; p is the estimated proportion of an element; and $q = 1 - p$.

Assuming $p = 0.5$ (maximum variability), a 95% confidence interval, a $\pm 7\%$ accuracy level, and a 1.96 Z value, 196 samples were extracted to represent the farmers living in the province.

2.3. Measuring RFP indicators

The technical efficiency (TE) was estimated to check the efficient use of farming resources. TE allows for lower inputs while increasing output or reducing inputs while increasing output (Shahbaz et al., 2022a). Data on all inputs used on farms to produce various crops and their output was obtained from farm producers in order to

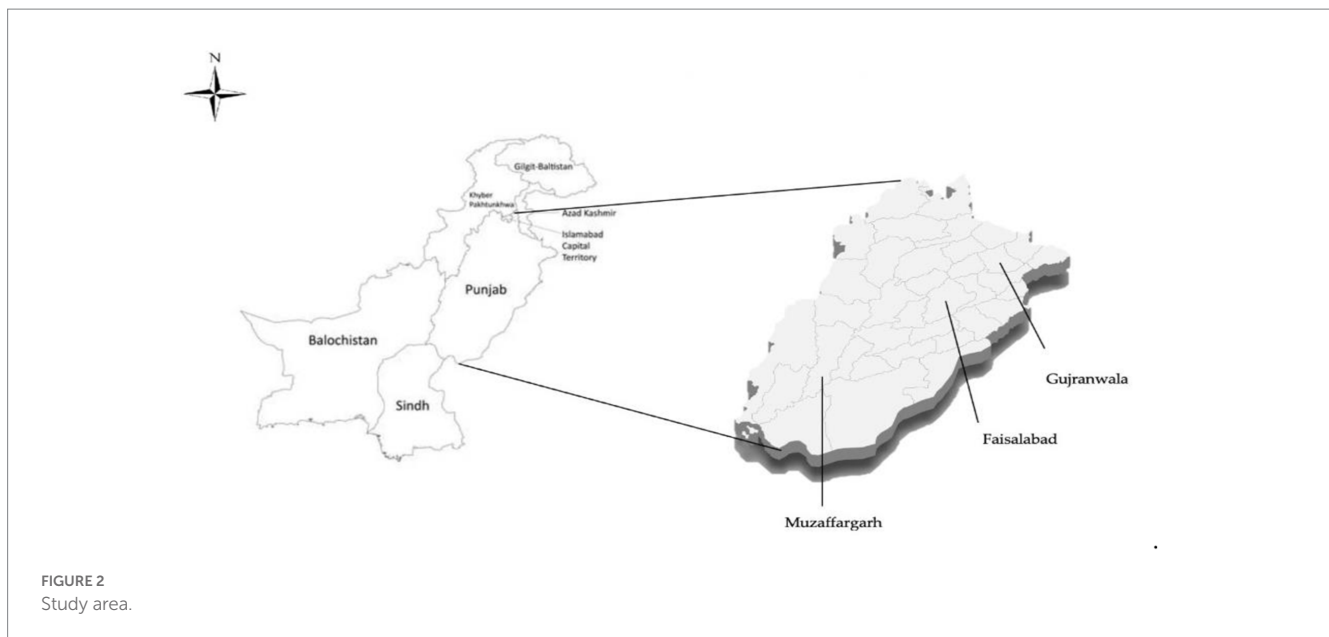


FIGURE 2
Study area.

determine farm technical efficiency. The crops grown on farms vary from farm to farm and region to region due to differences in the climatic conditions of specific agro-ecological zones. Therefore, the input requirements fluctuate, and some crops may require more inputs for production. As a result, in the TE model, all inputs except land and output were expressed in monetary terms.

The farmers' farm technical efficiency was estimated using data envelopment analysis (DEA). DEA can be either input- or output-oriented (Shahbaz et al., 2022b). In agriculture, an input-oriented approach is generally preferred because of its ability to manage inputs rather than outputs. Input-oriented BCR models aimed at reducing inputs were deemed more appropriate for assessing the TE of farms in this study. Thus, the input-oriented Banker, Charnes, and Cooper method (BCC) was used in this study to measure farm technical efficiency. Solving the following linear programming (LP) problem provides technical efficiency scores for the farmer:

$$\begin{aligned}
 &\text{Minimize} && \theta, \lambda\theta \\
 &\text{Subject to} && y_i + Y\lambda \geq 0 \\
 &&& \theta x_i - X\lambda \geq 0 \\
 &&& \lambda \geq 0
 \end{aligned} \tag{2}$$

Where, Y represents the vector of outputs; X represents the vector of inputs; and λ is the vector of $N \times 1$.

Total farm income was employed as an indicator to assess the farms' economic returns. Farm income was calculated by multiplying the quantity of various crops produced on the farm by their sale price. The sale value of all crops grown on the farms was added to obtain the total farm income of the farm producers.

Minimum environmental degradation was measured by estimating carbon footprints from the farms as carbon footprints are the primary source of ecological degradation. Agriculture is a major contributor to carbon footprints, with fertilizer as the primary

agricultural input contributing to carbon emissions. Therefore, this study used the following method by Jayasundara et al. (2014) and Jayasundara (2015) to figure out the carbon footprints of different amounts of fertilizer used on farms:

$$2.792 \text{ kg CO}_2 \text{ equivalents / kilogram N}$$

$$0.738 \text{ kg CO}_2 \text{ equivalents / kilogram P}_2\text{O}_5$$

$$0.352 \text{ kg CO}_2 \text{ equivalents / kilogram K}_2\text{O}$$

The adoption of climate-smart farming practices was used as an indicator to assess the level of climate change adaptation. The literature on the adoption of climate change practices was thoroughly reviewed before selecting climate change practices on farms. The available literature yielded a total of 11 climate-smart practices appropriate in the study area. Farmers who implemented smart climate change practices to alleviate the impact of climate change on their farms were classified as adopters of that strategy. The level of climate change adoption on a farm is shown by the number of climate change strategies that farm has put into place.

2.3.1. Normalization of indicators

All of the indicators used to assess the RFP had different measurement units. For example, farm resource efficiency was assessed in percent, economic returns in US dollars, carbon footprints in kilograms, and climate change adaptation in numbers. Because estimated indicators are heterogeneous, they must be normalized before being aggregated into a single index. There are several methods for normalizing indicators, but minimum-maximum normalization is a simple and straightforward method for converting variously observed indicators into dimensionless indicators ranging from 0 to 1 or 0 (−1 to 1). The range is determined

by the type of data analyzed. Therefore, this study also used the minimum–maximum normalization method to normalize the actual RFP indicators before adding them to a single index. Gunduz et al. (2011) and Ul Haq and Boz (2020) used the same procedure to normalize the various indicators before combining them into a single index.

For those indicators (technical efficiency, farm income, and climate practices) where a higher score is better for a higher RFP, the following minimum–maximum normalization formula was used:

$$\frac{Z - \text{Minimum Value}}{\text{Maximum Value} - \text{Minimum Value}} \quad (3)$$

Where, Z is actual value of indicators.

Similarly, the following formula was applied to the RFP indicator (carbon footprints), whose lower score is preferred for a higher RFP:

$$\frac{Z - \text{Maximum Value}}{\text{Minimum Value} - \text{Maximum Value}} \quad (4)$$

Where, Z is actual value carbon footprints.

2.3.2. Estimating the responsible farm production index (RFPI)

The next issue, after normalizing RFP indicators, was to assign weights to distinct indicators before combining these indicators into a responsible farm production index (RFPI). One option was to give weights to the RFP indicators subjectively, but doing so has numerous drawbacks. To avoid bias, the following formula was used to figure out the weight of the RFP indicator:

$$w_i = \frac{D_{ik}}{\sum D_{ik}}; i = 1, \dots, 4 \text{ and } k = 1, \dots, 196 \quad (5)$$

Where, w_i represents the weight of each RFP indicator; D_{ik} is the actual normalized value of indicator i for farm k ; and $\sum D_{ik}$ is the sum of the normalized values of four indicators for farm k . The advantage of employing this weight estimation formula is that it distributes weight to each indicator based on its RFP share. For example, if the normalized value of farm technical efficiency is greater than the values of the other three indicators, technical efficiency will be given more weight than the other indicators. As a result of the change in share of each indicator, the weight allocated to all indicators will vary from farm to farm for each indicator. The weighted results showed that technical efficiency received the highest weight, whereas farm income received the least. The following formula was used to determine RFP status for farm producers:

$$\text{RFPI} = \sum_{i=1}^n w_i * D_{ik} \quad (6)$$

Where, RFPI represents the responsible farm production index; w_i is the weight of the i th indicator for the k th farm; and D_i represents the normalized value of the i th indicator for the k th farm.

The RFPI has a value between 0 and 1. This value reflects the RFP status of different farms. A score near 1 suggests a higher RFP status for farm producers, whereas a value near 0 indicates a lower RFP status for farm producers.

2.4. Selection of farm and farmer characteristics and hypothesizing their effect on RFP

Literature (Nowak et al., 2015; Haq et al., 2017; Khanal et al., 2018; Trinh et al., 2018; Hamid et al., 2021; Kryszak et al., 2021; Savari and Amghani, 2021; Shahbaz et al., 2022c) related to factors affecting the different indicators (technical efficiency, carbon footprints, economic returns, and climate change adaptation) of RFP was thoroughly examined to select the farm and farmer characteristics for this study as well as their expected contribution to RFP. As a result, 11 socioeconomic variables with a logical relationship to RFP and applicable in the study area were chosen as potential RFP factors. The age of the farm producers was chosen as the first socioeconomic characteristic. The findings on the effect of age on RFP indicators present mixed results. Therefore, this study also assumes both positive and negative effects of age on RFP. The education of farm producers is regarded as one of the most critical RFP determinants. This study assumes a positive relationship between education and RFP because educated farmers are expected to be more responsible in agricultural production.

Total land is an indicator of a farmer's economic strength, and earlier research has shown that farmers with larger land sizes are more likely to receive institutional support than farmers with smaller land sizes. Furthermore, a greater landholding allows farmers to devote more area to agricultural production, which can lead to increased farm productivity and efficiency. This study anticipates that this variable will have a positive impact on the RFP. Farming is a laborious activity, especially in developing countries where traditional agricultural methods still prevail. The promotion of gender equality and the empowerment of women are widely recognized as crucial factors in the global socio-economic advancement of nations. The concept of women empowerment entails enabling women to gain power and agency in all facets of their lives including agriculture. Women's empowerment is multidimensional, and it is important to note that empowerment in one dimension does not guarantee empowerment in others (Mahmud et al., 2012). Women empowerment in agriculture can contribute positively to attaining many of these SDGs, as half of women labor is involved in agricultural activities. Family labor and women's participation in agriculture have a range of implications for land use, crop productivity, family wages, and resource governance. Thus, family labor and women's participation in farming activities aid in the efficient use of farm resources by providing labor at important times. Furthermore, family labor and female engagement support in climate change adaptation, which can boost economic returns by mitigating the consequences of climate change on farms. This study hypothesizes that these characteristics will have a positive effect on RFP. Due to the contradictory results in the literature about the influence of farming experience on several RFP indicators, both a positive and a negative effect of farming experience on RFP were assumed. Due to differences in farm-related priorities, owner and tenant farmers behave

differently. Owners retain the farm permanently, and they are more likely to implement long-term sustainable practices. Tenant farmers, on the other hand, have a share of the crop harvest or have possession of land for a fixed period of time. Their goal may be to maximize profit or crop share during this specific time period, which may lead to these farmers engaging in unsustainable farming techniques. Therefore, this study hypothesizes that ownership has a favorable effect on RFP. Similarly, agricultural extension services, land fragmentation credit utilization are likely to affect RFP positively.

Apart from these socioeconomic characteristics, the study also employed two additional variables as explanatory variables: information and communication technology (ICT) and farmer entrepreneurship. ICT has become a source of information for the farming community, and the usage of ICT for farm-related information is growing by the day. For agricultural information, ICT includes the use of television, radio, and the internet (Das, 2021; Ayim et al., 2022). This study anticipates a positive contribution of ICTs to RFP since contemporary agriculture is heavily reliant on ICTs. Farmer entrepreneurship is crucial in shaping RFP in developing countries. Farmer entrepreneurship, in broad terms, refers to the process of leveraging resources in novel ways to explore opportunities toward the accomplishment of economic and social goals (Fitz-Koch et al., 2018). Farmer entrepreneurship orientation has three dimensions: (1) risk-taking, (2) innovativeness, and (3) pro-activeness. The combination of innovativeness, pro-activeness, and risk-taking behavior opens up new opportunities for farmers. This study hypothesizes that all dimensions of farmer entrepreneurial orientation play a positive role in RFP decisions (Table 1). Different Likert scale statement questions were used to assess three dimensions of farmer entrepreneurship.

2.5. Empirical model

The farm-producers were categorized into three groups by applying the K-mean cluster analysis using their RFPI scores. These were classified as low, moderately, and highly responsible farm producers. Farmers included in the low-responsible farm producer category had a RFPI score less than or equal to 0.69. Similarly, farmers included in the highly responsible farm production category had RFPI scores greater than to 0.79. The farmers were almost equally divided among the low, moderately, and highly responsible farm producer categories. Table 2 shows that there were more farm producers in the moderately responsible farm producer group than in the low and highly responsible farm producer groups.

Following that, these three farmer producer categories were coded as 0 = farmers in the low-responsible farm production category, 1 = farmers in the moderately responsible farm production category, and 2 = farmers in the highly responsible farm production category as the dependent variable of the ordered probit model. The ordered probit model is defined as follows:

$$\begin{aligned} y^* &= \beta'x_i + \varepsilon, \varepsilon \sim N(0, 1) \\ y &= 0 \quad \text{if } y^* \leq 0 \\ y &= 1 \quad \text{if } 0 < y^* \leq \mu_1 \\ y &= 2 \quad \text{if } \mu_1 < y^* \leq \mu_2 \end{aligned} \quad (7)$$

Where, y^* is the dependent variable as probability of farmer belonging to a responsible farm producers' category; β' is vector of coefficients; x_i represents vector of explanatory variables.

ε is vector of normally distributed error terms [0, 1]; y is the observed dependent variable as the probability of farmer to be highly responsible farm producer; and μ are the cut off points which indicates the level of inclination of a farmer to be highly responsible farm producer. It explains if there is a natural ordering among the three categories of the dependent variable.

Chen et al. (2002) suggested the following formula for calculating marginal effects:

$$\frac{\partial P(y_i = j)}{\partial x_k} = \left[\Phi \left[\mu_{j-1} - \sum_{k=1}^k \beta_k x_k \right] - \Phi \left[\mu_j - \sum_{k=1}^k \beta_k x_k \right] \right] \beta_k \quad (8)$$

Where, $\partial P / \partial x_k$ is a partial derivative of probability with respect to the independent variable x_k . The positive value of marginal effect of x_k explains that the probability of a farmer selecting the specific category increases with x_k and vice versa. The sum of the marginal effects should be zero because the responses are exclusive and thus cancel each other out (Greene, 2002). The marginal effects were used to figure out how much each explanatory variable increased or decreased the chance of a farmer moving to one of the three categories of the dependent variable.

3. Results and discussion

3.1. Farm and farm producers' characteristics

Farm and farmer characteristics reveal important information about the farm producer's personal backgrounds and socioeconomic status. Moreover, farm and farmer characteristics influence farm producers' activities throughout the production process. Table 3 illustrates the various farm and farmer characteristics of farm producers. Farm producers that are highly responsible were found to be younger and better educated than moderately and lowly responsible farm producers. Low and moderately responsible farm producers had less acreage than highly responsible farm producers. Agriculture is the mainstay of life for the majority of rural households, and about two-fifths of the whole country's population is directly or indirectly involved in farming activities for their livelihood (Government of Pakistan, 2021). In the research area, more than three people were engaged in farming activities from each participating house on average. On highly responsible farms, more people were found to be participating in farming operations than on low and moderately responsible farms. This could be because highly responsible farm producers have larger landholdings, which necessitates having more people to conduct and oversee farm operations due to the dominance of conventional and traditional farming. Women are an integral part of farming activities, and their participation adds labor to farm operations. On low-responsible farms, women

TABLE 1 Selection of farm and farm producer characteristics and their expected contributions.

Farmer and farm producer characteristics	Description (unit)	Expected contribution
<i>Socioeconomic</i>		
Age	Age of the farm producer (years)	±
Education	Education of the farm producer (years)	+
Total land	Total operated land (acres)	+
Agriculture labor force	Adult family members involved in agricultural activities (number)	+
Women participation	Dummy, 1 if women participate in farm activities, otherwise 0	+
Farming experience	Farming experience of the farm producer (years)	±
Land tenure status	Dummy, 1 if farm producer is owner, otherwise 0	+
Extension services	Dummy, 1 if extension workers visit the field, otherwise 0	+
Credit utilization	Dummy, 1 if credit obtained for farming, otherwise 0	+
Land fragmentation	Parcels of total land situated at different places (Number)	+
<i>Information and communication technology (ICT) use for agricultural information</i>		
Television	Dummy, 1 if farm producer watches TV for agriculture purpose, otherwise 0	+
Radio	Dummy, 1 if farm producer listens to radio for agriculture purpose, otherwise 0	+
Internet	Dummy, 1 if farm producer use internet for agriculture purpose, otherwise 0	+
<i>Farmer entrepreneurship orientation dimensions</i>		
Risk-taking	Measured through different Likert scale questions	+
Innovativeness	Measured through different Likert scale questions	+
Pro-activeness	Measured through different Likert scale questions	+

TABLE 2 Farmer categories based on responsible farm production index (RFPI) scores.

Farmer category (Mean RFPI score)	Frequency	Percentage
Low responsible farm producers (≤ 0.69)	59	30.10
Moderately responsible farm producers (> 0.69 and ≤ 0.79)	71	36.23
Highly responsible farm producers (> 0.79)	66	33.67

participated in farm operations at a lower rate than on moderately and highly responsible farms. More than half of the farmers managed their farms without the participation of women. The explanation for women's lower engagement in farming activities could be related to societal and cultural constraints that exist in rural regions and hinder women's ability to work outside the home (Mohiuddin et al., 2020). Experience in farming is also an important component of human capital. Farm producers learn from their previous crop production experiences and conduct their businesses more efficiently in the future because of their previous experience. In this study, farmers were well experienced, as their average farming experience was assessed to be more than half of their average age. However, in comparison to the other two farm producer types, highly responsible farm producers had the least agricultural experience.

Land tenure status is an important farm attribute because farmers with different land tenures behave differently in relation to similar

farm operations (Akram et al., 2019). A large majority of highly responsible farm producers were operating on their own land, compared to low and moderately responsible farm producers. Additionally, farm producers in the highly responsible farming category received more extension services than farm producers in the low and moderately responsible farming categories, where agricultural extension services assist with information dissemination. Due to the time lag between agricultural investment and return, the farming community lacks financial resources. Credit usage provides the financial means to acquire farm inputs on time. A lower number of farm producers in the low-responsible farming category utilized credit for farm operations than moderately and highly responsible farm producers. Land fragmentation refers to the presence of many spatially dispersed pieces of farmland controlled by the same farm producer (Alemu et al., 2017). Low-responsible farm producers had a higher number of land fragments than moderately and highly responsible farm producers.

Information and communication technology benefits farm producers by facilitating access to growing contemporary farming technologies, cropping patterns, and real-time market data (Das, 2021; Ayim et al., 2022). The highly responsible farm producers used ICT for agricultural information the most in comparison to the other two farm producer categories. The plausible explanation could be that farmers in the highly responsible farming group had a greater degree of education than farmers in other categories. Farm entrepreneurship is critical for agriculture due to increased competition for natural resources across diverse sectors. Farm producers in the highly RFP group were shown to be more risk-taking, innovative, and proactive in their farming activities than farm producers in the low and moderate farm production categories.

TABLE 3 Farm and farm producers' characteristics.

Characteristics	Low responsible farm producers		Moderately responsible farm producers		Highly responsible farm producers		p-value	Overall	
	Mean	SD	Mean	SD	Mean	SD		Mean	SD
Socioeconomic									
Age (years)	43.14	10.46	38.85	6.97	34.44	6.71	0.00	38.65	8.78
Education (years)	7.34	2.87	9.49	3.04	10.97	2.79	0.00	9.34	3.24
Total land (acres)	9.18	5.24	9.78	6.94	13.78	15.10	0.02	10.95	10.27
Agriculture labor force (persons)	2.53	0.88	3.11	0.84	4.14	1.31	0.00	3.28	1.22
Women participation (1 = yes)	0.27	0.45	0.46	0.50	0.71	0.46	0.00	0.49	0.50
Farming experience (years)	23.64	9.80	20.33	7.85	20.30	8.53	0.05	21.33	8.79
Land tenure status (1 = owner)	0.39	0.49	0.49	0.50	0.79	0.41	0.00	0.56	0.50
Extension services (1 = yes)	0.47	0.50	0.51	0.50	0.61	0.49	0.30	0.53	0.50
Credit utilization (1 = yes)	0.34	0.48	0.44	0.50	0.67	0.48	0.00	0.48	0.50
Land fragmentation (numbers)	1.36	0.58	1.68	1.38	1.08	0.27	0.00	1.38	0.93
Information and communication technology (ICT) use for agricultural information									
Radio (1 = yes)	0.25	0.44	0.38	0.49	0.62	0.49	0.00	0.42	0.50
Television (1 = yes)	0.34	0.48	0.56	0.50	0.62	0.49	0.00	0.52	0.50
Internet (1 = yes)	0.32	0.47	0.49	0.50	0.59	0.50	0.01	0.47	0.50
Farmer entrepreneurship orientation dimensions									
Risk taking (mean)	2.22	0.90	2.31	0.97	3.24	1.21	0.00	2.60	1.13
Innovativeness (mean)	2.19	0.89	2.54	1.03	3.22	1.13	0.00	2.66	1.10
Pro-activeness (mean)	2.15	1.22	2.70	1.15	3.28	1.16	0.00	2.73	1.25

SD stands for standard deviation.

3.2. Graphical presentation of RFP status of all farm producers

A radar presentation of all RFPI scores revealed significant variations in the RFP status of various farm producers. The disparity in their farms and farmers' characteristics could be the reason for this variation. Although the overall status of farmers was satisfactory, with the vast majority of farm producers having RFPI scores greater than 0.50, no farm producer was fully responsible for farm production. Farmers' RFPI scores range from 0.38 to 0.92 (Figure 3). This shows that there is a chance for individual farmers to improve their RFP status.

3.3. Relationship between RFP and its indicators

Figure 4 depicts the relationship between RFP and its indicators (CO₂ emissions, technical efficiency, farm income, and climate change adaptation). Except for CO₂ emissions, all indicators were positively associated with RFP. This indicates that a rise in technical efficiency, farm income, and climate change adaptation will improve farm producers' overall RFP status. Therefore, farm producers should make better use of their farm resources and boost climate change adaptability to increase RFP. Increased CO₂ emissions, on the other hand, will reduce farm producers' overall RFP status (Figure 4A). For example, a unit increase in CO₂ emissions reduces RFP by 0.01. Farm

producers should endeavor to reduce CO₂ emissions from their fields in order to improve the RFP status. Farmers can reduce CO₂ emissions by using less synthetic fertilizer. The trend line between technical efficiency (Figure 4B) is steeper than the trend lines of farm income (Figure 4C) and climate change adaptation (Figure 4D). This result shows that a unit change in technical efficiency has a greater impact on RFP status than a unit change in the other two positively influencing factors. A unit increase in farm technical efficiency, for example, will improve the overall RFP status by 0.318. Similarly, increasing farm climate change adaptation by one unit raises the total RFP status by 0.022. As a result, in order to be more responsible farm producers, farmers need to focus more on using farming resources efficiently.

3.4. Mean RFPI scores

Figure 5 portrays the RFP status of low, moderately, and highly responsible farm producers based on their mean RFPI scores. The figure also depicts the overall mean RFPI score of all farm producers, which was assessed to be 0.69. Low responsible farm producers had 0.15 and 0.25 lower mean RFPI scores, respectively, than moderately and highly responsible farm producers. The mean RFPI score of highly responsible farm producers was likewise 0.10 higher than that of moderately responsible farm producers. Only low-responsible farm producers had a lower mean RFPI score than all farmers combined. This suggests that poorly responsible farm

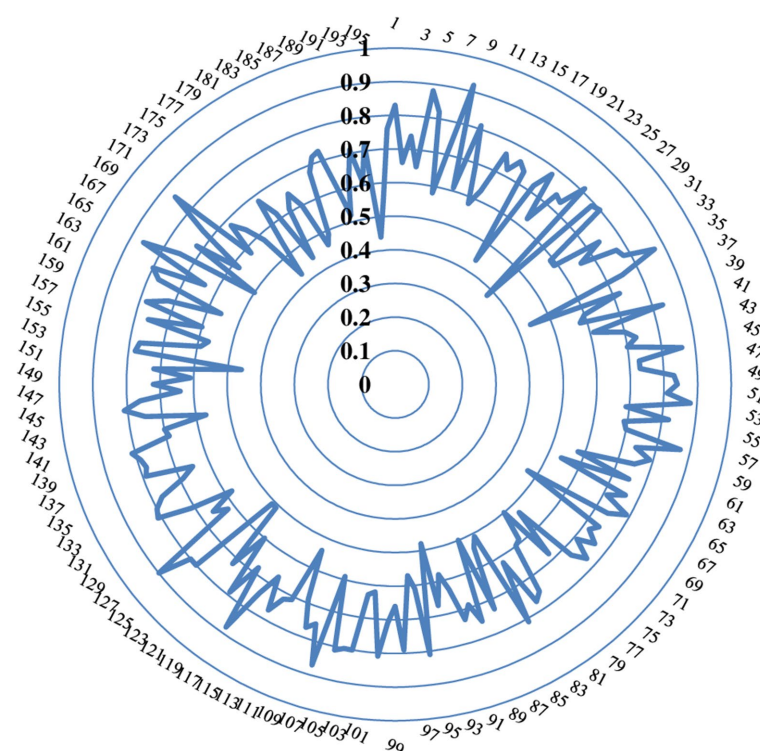


FIGURE 3
Responsible farm production (RFP) status of all farm producers.

producers are the primary cause of the farmers' overall poorer RFP status.

3.5. Factors affecting the RFP

Farm producers' actions in the field are important to the RFP. A total of 16 farm and farmer characteristics were considered for analyzing their impact on the RFP. Out of which, nine variables (age, education, women's participation, extension services, TV and Internet use for agricultural purposes, risk taking, innovativeness, and pro-activeness) were found to significantly affect the RFP. The overall ordered probit model was significant, with a log likelihood ratio of chi square value of 120.666 and a probability of Chi-square of less than 1%.

The age of the farm producers was negatively associated with the RFP (Table 4), which indicates that younger farmers are likely to act more responsibly in farm production as compared to older farmers. This can be explained by the fact that younger farm producers are expected to be better aware of RFP than older farm producers due to their knowledge of modern techniques necessary for efficient use of natural resources, raising income, and implementing climate change adaptation practices. A one-year increase in farm producers' age increases the likelihood of belonging to the low and moderately responsible farm producer categories by 0.6% points and 1% points, respectively. However, a one-year increase in farm producers' age reduces the probability of belonging to the highly responsible farming category by 1.6% points. The education of farm producers was also found to significantly affect

the RFP. If farm producers' education improves by a year, their chances of belonging to a highly RFP category increases by 3.5% points. In addition, a one-year decrease in the education of farm producers reduces the probability of being a low- or moderately responsible farm producer by 1.2% points and 2.3% points, respectively. The reason may be that educated farmers can communicate easily with extension workers and credit-providing institutions, helping these farmers utilize their farm resources productively and efficiently, which is necessary for RFP. Moreover, educated farm producers can also use internet facilities to get agriculture-related information, which assists them in different farm operations directly linked to the RFP.

Women's participation in agricultural activities was also significant in influencing the RFP. This may be because women provide the additional labor force necessary for certain farm operations in traditional agriculture. Traditional agriculture requires more labor for farming activities. Moreover, women tend to be more resource efficient and have healthier environmental behaviors. Thus, the involvement of women in farming activities enhances the probability of a farm producer belonging to a higher RFP category. Farms with women's participation in agricultural activities were 33.5% points more likely to belong to the highly responsible farm producer category as compared to farms where only males perform agricultural operations. Similarly, women's participation in agricultural activities decreases the chances of a farm producer belonging to a low or moderately responsible farming category by 11.9% points and 21.6% points, respectively, compared to only male-managed farms.

Agriculture extension services increase farmers' knowledge, which in turn increases responsible farming by increasing farm

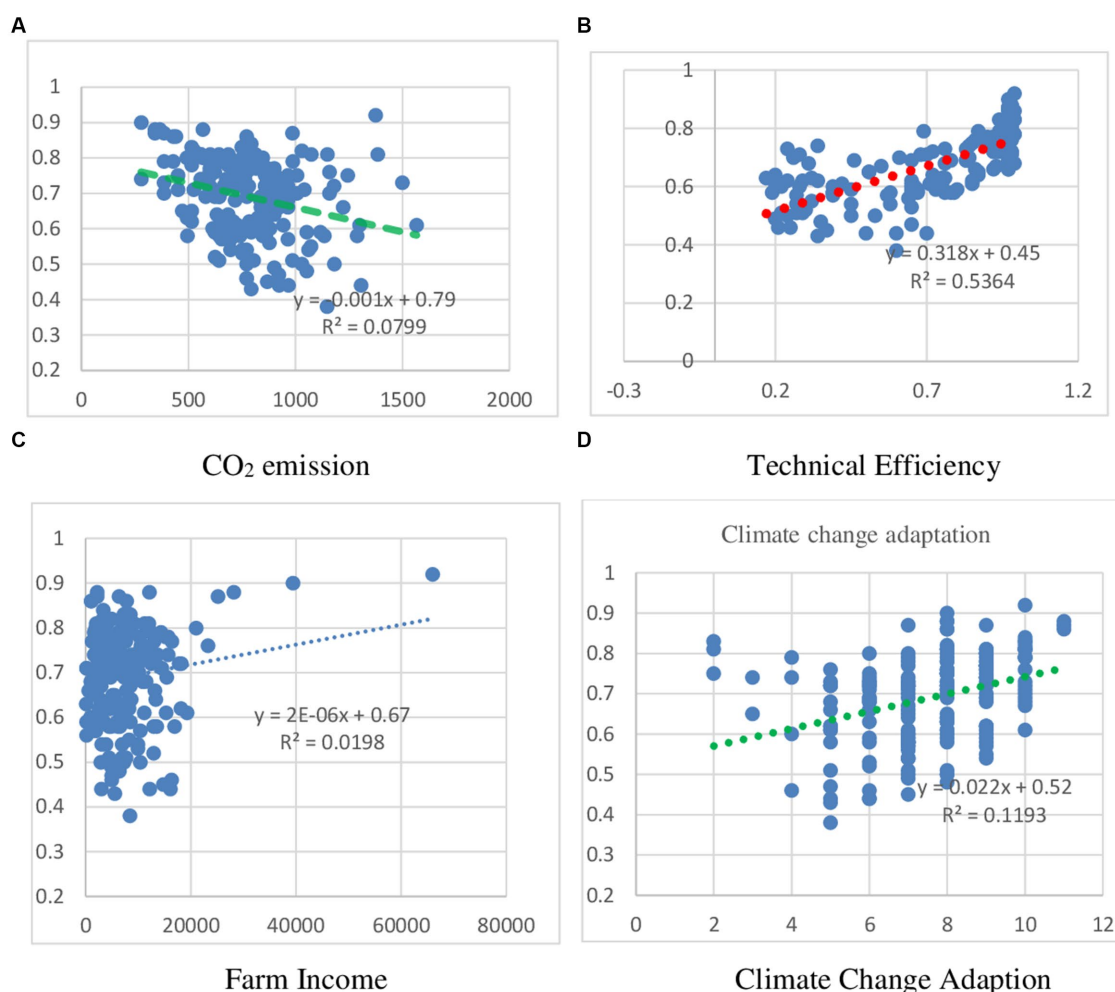


FIGURE 4

Relationship between RFP and its four indicators (CO₂ emissions, technical efficiency, farm income, and climate change adaptation).

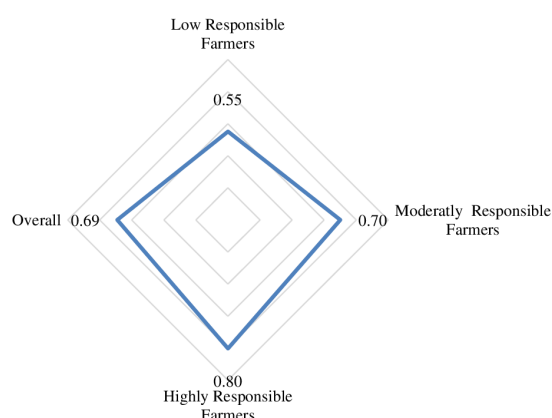


FIGURE 5

Mean responsible farm production index (RFPI) scores for low, moderately, and highly responsible farm producers.

efficiency, climate change adaptation, and farm income. Agriculture extension services were found to be positively related to the RFP. Even though the use of other sources for information in agriculture is

increasing with the passage of time, extension workers are still the primary source of information on modern farming techniques and the agronomic requirements of different crops for the majority of the farming community in the country. This information is vital for farmers to act more responsibly on their farms. Farm producers who availed of extension services had 7.3% points higher chances of belonging to the highly responsible farming category than those who did not utilize extension services. On the other hand, farm producers who used extension services were less likely to be in the low or moderately responsible farming groups by 2.6% points and 4.7% points than farmers who did not use extension services. This shows that a proactive extension system in the country can contribute to RFP.

Agro-informatics plays a significant role in agriculture. ICT are important sources of information, and their use among the farming community is on the rise worldwide owing to their benefits and the increasing agricultural-related information on these platforms (Nnadi et al., 2012). Moreover, awareness among farmers about the use of ICT is also rising with the passage of time. Farm producers who watch TV for agricultural-related information were 23.9% points more likely to belong in the highly RFP category compared to those who do not watch TV for agricultural information. Contrarily, farm producers who watch TV for agricultural-related information were 8.5% points and

TABLE 4 Factors affecting RFP.

Explanatory variables	Coef.	Std. Err.	Marginal effects		
			Low responsible farm producer category	Moderately responsible farm producer category	Highly responsible farm producer category
Socioeconomics					
Age (years)	0.051*	0.013	0.006	0.010	−0.016
Education (years)	0.115*	0.035	−0.012	−0.023	0.035
Total land (acres)	0.024	0.015	−0.003	−0.005	0.008
Agriculture labor force (persons)	0.133	0.118	−0.047	−0.085	0.132
Women participation (1 = yes)	1.093*	0.234	−0.119	−0.216	0.335
Farming experience (years)	0.005	0.016	0.001	0.001	−0.002
Land tenure status (1 = owner)	−0.207	0.134	0.023	0.041	−0.064
Extension services (1 = yes)	0.238**	0.115	−0.026	−0.047	0.073
Credit utilization (1 = yes)	0.177	0.219	−0.0625	−0.114	0.176
Land fragmentation (numbers)	0.008	0.098	−0.001	−0.002	0.003
Information and communication technology (ICT) use for agricultural information					
TV (1 = yes)	0.782*	0.221	−0.085	−0.154	0.239
Radio (1 = yes)	0.186	0.113	−0.020	−0.037	0.057
Internet (1 = yes)	0.048*	0.018	−0.005	−0.009	0.014
Farmer entrepreneurship orientation dimensions					
Risk taking (mean)	0.124**	0.057	−0.014	−0.025	0.039
Innovativeness (mean)	0.375*	0.109	−0.041	−0.074	0.115
Pro-activeness (mean)	0.304*	0.088	−0.033	−0.060	0.093

* and ** represent coefficients with $p < 0.01$ and $p < 0.05$, respectively. N is 196. Log Likelihood is −120.666. LR χ^2 (16) is 189.200. $p > \chi^2$ equals 0.000. Pseudo R^2 is 0.438.

15.4% points less likely to belong in the low or moderately RFP categories compared to those who do not watch TV for agricultural information. Similarly, internet use for obtaining information was also found to be positively associated with RFPs. Farm producers using the internet for agriculture had a 1.4% points higher probability of belonging to the highly responsible farm producer category compared to those who do not use the internet for obtaining agricultural information. This implies that the use of ICT among the farming community can make farm production more responsible. Hamad et al. (2018) and Irungu et al. (2015) found that farmers successfully utilized the internet and social media for sharing production technologies, market information, and money transactions. Similarly, Ma et al. (2020) revealed that the use of ICT, such as smart phones, substantially increases the farm income of farm producers. Thus, the use of ICT assists farmers in improving farm efficiency, income, and climate change adaptation, which ultimately contributes to RFP.

All dimensions of farm entrepreneurial orientation were positively associated with RFP. This means that a farmer acting entrepreneurially in farming activities is likely to be more responsible for farm production than those farmers who do not work entrepreneurially in farm production. The reason may be that farmers working as entrepreneurs have the ability to deviate from traditional farming methods, enabling them to use farm resources more efficiently and cost-effectively. The efficient and cost-effective use of resources is essential part of the RFP. A more risk-taking and innovative farm producer is 3.9% points and 11.5% points more likely to belong to the highly responsible farm

producer category, respectively. Similarly, proactive farm producers were, respectively, 3.3% points and 6% points less likely to belong to the low and moderately responsible farm producer categories. The reason may be that pro-activeness entails the capacity to anticipate and respond to future difficulties and opportunities. The literature on the relationship between farmer entrepreneurship and RFP indicators reflects that farmer entrepreneurship positively affects different indicators (farm income, technical efficiency, and climate change adaptation) of RFP (Abbas et al., 2016; Arellano and Reyes, 2019; Kangogo et al., 2021). Thus, farmer entrepreneurship positively affects responsible farming, as found in this study.

3.6. Responsible farm production status based on important farm and farm producer characteristics

Table 5 describes the RFP status in terms of RFPI scores on the basis of important farm and farm producer characteristics. The comparison of the RFPI scores of old and young farm producers revealed that farms managed by young producers were more responsible for farm production than farms operated by old ones. The young farm producer had a 0.06 higher RFPI score than the old farm producer. Similarly, the RFPI scores of high and low-educated farm producers showed that high-educated farm producers performed comparatively better in RFP, as indicated by their 0.08 higher RFPI

score than low-educated farm producers. Tenant farm producers were relatively less responsible for farm production than owner farm producers. The reason may be the difference in attitudes towards farm operations. For example, owner farmers take more responsible care of farm resources and use these resources efficiently as compared to tenant farmers. Moreover, owner farmers adopt more sustainable farm practices such as climate-smart practices than tenant farmers. Soule et al. (2000) found that owner-operated farms compared to

farms under other land tenure statuses were more likely to adopt practices at their farms with long-run benefits.

Farm producers utilizing ICT such as TV and the Internet for obtaining agricultural information were found to be more responsible farm producers than those who did not use these modern sources of information. The farm producers not utilizing TV and the Internet for farming purposes had 0.09 and 0.18 lower RFPI scores, respectively, than farmers utilizing modern information sources. High-risk-taking farm producers performed better by attaining a higher RFPI score than low-risk-taking farm producers. Similarly, high-innovating farm producers had a 0.012 higher RFPI score than low-innovating farm producers. Low-proactive farm producers had a lower RFPI score than highly proactive farm producers. These results show that farm producers managing their farms as an enterprise and working more entrepreneurially can contribute to RFP than other farm producers working traditionally.

4. Conclusion and policy recommendations

In recent academic studies on responsible production, the agriculture sector, which uses the most natural resources, has been ignored. The purpose of this study was to contribute to theory by analyzing responsible production, specifically with regard to farming. The study examined the status of RFPs as well as the factors influencing them. Specifically, our findings addressed three research questions: (1) What is the current status of RFP on farms? (2) What farm and farmer characteristics of farm producers determine RFP status? (3) How does the status of the RFP change in relation to key farm and farmer characteristics? Findings showed that the overall status of the RFP was satisfactory, while the empirical model results showed that farm and producer characteristics significantly affect the RFP. Socio-economic characteristics such as age, education, women's participation in farming activities, and extension services were found to be positively correlated with the RFP. Similarly, ICT and farmer entrepreneurship also positively affected the RFP.

RFP status was determined by both farm and farmer characteristics, which revealed that owners tend to be more responsible farm producers compared to tenants. Similarly, farmers who managed their farms in a more entrepreneurial manner were more responsible farm producers than farmers managing their farms in a less entrepreneurially manner.

This study has significant policy implications for Pakistan as well as for other developing countries. To begin with, this study proposes a method for measuring farm producers' RFP status in agriculture. Second, the study emphasizes the significance of ICT in agriculture for enhancing RFP. Therefore, policymakers can adopt policies to increase the use of ICT in agriculture to increase RFP. Furthermore, ICT can also be used to raise farmers' knowledge and awareness about RFP. Thirdly, the empirical model results show that women's engagement in agricultural activities is important for enhancing RFP. The government should aim to increase female participation in farming, particularly their role in agricultural decision-making, in order to improve RFP. This can only be accomplished by changing the farming community's mindset and attitudes towards women's roles in society. Fourth, the study results demonstrated the importance of managing a farm entrepreneurially for RFP. As a result, developing countries should endeavor to promote agripreneurship culture in

TABLE 5 Responsible farm production index (RFPI) scores based on important farm and producer characteristics.

Farm or producer characteristics	RFPI score (SD)	p-value
Age ^a		
Old	0.66 (0.11)	0.000
Young	0.72 (0.10)	
Education ^a		
High	0.73 (0.09)	0.000
Low	0.65 (0.11)	
Land size ^a		
Large	0.70 (0.13)	0.764
Small	0.68 (0.12)	
Land tenure status		
Owner	0.74 (0.14)	0.000
Tenant	0.64 (0.11)	
Extension services		
Yes	0.69 (0.10)	0.778
No	0.68 (0.16)	
ICT		
TV		
Yes	0.73 (0.09)	0.000
No	0.64 (0.11)	
Radio		
Yes	0.71 (0.15)	0.172
No	0.68 (0.09)	
Internet		
Yes	0.78 (0.13)	0.000
No	0.60 (0.07)	
Farmer entrepreneurship		
Risk taking ^a		
High	0.71 (0.12)	0.010
Low	0.67 (0.10)	
Innovativeness ^a		
High	0.75 (0.10)	0.000
Low	0.63 (0.11)	
Pro-activeness ^a		
High	0.72 (0.11)	0.010
Low	0.66 (0.11)	

^aRepresents the sample was separated into two groups by taking average of the sample as the cut-off point. SD stands for standard deviation.

agriculture in order to increase RFP involving all agricultural socioeconomic networks.

Moreover, this study urges governments in Pakistan and other developing countries to develop a sustainable agricultural strategy immediately, as formulating policy and its implementation may take some time. For this purpose, developing nations should embrace the sustainable agricultural strategies employed by affluent ones. Explicit rules may also be used to put pressure on farmers to adopt responsible farming methods in developing countries. Agriculture extension organizations must invest in staff training, particularly for agriculture sustainability. This study also proposes setting up a forum where farmers may exchange their best farming practices and models and debate issues pertaining to agricultural sustainability. Governments should take the lead in organizing such meetings to support the RFP in their countries.

As all studies have limitations, this study is no exception. In this study, we relied on farmers' recall abilities for information regarding several variables, such as farm inputs and pricing, which may lack accuracy. The second limitation of the study was its geographical coverage, as it was undertaken in two agro-ecological zones of Pakistan's Punjab province. Furthermore, the study's other drawback was that it used only fertilizers for estimating carbon footprints from the fields. Even with these limitations, this work makes a contribution to theory, and researchers in other developing countries can build on it by gathering more data using different sampling methods and including more indicators for measuring RFP.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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Ethics statement

The studies involving humans were approved by the University of Education Lahore Pakistan. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin because Verbal consent was obtained from the participants.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Optimizing fertilizer use for sustainable food systems: an evaluation of integrated water-fertilizer system adoption among cotton farmers in China

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Introduction: In the face of escalating apprehensions surrounding food security, the sustainability of food systems, and food quality, the ingenuity of resource management strategies becomes paramount. A key component within these strategies is the enhancement of chemical fertilizer utilization, an element that bears significant weight on agricultural yields and the preservation of our environment. The emergence of Integrated Water-Fertilizer Systems (IWFS) thus presents a significant innovation in boosting the efficiency of chemical fertilizer usage, necessitating in-depth examination.

Methods: Utilizing a rigorous analytical framework that combines meta-frontier production function with a Two-Stage Residual Inclusion model, this study delves into the multi-dimensional impacts of IWFS adoption on fertilizer use efficiency among cotton growers in Xinjiang, China.

Results: Empirical evidence demonstrates that those who have adopted IWFS achieve a fertilizer use efficiency score of 0.452, markedly outstripping the mean score of 0.382 among non-adopters. Intriguingly, efficiency increases proportionately with the size of the farm, hinting at a sophisticated interplay between the adoption of technology and operational parameters.

Discussion: The research further unveils additional benefits including augmented cotton yields and diminished labor inputs among adopters. These multifaceted outcomes bear significant policy implications, highlighting the transformative potential of IWFS in promoting sustainable food systems, bolstering food security, and enhancing food quality.

KEYWORDS

chemical fertilizer, meta-frontier, 2SRI, integrated water-fertilizer system, cotton

1 Introduction

Chemical fertilizers serve a dual role in contemporary society: they are essential yet problematic. On one hand, they have significantly increased global crop yields by 30–50%, supporting the livelihoods of approximately 4 billion people born in the last century (Stewart et al., 2005; Erisman et al., 2008; Zhang et al., 2020). However, their usage has also led to various environmental issues (Wu, 2011; Zhang et al., 2015; Hu et al., 2019; Yuan and Zhang, 2021; Zhang and Yu, 2021). These adverse environmental effects primarily result from the excessive release of reactive nitrogen, phosphorus, and potassium into the environment. For example,

ammonia gas, nitrous oxide, and nitrogen oxides escape into the atmosphere, contributing to air pollution and tropospheric ozone degradation (Liu et al., 2013). Likewise, the leaching and runoff of ammonium and nitrate contaminate groundwater and promote eutrophication in aquatic ecosystems (Zhang et al., 2015). Therefore, it is crucial to carefully consider the benefits and drawbacks of chemical fertilizer use in order to address both food security and environmental concerns. This study aims to explore strategies for optimizing the efficiency of chemical fertilizer use.

The concept of chemical fertilizer use efficiency has different interpretations in scholarly discourse. Agricultural scientists commonly define it as the proportion of chemical fertilizer converted into harvested crop products, a metric adopted by over 130 countries to achieve Sustainable Development Goals (Zhang et al., 2015). This efficiency is calculated using inputs and outputs either estimated from historical data and key variables (Zhang et al., 2015) or measured in the field trials (Zhang et al., 2016; Cui et al., 2018). However, this method relies on multiple parameters, and can be influenced by factors like weather conditions, soil quality, measurement errors, and farming practices (Zhang G. et al., 2014; Zhang and Yu, 2021). In contrast, economists in the agricultural sector often define it as the ratio of minimum required chemical fertilizer to the actual amount used (Wu, 2011; Hu et al., 2019). This definition considers technological constraints and other determinants. Some literature also conceptualizes it as allocation efficiency, examining the marginal utility of chemical fertilizer relative to its cost (Zhang et al., 2017; Yuan and Zhang, 2021; Zhang and Yu, 2021). For this research, we adopt the economist's perspective and measure efficiency as the ratio of minimum required to actual chemical fertilizer use.

Integrated Water-Fertilizer Systems (IWFS) present a promising approach to enhance fertilizer use efficiency. Extensive literature has explored various factors influencing chemical fertilizer efficiency, including technological advancements and socio-economic variables. Among technological innovations, integrated soil-crop system management has been identified as a crucial element in improving fertilizer use efficiency (Chen et al., 2014). Socio-economic determinants, such as management practices, farm size, policy distortions, land leasing, and pricing, have also received significant attention in scholarly research (Zhang et al., 2015; Wu et al., 2018; Hu et al., 2019; Zhang et al., 2023a). Research by Zhang et al. (2016) suggests that platforms like the Science and Technology Backyard, which embed agricultural scientists in farming communities to enhance farming practices and technology adoption, can reduce nitrogen use by 32% in wheat and 7.5% in maize. IWFS is a notable technological innovation that combines water and fertilizer, delivering them directly to crops through drip or sprinkler irrigation systems, thus minimizing fertilizer loss through volatilization and soil residue (Zhong et al., 2012; Gao et al., 2015). IWFS integrates the advantages of mulched drip irrigation (Hu et al., 2009; Wang et al., 2014; Zhang Z. et al., 2014; Qi et al., 2018) and integrated soil-crop system management (Chen et al., 2014), offering the potential to mitigate the negative impacts of socio-economic factors, weather conditions, and soil conditions on fertilizer efficiency.

Empirical evaluations of IWFS heavily rely on field trials, which provide valuable insights into its impact on fertilizer efficiency across various crop types. While the global average for chemical fertilizer use efficiency is approximately 40%, China's rate lags behind at around 30%, which is 15–30% lower than that of developed countries (Zhang

et al., 2015; Liu et al., 2019). Zhang G. et al. (2014) demonstrated that the adoption of IWFS with drip irrigation could increase phosphorus fertilizer efficiency to 40.6% for corn production. Similarly, Wu et al. (2016) reported that implementing IWFS through mulched drip irrigation not only enhanced the yield and quality of potatoes but also improved the efficiencies of nitrogen, phosphorus, and potassium fertilizers by 22.7, 20.5, and 23.5%, respectively. It is important to note that these field trials are typically conducted by experts, setting an upper limit on efficiency that may not be fully attainable for average farmers. This study aims to assess the effectiveness of IWFS in enhancing chemical fertilizer use efficiency from the perspective of farmers.

This study makes two primary contributions to the existing literature. Firstly, it sheds light on the impact of IWFS on chemical fertilizer efficiency, using data from cotton farmers in Xinjiang, China. Xinjiang, known for its arid climate with high water evaporation rates, low fertilizer efficiency, and delicate ecosystems, accounts for nearly 90% of China's cotton production (Zhang et al., 2023b). Given the significance of cotton in the region and the ecological challenges poses, it is crucial to explore the potential benefits of IWFS in improving chemical fertilizer efficiency.

Secondly, this research addresses the potential endogeneity of IWFS adoption by employing a two-stage residual inclusion approach (2SRI) and utilizes a meta-frontier analysis to accurately assess chemical fertilizer use efficiency, considering differentiated production frontiers between IWFS adopters and non-adopters (Zhang et al., 2023c). The decision to adopt IWFS is not random, as farmers self-select based on unobservable factors such as environmental motivation or inherent capabilities (Ma et al., 2018). Furthermore, IWFS not only enhances fertilizer efficiency but also crop yield, potentially leading to a shift in the production frontier (Bravo-Ureta et al., 2020).

We find that the chemical fertilizer use efficiency of IWFS adopters is 0.452, 1.6 times larger than that of non-adopters, with a mean value of 0.382. Adopting IWFS can contribute to 0.223 increases in chemical fertilizer use efficiency, and efficiency gains increase with farm size. In the context of sustainable food production and consumption, the findings of this paper have significant implications. Efficient fertilizer use facilitated by IWFS adoption can contribute to improved food security, food quality, and safety, while mitigating environmental degradation. This aligns with broader goals of agricultural sustainability, particularly in regions like Xinjiang that face complex ecological challenges.

The remainder of this paper is structured as follows: Section 2 provides background information on chemical fertilizer consumption and IWFS adoption in China. Section 3 outlines the meta-frontier production function and describes the estimation strategy using the 2SRI approach. Section 4 presents the data and descriptive statistics, followed by a discussion of empirical results in Section 5. Finally, Section 6 offers the conclusion.

2 Background

2.1 Chemical fertilizer use in China

China holds the position of the world's largest consumer of chemical fertilizers. The country's global share of nitrogen usage

peaked at 30.6% in 1995, but has declined to 19.6% in 2021. Specifically, nitrogen consumption in China has risen from 0.54 million tons in 1961 to 21.27 million tons in 2021, with a peak of 30.98 million tons in 2014. This represents an average annual growth rate of 6.3% (Figure 1). Furthermore, the intensity of nitrogen use in China has significantly increased, with per hectare usage rising from 5.21 kilograms in 1961 to 166.4 kilograms in 2021, which is 2.54 times higher than the global average (Figure 2). This significant expansion in chemical fertilizer application has contributed to a 40% increase in China's grain production (MOARA, 2015).

The intensity of chemical fertilizer application has shown an upward trend, increasing from 382.50 kilograms/hm² in 2004 to 622.05 kilograms/hm² in 2021 (Figure 3). However, the amount of chemical fertilizer used per kilogram of cotton has remained relatively stable at around 0.33 kilograms, primarily due to consistent increases in yield per hectare (Figure 4). It is worth noting that while fertilizer use per unit area in Xinjiang exceeds the national average, the opposite is true for fertilizer use per kilogram of cotton. The climatic conditions in Xinjiang contribute to higher cotton yields per unit area, but they may also result in lower fertilizer use efficiency. Nevertheless, the widespread adoption of IWFS has the potential to alleviate this effect.

A significant quantity of nitrogen fertilizer is utilized in crop production; however, a considerable portion remains unabsorbed, persisting in the soil and atmosphere. The global average for chemical fertilizer use efficiency is approximately 0.4, indicating that only 40% of applied fertilizers contribute to crop yields (Zhang et al., 2015). Although China's efficiency rate falls below the global average, there has been an upward trend, with an estimated 35.2% efficiency rate for grain production in 2014 (MOARA, 2015; MOARA, 2016). Several factors influence this efficiency, providing substantial opportunities to bridge the gap between China and developed nations (Gao et al., 2015).

2.2 Adoption of IWFS in China

Conventional methods of applying chemical fertilizer involve the spreading of solid fertilizer over soil surfaces. In this approach, the fertilizer dissolves upon encountering soil moisture, allowing the nutrients (nitrogen, phosphorus, and potassium) to be absorbed by crop roots. This technique, however, has limitations. It requires specific environmental conditions, such as adequate soil moisture, and rapid dissolution of fertilizers to prevent nutrient evaporation and air dispersal. Additionally, this method results in nutrient dispersion across the field, reducing the likelihood of nutrient uptake by roots located at a distance. Consequently, this traditional method exhibits low use efficiency.

IWFS offers a more efficient alternative by integrating solid fertilizer with water (Geng et al., 2014). This combined solution is directly delivered to the roots or foliage of crops through a piping system, shifting the focus of application from soil to crops themselves. The IWFS system enhances both water and fertilizer efficiency, promoting sustainable agricultural practices by reducing fertilizer volatilization and soil residues. Furthermore, the integration of IWFS with information and intelligent technologies enables automated, on-demand fertilizer application, reducing labor requirements.

The concept of IWFS originated from soilless agriculture practices in the United Kingdom and has evolved alongside efficient irrigation technologies like plastic conduits (Gao et al., 2015). The United States leads in global micro-irrigation areas, with IWFS being employed in 60% of potato, 25% of corn, and 33% of fruit production (Gao et al., 2015). The Netherlands also implements IWFS in its greenhouses. In China, IWFS was initially applied to cotton production in Xinjiang due to the region's arid climate and high evaporation rates. In 2002, China invested over 100 million RMB to promote IWFS, establishing demonstration bases in more than 20 provinces, covering an area of 3 million hectares. Subsequent policies, such as the National Agricultural Water Conservation Outlines (2012–2020) and the

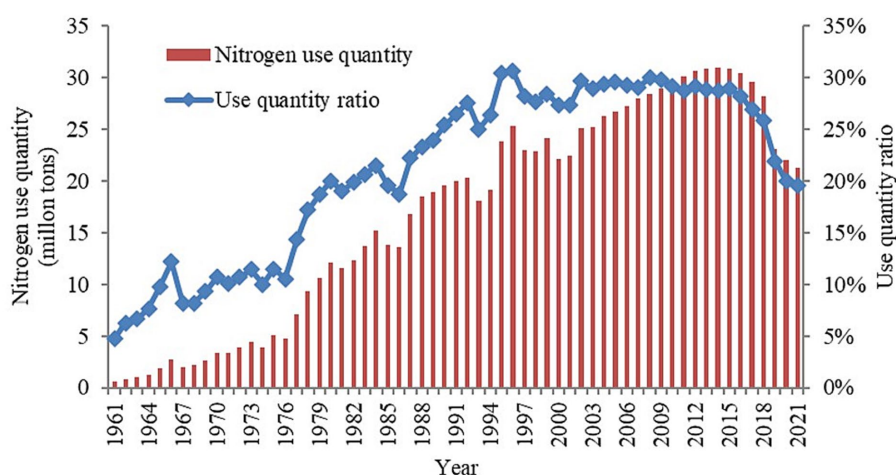


FIGURE 1
China's nitrogen use quantity and the ratio to the world. Data is from FAO.

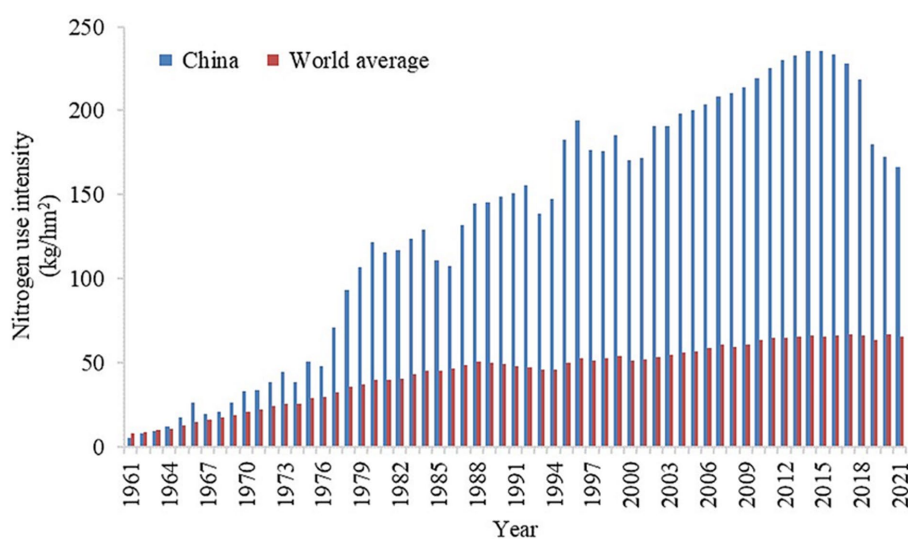


FIGURE 2
Nitrogen use intensity in China and the world average. Data is from FAO.

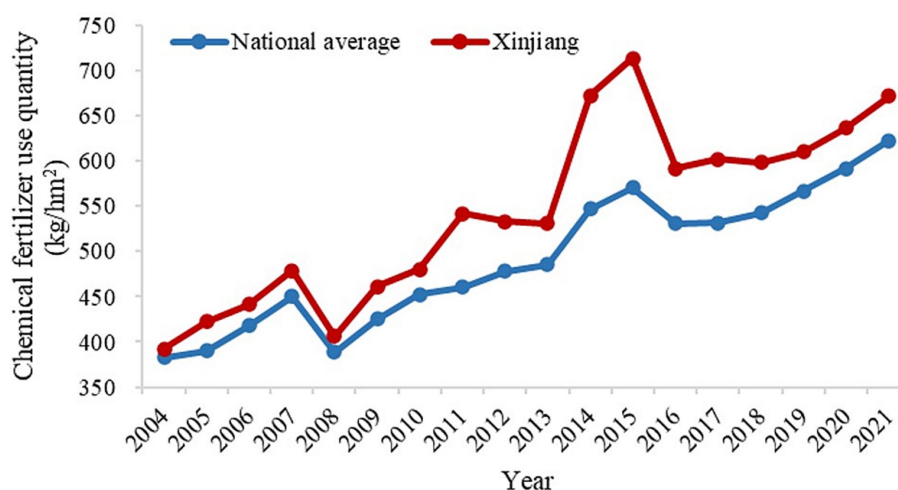


FIGURE 3
Chemical fertilizer use quantity per area for cotton production. Data is from China Agricultural Product Cost–Benefit Compilation.

Implementation Plan for Promoting Integrated Water-Fertilizer System (2016–2020), have further encouraged the adoption of IWFS, with the aim of expanding its use to 150 million mu by 2020.

3 Estimation strategies

3.1 Meta-frontier production function and fertilizer use efficiency

IWFS represents a technological innovation that could alter the relationship between inputs and outputs. Therefore, different production frontiers may exist for IWFS adopters and non-adopters in cotton production. Estimating a single production function could

lead to biased technical efficiency assessments (Bravo-Ureta et al., 2020). Technical efficiency is calculated relative to the production frontier and constitutes a vital component in determining chemical fertilizer use efficiency. Consistent with prior research (Battese et al., 2004; O'Donnell et al., 2008; Zhang et al., 2023c), this paper estimates separate production functions for both groups and calculates comparative technical efficiencies via a meta-frontier encompassing both.

Battese et al. (2004) and O'Donnell et al. (2008) employed a mathematical programming technique to estimate the meta-frontier production function. Huang et al. (2014) argued that such techniques lack meaningful statistical interpretation and proposed a stochastic frontier regression method instead. In the present study, we employ the stochastic frontier regression technique developed by Huang et al.

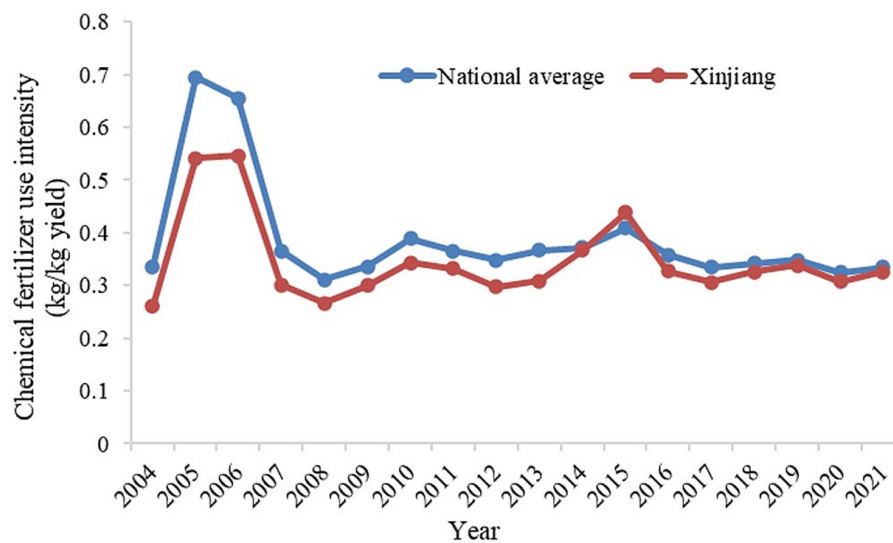


FIGURE 4

Chemical fertilizer use quantity per kilogram cotton. Calculating by authors using data from China Agricultural Product Cost–Benefit Compilation.

(2014) to estimate the meta-frontier production function and ascertain chemical fertilizer use efficiency. This method comprises two stages.

In the first stage, separate production frontiers are estimated for IWFS adopters and non-adopters.

$$\ln Y_i^F = \alpha_0 + \sum_{k=1}^3 \alpha_k \ln x_{ik} + \alpha_f \ln f_i + \frac{1}{2} \sum_{k=1}^3 \sum_{m=1}^3 \alpha_{km} \ln x_{ik} \ln x_{im} + \sum_{k=1}^3 \alpha_{kf} \ln x_{ik} \cdot \ln f_i + \frac{1}{2} \alpha_{ff} (\ln f_i)^2 + \varepsilon_i - u_i \quad (1)$$

where $\ln Y_i^F$ denotes the logarithm of cotton yield of farmer i among IWFS adopters ($F = 1$) and non-adopters ($F = 0$). $\ln x_{ik}$ denotes the logarithm of the input vectors for farmer i , where $k = 1, 2, 3$ correspond to land, labor, and intermediate input, respectively. $\ln f_i$ is the logarithm of chemical fertilizer input for farmer i . The parametric vectors α are to be estimated associated with the inputs. The error term ε_i is independently and identically distributed as $N(0, \sigma^2)$. u_i refers to technical inefficiency and is independently and identically distributed as $N^+(u, \sigma_u^2)$.

The optimal yield $\ln Y_i^*$ can then be predicted for both groups using the estimated parameters from Equation 1. Subsequently, these optimal yields replace observed yields $\ln Y_i$ with optimal yields $\ln Y_i^*$ to estimate the meta-frontier production function, which serves as a smooth envelope corresponding to the separate frontiers for both groups. The meta-frontier production function for both IWFS adopters and non-adopters is as follows:

$$\ln Y_i^* = \alpha_0 + \sum_{k=1}^3 \alpha_k \ln x_{ik} + \alpha_f \ln f_i + \frac{1}{2} \sum_{k=1}^3 \sum_{m=1}^3 \alpha_{km} \ln x_{ik} \ln x_{im} + \sum_{k=1}^3 \alpha_{kf} \ln x_{ik} \cdot \ln f_i + \frac{1}{2} \alpha_{ff} (\ln f_i)^2 + v_i - u_i^M \quad (2)$$

All symbols retain their meanings from Equation 1. Huang et al. (2014) suggested that the comparable technical efficiency for both groups can be calculated as follows:

$$TE_i^* = (1 - u_i) \times (1 - u_i^M) \quad (3)$$

Where $1 - u_i^M$ is defined as the production technology gap relative to the meta-frontier. The comparable technical efficiency metric specifically accounts for potential differences in production technologies between IWFS adopters and non-adopters.

Based on the estimated comparable technical efficiency TE_i^* , we extend our analysis to compute chemical fertilizer use efficiency. By definition, an environmentally efficient farmer minimizes fertilizer input to achieve a given cotton yield, with technology held constant. Thus, we substitute $\ln f_i$ with $\ln f_i^E$, and set $u_i^M = 0$ in Equation 2. Rewriting Equation 2 yields:

$$\ln Y_i^* = \alpha_0 + \sum_{k=1}^3 \alpha_k \ln x_{ik} + \alpha_f \ln f_i^E + \frac{1}{2} \sum_{k=1}^3 \sum_{m=1}^3 \alpha_{km} \ln x_{ik} \ln x_{im} + \sum_{k=1}^3 \alpha_{kf} \ln x_{ik} \cdot \ln f_i^E + \frac{1}{2} \alpha_{ff} (\ln f_i^E)^2 + v_i \quad (4)$$

Chemical fertilizer use efficiency equates to the ratio of minimum fertilizer input f_i^E to the observed input f_i . When expressed in logarithmic form, this is $\ln f_e = \ln f_i^E - \ln f_i$. By combining Equations 2 and 4, we can derive a quadratic equation in terms of $\ln f_i^E - \ln f_i$.

$$0.5 \alpha_{ff} (\ln f_i^E - \ln f_i)^2 + \left(\alpha_f + \sum_{k=1}^3 \alpha_{kf} \ln x_{ik} + \alpha_{ff} \ln f_i \right) \times (\ln f_i^E - \ln f_i) + u_i^M = 0 \quad (5)$$

The solution for chemical fertilizer use efficiency can be found in Equation 5 as:

$$\ln fe_i = \left\{ \begin{array}{l} - \left(\alpha_f + \sum_{k=1}^3 \alpha_{kf} \ln x_{ik} + \alpha_{ff} \ln f_i \right) \\ + \left[\left(\alpha_f + \sum_{k=1}^3 \alpha_{kf} \ln x_{ik} + \alpha_{ff} \ln f_i \right)^2 - 2\alpha_{ff} u_i^{M'} \right]^{0.5} \end{array} \right\} / \alpha_{ff} \quad (6)$$

In theory, Equation 5 offers two possible solutions. However, following Zhou et al. (2015) suggestion, we only use the solution reported in Equation 6. It is noteworthy that $u_i^{M'}$ in equation (2) is the technology gap between the individual frontiers and meta-frontier. For Equation 6, it is essential to use farmers' technical inefficiency, gauged by the distances from production points to the meta-frontier, thus, $u_i^{M'} = 1 - TE_i^*$.

3.2 Two-stage residual inclusion approach

Given that farmers make a self-selection choice to adopt IWFS, the IWFS variable is potentially endogenous. To address this issue, this study employs a Two-Stage Residual Inclusion (2SRI) model. In this paper, the treatment variable is the IWFS adoption decision which is a binary variable. Thus, a 2SRI model is used to address the endogeneity issue of a binary treatment variable, while 2SLS model is used for a continuous endogenous treatment variable. A 2SRI model consists of two steps.

Step 1: To estimate the probability of farmer i adopting IWFS by using a logit model:

$$IWFS_i^* = \beta_0 + \beta_1 IV_i + \beta_2 Z_i + \beta_3 C_i + \theta_i, \quad (7)$$

$$IWFS_i = \begin{cases} 1, & \text{if } IWFS_i^* > 0 \\ 0, & \text{otherwise} \end{cases}$$

Where $IWFS_i^*$ is the propensity of a farmer to adopt IWFS, which is observed by $IWFS_i$. Specifically, $IWFS_i = 1$ if the farmer is an IWFS adopter, and 0 otherwise. IV serves as an instrumental variable that isolates the part of the IWFS variable uncorrelated with unobservable factors. Z_i refers to a vector of control variables, including gender, nationality, age and education level of the household head, and agricultural training, price of cotton and fertilizer, cooperation organization participation, household size, subsidy, and share of agricultural income. C_i is a dummy variable to control county fixed effect. θ_i is an error term. β_0 is a constant. β_1 , β_2 and β_3 are parameters to be estimated.

The ratio of IWFS adoption in the village, excluding the individual farmer, is used as the instrumental variable to estimate Equation 7. This instrument must be correlated with the endogenous variable and uncorrelated with unobservable factors. A higher ratio of IWFS adoption in the village likely influences a farmer's choice to adopt IWFS due to peer effects. Moreover, this ratio is uncorrelated with the individual farmer's motivation or inherent environmental conservation abilities.

Step 2: Estimating the 2SRI model to reveal the impacts of IWFS adoption on chemical fertilizer use efficiency. The empirical specification is as follows:

$$fe_i = \lambda_0 + \lambda_1 IWFS_i + \lambda_2 Z_i + \lambda_3 C_i + \lambda_4 R_i + \delta_i \quad (8)$$

where fe_i is farmer i 's chemical fertilizer use efficiency. $IWFS_i$, Z_i and C_i are defined above. R_i is the residual term in Equation 7. We add the residual term in Equation 8 to control the unobserved heterogeneity that is correlated with IWFS variable and will result in biased estimation for IWFS variable. δ_i is an error term. λ_0 is a constant. λ_1 , λ_2 and λ_3 are parameters to be estimated.

4 Data sources and descriptive statistics

The farm-level data used in this paper was collected in 2019 from Xinjiang, China, by Xinjiang Agricultural University and China Agricultural University. The survey methodology, which involved multistage random sampling, is detailed in Zhang et al. (2023b). First, three counties in north Xinjiang and five counties in south Xinjiang were chosen based on their agricultural output values. Second, two towns from each county and three villages from each town were randomly selected. Finally, the dataset includes information from 352 cotton producers located in 41 villages across seven counties within Xinjiang. Within this sample, the adoption prevalence of IWFS stands at 75%.

Table 1 presents a statistical summary of the dataset, including the mean values for variables, as reported in Zhang et al. (2023b). This study primarily focuses on a comparative analysis between IWFS adopters and non-adopters, revealing statistically significant differences in both inputs and outputs. IWFS adopters, for instance, manage larger farms with an average size of 118.2 mu, which is nearly eight times larger than their non-adopter counterparts. In terms of demographic and household variables, IWFS adopters tend to be older, predominantly of Han ethnicity, and more likely to participate in cooperative organizations. They also have higher levels of educational attainment, smaller household sizes, and a decreased reliance on agricultural income. Despite these differences, gender distribution and agricultural training remain consistent across both groups. It is important to note that although IWFS adopters face higher fertilizer costs, they also benefit from increased subsidies.

The notable disparities outlined in Table 1 call for additional scrutiny since they do not accommodate potential confounding variables. Consequently, the succeeding section will focus on a more rigorous examination of the impact of IWFS adoption on fertilizer use efficiency, factoring in these variables.

5 Results and discussion

This section is structured to provide a detailed explanation of the estimation of separate production frontiers and the meta-frontier, followed by the calculation of chemical fertilizer use efficiency. Subsequently, a Two-Stage Residual Inclusion (2SRI) model is deployed to assess the influence of IWFS adoption on both chemical fertilizer use efficiency and intensity, which is a fundamental measure

TABLE 1 Descriptive statistics for variables.

Variables	IWFS Adopter	IWFS Non-adopter	Differences
Yield (kilogram)	38039.9 (3929.4)	3342.9 (417.6)	34696.9*** (6791.0)
Farm size (mu)	118.2 (12.8)	15.3 (2.0)	102.9*** (22.1)
Labor (day)	857.5 (96.4)	123.1 (16.6)	734.5*** (166.7)
Fertilizer (kilogram)	11112.0 (1554.7)	11307.4 (234.5)	9804.6*** (2688.6)
Intermediate inputs (RMB yuan)	52233.4 (5181.9)	4320.2 (599.4)	47913.2*** (8956.7)
Gender	0.796 (0.02)	0.787 (0.04)	0.010 (0.05)
Nationality	0.242 (0.03)	0.989 (0.011)	−0.747*** (0.05)
Age of household head (Year)	52.5 (0.53)	47.2 (1.20)	5.3*** (1.15)
Education level (year)	8.23 (0.16)	7.71 (0.31)	0.52* (0.33)
Agricultural Training	0.75 (0.03)	0.70 (0.05)	0.05 (0.05)
Price of cotton (yuan/kilogram)	3.02 (0.03)	3.52 (0.08)	−0.49*** (0.07)
Price of fertilizer (yuan/kilogram)	3.07 (0.07)	2.92 (0.11)	0.15 (0.14)
Cooperation organization	0.22 (0.03)	0.15 (0.04)	0.08* (0.05)
Household size (person)	3.91 (0.09)	4.65 (0.18)	−0.73*** (0.18)
Subsidy (RMB yuan)	9.30 (0.15)	7.79 (0.19)	1.51*** (0.28)
Share of agricultural income (%)	0.52 (0.16)	0.60 (0.03)	−0.08**** (0.03)

Nationality: 1 if minority, 0 for Han; Subsidy: it is the log form of agricultural subsidies (Yuan). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; Standard deviations are presented in parentheses.

of use efficiency. Additionally, the impact of IWFS adoption on yield and labor utilization will be elucidated.

5.1 Chemical fertilizer use efficiency of cotton farmers

The current study employs a translog production function, integrating linear, quadratic, and interaction terms of inputs. The selection of the translog function is driven by its flexibility and its capability to approximate any unknown function to the second order (Zhou et al., 2015). The estimators linked to both separate frontiers and the meta-frontier are displayed in Table 2. It merits emphasis that, among IWFS adopters, linear terms pertaining to labor, fertilizer, and intermediate inputs, the quadratic term for intermediate inputs and numerous interaction terms exert a considerable influence on cotton yields. In contrast, for IWFS non-adopters, linear terms of fertilizer

and intermediate inputs, coupled with quadratic terms for farm size and fertilizer, significantly affect cotton production.

The discrepancy in estimators between columns (1) and (2) verifies that IWFS adopters and non-adopters function under unique production frontiers. Consequently, it is essential to estimate separate frontiers for each group, culminating in a meta-frontier that encompasses both. The results from the meta-frontier estimation reveal that all terms, encompassing linear, quadratic, and interaction terms—with the exception of the labor-fertilizer interaction term—make substantial contributions to cotton yields.

Before proceeding to the computation of chemical fertilizer use efficiency, it is imperative to estimate the comparative technical efficiency. This is gauged by two metrics: the distance from the separated frontiers to the meta-frontier (denoted as the technology gap u_i^M) and the distance from the operational point to the separated frontiers (termed incomparable technical inefficiency u_i). Table 3 reveals that IWFS adopters are proximate to the meta-frontier, signifying a higher level of technological sophistication. The calculated comparative technical efficiencies suggest potential increases of 24.8 and 41.6% in cotton yield for IWFS adopters and non-adopters, respectively, under existing technological and input conditions, if technical inefficiencies are fully eradicated. In simpler terms, IWFS adopters are capable of either producing the same cotton yield with fewer inputs or achieving higher yields with the same number of inputs compared to non-adopters.

Using the parameters outlined in Table 2 and the derived comparative technical efficiency, the calculation of chemical fertilizer use efficiency for both IWFS adopters and non-adopters is performed using Equation 6. The results, presented in Table 3, reveal an average chemical fertilizer use efficiency of 0.382 among cotton farmers in Xinjiang. This indicates that more than 60% of chemical fertilizers are not utilized effectively, contributing to environmental degradation. MOARA (2015), MOARA, 2016 states that the national average efficiency of chemical fertilizer use in grain production is 0.352. However, caution should be exercised when comparing these two efficiency metrics due to variations in definitions and measurement methods. In addition, Hu et al. (2019) reveals that the average chemical fertilizer use efficiency of rice in Jiangsu province is 0.6, which is higher than that of cotton production in Xinjiang China. The differentiated chemical fertilizer use efficiency may be arised from the different capacity of fertilizer absorption between cotton and rice, and geographical condition. Few literature studied cotton farmers chemical fertilizer use efficiency. Hu et al. (2009) argue that drip irrigation could promote cotton root growth. Geng et al. (2014) calculate the technical efficiency of cotton farmers in Xinjiang, and pointed out that 15% of potential yield could be achieved without any other inputs, which is 29.1% in this paper. We also find that the efficiency for IWFS adopters is 0.452, which is 1.6 times higher than that for non-adopters.

Although the summary statistics in Table 3 suggest that IWFS adoption enhances chemical fertilizer use efficiency, a direct comparison between IWFS adopters and non-adopters lacks causal validity. The decision to adopt IWFS is endogenous, and variations in chemical fertilizer use efficiency could also be influenced by other variables. Hence, the subsequent analysis employs a 2SRI model to ascertain the causal effect of IWFS adoption on chemical fertilizer use efficiency.

TABLE 2 The estimators of separated frontiers and meta-frontiers.

Variables	IWFS adopter	IWFS non-adopter	Meta-frontier
	(1)	(2)	(3)
Farm size	−0.742 (1.60)	0.880 (0.61)	−1.030*** (0.28)
Labor	−1.861*** (0.68)	−0.788 (0.66)	−1.172*** (0.12)
Fertilizer	1.771** (0.69)	0.569** (0.231.)	1.190*** (0.15)
Intermediate inputs	2.698*** (0.60)	1.167* (0.66)	2.449*** (0.13)
Farm size×Farm size	0.080 (0.44)	−0.604*** (0.21)	−0.152** (0.08)
Labor×Labor	−0.040 (0.09)	−0.704 (0.46)	−0.084*** (0.02)
Fertilizer×Fertilizer	−0.018 (0.13)	0.490** (0.23)	0.083*** (0.03)
Intermediate inputs×Intermediate inputs	−0.291*** (0.08)	−0.093 (0.06)	−0.240*** (0.02)
Farm size×Labor	−0.325* (0.19)	0.520** (0.21)	−0.218*** (0.03)
Farm size×Fertilizer	0.192 (0.19)	−0.026 (0.29)	0.177*** (0.04)
Farm size×Intermediate inputs	0.168 (0.15)	−0.097 (0.07)	0.242*** (0.03)
Labor×Fertilizer	0.032 (0.09)	−0.100 (0.17)	0.020 (0.02)
Labor×Intermediate inputs	0.302*** (0.08)	0.409*** (0.15)	0.228*** (0.02)
Fertilizer×Intermediate inputs	−0.253*** (0.10)	−0.261* (0.16)	−0.268*** (0.02)
Constant	−6.270*(3.20)	3.878(3.28)	−3.972*** (0.57)
Number of observations	263	89	352

*** $p < 0.01$, ** $p < 0.05$ and * $p < 0.1$; Robust standard errors are presented in parentheses.

TABLE 3 The differences of technical efficiency and fertilizer use efficiency between IWFS adopter and non-adopter.

	Means	Adopter	Non-adopter	Differences
Technology gaps	0.952 (0.048)	0.965 (0.001)	0.913 (0.008)	0.052*** (0.005)
Comparable technical efficiencies	0.709 (0.196)	0.752 (0.011)	0.584 (0.022)	0.167*** (0.022)
Fertilizer use efficiencies	0.382 (0.257)	0.452 (0.015)	0.173 (0.014)	0.280*** (0.028)

*** $p < 0.01$, ** $p < 0.05$ and * $p < 0.1$; Standard errors are presented in parentheses.

5.2 Effects of IWFS adoption on fertilizer use efficiency

The first-stage results of the 2SRI model are provided in [Supplementary Table A1](#), indicating that the instrumental variable,

represented by the ratio of IWFS adoption in the village, as well as factors such as agricultural training, subsidies, farm size, and participation in cooperative organizations, significantly influence cotton farmers' adoption of IWFS. The impact of IWFS adoption on chemical fertilizer use efficiency is elucidated in [Table 4](#) through the 2SRI model. Columns (1) and (2) of [Table 4](#) indicate that the coefficients of the residual terms are statistically significant, confirming the presence of unobserved factors correlated with the IWFS adoption variable. Consequently, addressing endogeneity becomes necessary.

The coefficient for IWFS adoption in Column (1) of [Table 4](#) indicates that adopting IWFS enhances chemical fertilizer use efficiency by 0.146 units. It is noteworthy that irrigation method used to deliver the mixed solution of chemical fertilizer and water may have different impacts on chemical fertilizer use efficiency. We do not distinguish the differentiated effects of these two methods for the following reasons. First, the data used in this paper did not distinguish the irrigation method to deliver the mixed solution of chemical fertilizer and water. Second, we found that most of surveyed farmers use drip irrigation to deliver the mixed solution to cotton.

To examine the heterogeneous effects across different farm sizes, an interaction term between IWFS adoption and farm size is introduced into the empirical model. The coefficient of this interaction term suggests that efficiency gains increase with farm size. This finding diverges from [Hu et al. \(2019\)](#) who reported an inverse relationship between farm size and chemical fertilizer use efficiency. A plausible rationale is that IWFS reduces reliance on managerial capabilities, thereby preventing a decline in chemical fertilizer efficiency as farm size increases. Specifically, the marginal effect of adopting IWFS on chemical fertilizer use efficiency is 0.223, indicating an average increase of 0.223 units in a farmer's efficiency upon IWFS adoption. [MOARA \(2015\)](#) noted that integrated soil-crop system management led to incremental efficiencies of 0.05, 0.12, and 0.1 for nitrogen, phosphorus, and potassium fertilizers in grain production, respectively, reaching levels of 0.33, 0.24, and 0.42 in 2015. Therefore, the IWFS effect surpasses that of integrated soil-crop system management, benefiting from the synergies of both systems.

The control variables also provide noteworthy insights. For example, higher prices for both fertilizer and cotton appear to enhance chemical fertilizer use efficiency, possibly due to increased diligence in production when input and output prices rise. Conversely, the negative coefficient associated with age implies a decrease in chemical fertilizer use efficiency among older farmers.

To ensure robustness, we extend our analysis to assess the impact of IWFS adoption on the quantity of chemical fertilizer used per unit land area, which serves as a valid proxy for fertilizer use efficiency. Columns (3) and (4) present the effects of IWFS adoption on this measure. The coefficient in Column (3) is -0.386 , statistically significant at the 5% level, indicating a 38.6% reduction in fertilizer use per unit area resulting from IWFS adoption. This finding is supported by [Cui et al. \(2018\)](#), who observed an 8.5–15.6% reduction through integrated soil-crop system management. The inclusion of an interaction term between IWFS adoption and farm size in Column (4) reveals that larger farms experience an even greater reduction in chemical fertilizer use intensity upon IWFS adoption.

TABLE 4 The impacts of IWFS adoption on fertilizer use intensity and use efficiency.

Variables	Fertilizer use efficiency	Fertilizer use efficiency	Fertilizer use quantity per land area (log)	Fertilizer use quantity per land area (log)
	(1)	(2)	(3)	(4)
IWFS adoption	0.146*** (0.05)	0.131** (0.05)	−0.386** (0.18)	−0.083*** (0.021)
IWFS adoption × Farm size		0.001** (0.00)		−0.020** (0.01)
Farm size	−0.000** (0.00)	−0.001 (0.00)	−0.023** (0.01)	−0.002*** (0.00)
Gender	−0.025 (0.04)	−0.025 (0.038)	0.117 (0.16)	0.104 (0.16)
Nationality	−0.202** (0.08)	−0.201** (0.08)	−0.281 (0.34)	−0.312 (0.33)
Age of household head	−0.005*** (0.00)	−0.005*** (0.00)	0.009 (0.01)	0.007 (0.01)
Education level	0.007 (0.01)	0.007 (0.01)	−0.017 (0.02)	−0.023 (0.02)
Agricultural Training	0.021 (0.03)	0.024 (0.03)	−0.086 (0.14)	−0.013 (0.13)
Price of cotton	0.031* (0.02)	0.033* (0.02)	−0.065 (0.10)	−0.025 (0.09)
Price of fertilizer	0.816** (0.39)	0.794* (0.40)	−1.195*** (0.19)	−1.854*** (0.53)
Cooperation organization	0.028 (0.04)	0.032 (0.04)	−0.715*** (0.14)	−0.576*** (0.14)
Household size	0.004 (0.01)	0.004 (0.01)	0.030 (0.04)	0.021 (0.03)
Subsidy	0.002 (0.01)	0.002 (0.01)	−0.115*** (0.03)	−0.094*** (0.03)
Share of agricultural income	−0.060 (0.06)	−0.060 (0.06)	0.055 (0.25)	0.057 (0.23)
Residuals	−0.164** (0.07)	−0.150** (0.07)	−1.838*** (0.35)	−1.423*** (0.38)
County fixed effects	Yes	Yes	Yes	Yes
Constant	−0.222 (0.15)	−0.226 (0.15)	3.172*** (0.65)	3.061*** (0.58)
N	352	352	352	352
R ²	0.224	0.226	0.675	0.707

*** $p < 0.01$, ** $p < 0.05$ and * $p < 0.1$; Robust standard errors are presented in parentheses.

5.3 Effects of IWFS adoption on yield and labor use

Table 5 presents the results pertaining to the influence of IWFS adoption on cotton yield per unit area. The coefficient for IWFS adoption is 0.222, indicating a 22.2% increase in cotton yield per mu with the adoption of IWFS. The findings from both Tables 4, 5 collectively demonstrate that IWFS adoption achieves the dual objectives of enhancing cotton production and promoting environmental sustainability. Notably, the interaction term between IWFS adoption and farm size lacks statistical significance, aligning with the classical inverse relationship between farm size and yield per unit area, as documented by (Zhang et al., 2019). Therefore, this inverse relationship counterbalances the positive effect of IWFS adoption on yield.

In theory, IWFS applies a combination of fertilizer and water directly to the cotton roots through tubing, thereby significantly reducing labor requirements. To empirically assess this, we examine the impact of IWFS adoption on labor inputs in cotton farming, as presented in Table 6. The coefficient for IWFS adoption is −0.536, suggesting a labor input reduction of 53.6% upon IWFS adoption. Furthermore, the coefficient of the interaction term indicates that this labor-saving effect is magnified with increasing farm size.

6 Conclusion

Chemical fertilizers have played a critical role in boosting crop yields in China, yet they have precipitated environmental challenges including soil salinization, air pollution, and water contamination. To address this conundrum, it is essential to improve chemical fertilizer efficiency to maintain yield levels and mitigate environmental damage. The Integrated Water-Fertilizer Systems present a promising technological innovation in this endeavor. Nevertheless, the existing body of knowledge primarily focuses on field trials, leaving an information gap regarding its impacts from the farmers' perspective. Utilizing data from 352 cotton farms in Xinjiang, China, this study employs meta-frontier production functions and a two-stage residual inclusion (2SRI) model to assess the implications of IWFS adoption for chemical fertilizer efficiency.

The empirical findings suggest that IWFS adopters achieve a chemical fertilizer use efficiency of 0.452, a figure that is 1.6 times greater than their non-adopting counterparts, whose average efficiency is 0.382. IWFS adoption contributes to an efficiency increase of 0.223, a gain that magnifies with farm size. Notably, IWFS's effectiveness in improving fertilizer use efficiency outperforms that of integrated soil-crop management systems due to the combined benefits of both techniques. In addition, IWFS adoption delivers

TABLE 5 The impacts of IWFS adoption on cotton yields.

Variables	Yield per unit area (log)	Yield per unit area (log)
	(1)	(2)
IWFS adoption	0.222*** (0.06)	0.251*** (0.08)
IWFS adoption × Farm size		−0.002 (0.00)
Farm size	−0.000** (0.00)	0.002 (0.00)
Gender	−0.019 (0.04)	−0.019 (0.04)
Nationality	−0.377*** (0.06)	−0.377*** (0.06)
Age of household head	0.003 (0.00)	0.003 (0.00)
Education level	0.007 (0.01)	0.008 (0.01)
Agricultural Training	0.113*** (0.04)	0.111*** (0.04)
Price of cotton	0.040 (0.04)	0.039 (0.04)
Price of fertilizer	−4.218** (1.87)	−4.300** (1.90)
Cooperation organization	0.049 (0.04)	0.044 (0.04)
Household size	0.020 (0.02)	0.020 (0.01)
Subsidy	0.034*** (0.01)	0.032*** (0.01)
Share of agricultural income	0.376*** (0.08)	0.376*** (0.08)
Residuals	0.214*** (0.028)	0.177*** (0.039)
County fixed effects	Yes	Yes
Constant	4.685*** (0.22)	4.663*** (0.22)
N	352	352
R ²	0.465	0.466

*** $p < 0.01$, ** $p < 0.05$ and * $p < 0.1$; Robust standard errors are presented in parentheses.

ancillary benefits such as increased cotton yields and reduced labor inputs.

To effectively tackle the urgent issues of sustainable food production and consumption, food security, and environmental conservation, it is essential for policy-makers to champion the widespread adoption of IWFS. Tailored interventions are particularly crucial for small-scale farmers who often encounter hurdles to adopting such innovative technologies. Enhancing infrastructural support can encourage these farmers to adopt IWFS, contributing to an array of interconnected objectives. For example, improving fertilizer use efficiency through IWFS can reduce environmental pollutants, promoting ecological sustainability. In the context of food security, efficient fertilizer use can optimize crop yields, ensuring a stable food supply. Additionally, minimization of fertilizer over-application could result in safer, higher-quality food products by reducing residual chemical content in crops. Therefore, policy interventions that promote IWFS have the potential to create a ripple effect, concurrently advancing environmental sustainability, food security, and food quality. As such, it is vital for policy-makers to facilitate the adoption of IWFS, especially among small-scale farmers, through enhanced infrastructural support. These initiatives are likely to make a significant contribution to the broader goals of food security, food quality, and environmental sustainability.

While offering valuable insights, this study acknowledges certain limitations. First, the analysis draws upon cross-sectional data, which precludes control for individual heterogeneity—an issue that could be addressed with the use of panel data. Second, the study does not

TABLE 6 The impacts of IWFS adoption on labor use.

Variables	Labor input per unit area (log)	Labor input per unit area (log)
	(1)	(2)
IWFS adoption	−0.536*** (0.15)	−0.471*** (0.17)
IWFS adoption × Farm size		−0.030*** (0.01)
Farm size	−0.003*** (0.00)	−0.033*** (0.01)
Gender	0.058 (0.09)	0.050 (0.09)
Nationality	−0.069 (0.18)	−0.077 (0.18)
Age of household head	0.010* (0.01)	0.009* (0.00)
Education level	−0.040** (0.02)	−0.044*** (0.02)
Agricultural Training	−0.017 (0.08)	0.019 (0.07)
Price of cotton	0.038 (0.09)	0.072 (0.09)
Price of fertilizer	−2.132 (3.32)	−1.364 (3.32)
Cooperation organization	−0.261*** (0.10)	−0.167* (0.09)
Household size	0.042 (0.04)	0.039 (0.03)
Subsidy	−0.084*** (0.02)	−0.065*** (0.02)
Share of agricultural income	−0.134 (0.18)	−0.140 (0.17)
Residuals	−1.667*** (0.333)	−1.198*** (0.359)
County fixed effects	Yes	Yes
Constant	−1.529*** (0.54)	−1.286*** (0.49)
N	352	352
R ²	0.742	0.780

*** $p < 0.01$, ** $p < 0.05$ and * $p < 0.1$; Robust standard errors are presented in parentheses.

make distinctions among different fertilizer types, including nitrogen, phosphorus, and potassium. Third, soil quality will affect fertilizer use efficiency which was documented by the effects of integrated soil-crop system management adoption. However, we did not collect soil information in the survey. These consideration presents an opportunity for further exploration in our future research.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding authors.

Author contributions

YY: Data curation, Funding acquisition, Writing – original draft, Writing – review & editing. CW: Data curation, Writing – original draft, Writing – review & editing. XuZ: Funding acquisition, Visualization, Writing – review & editing. YS: Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing. XiZ: Data curation, Formal analysis, Methodology, Software, Validation, Writing – review & editing.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2023.1310426/full#supplementary-material>

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The beauty in imperfection: how naturalness cues drive consumer preferences for ugly produce and reduce food waste

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Purpose: An important reason for food waste is the rejection of ugly produce by consumers. Most previous research has examined the absolute negative impacts of ugly produce on consumers' preferences, no research has examined the conditions in which consumers prefer ugly (vs. typical) produce instead. This research investigates the circumstances under which these aesthetic imperfections become advantageous.

Methods: We conducted two between-subject design randomized experiments featuring two produce categories to examine when and why consumers prefer ugly produce.

Results: We found that naturalness cues boost and even reverse consumers' preferences for ugly produce when combining ugly appearance with naturalness cues. The subtyping effect mediates the interaction of appearance (typical vs. ugly) of produce and naturalness cues (present vs. absent) on produce's evaluations.

Discussion: Our findings provide more cost-effective strategies for retailers to reduce food waste. This paper fills in the research gaps on tapping into the novel condition in which consumers prefer ugly (vs. typical) produce and the psychological mechanism behind this process. Based on schema incongruity theory, we argue that naturalness cues, as an enabler corresponding to the incongruous features of ugly produce, facilitate consumers to resolve the schema incongruity triggered by the ugly appearance and, in turn, boost consumers' preferences for ugly produce.

KEYWORDS

ugly produce, enablers, food waste, schema incongruity, naturalness cues, preference reversal

1 Introduction

Food waste has recently emerged as a threat with negative economic, social, and environmental consequences (Aka and Buyukdag, 2021). More than 1.3 billion tons of food are wasted along the supply chain each year (Amicarelli et al., 2020). Among the various causes of food waste at the consumer level, consumers' esthetic nitpicking and prejudices about the appearance of produce contribute to significant avoidable food waste and environmental pressures (Adel et al., 2022). Retailers waste a large number of fruits and vegetables (Obuobi et al., 2022), as one of the results of retailers' striving to provide consumers with perfect-looking produce (Loebnitz et al., 2015). Consumer rejection of unattractive produce, as well as retailers'

practices that are not conducive to sustainable consumption and development, has resulted in a considerable volume of produce appropriate for human consumption being wasted for deviating from these esthetic criteria (Tsalis, 2020).

Ugly produce is defined as having a significant natural deviation from prototypicality, whereas typical produce has a limited deviation from prototypicality if any at all (Grewal et al., 2019). Following previous studies on imperfect produce, we exclude deviations in appearance caused by damage, disease, or other external esthetic divergences that may influence the objective taste, flavor, or food quality (Grewal et al., 2019). Ugly produce is generally unpopular with consumers, who also tend to have the lay belief that “beauty is good and ugly is risky,” even though this is not justified because ugly produce does not differ in nutritional quality and safety from typical produce (Castagna et al., 2021; Pfeiffer et al., 2021). However, for ugly produce, unattractive appearance generally stems from nature (Grewal et al., 2019); In addition, previous research has shown that product attributes and extrinsic cues can interact (Bezençon et al., 2020). Therefore, we have a preliminary reason to anticipate that an ugly appearance is not always a negative attribute of produce; namely, there are external conditions in which an ugly appearance might become a “positive” attribute of produce instead.

Consumers prefer products that are typical of the category and use typical products as cognitive benchmarks when evaluating atypical products (Scarpi et al., 2019). Similarly, consumers prefer typical produce and reject ugly produce. To address this problem, prior research has mainly focused on price discounts and marketing communication strategies to reduce food waste. Mere price discounts are not sustainable strategies, because consumers view businesses selling ugly food at low prices as engaging in “abusive” commercial activities and may even lead to unintended food waste (Qi et al., 2022). Scholars have further investigated more cost-effective strategies. For example, anthropomorphizing unattractive produce (Chen et al., 2021), using external cues to enhance consumers’ positive self-perceptions (Grewal et al., 2019), and implementing ugly labels (Mookerjee et al., 2021) are examples of strategies that promote ugly produce. However, most of these previous studies on marketing strategies considered ugly appearance as an absolutely negative attribute of produce (for a last review, see Varese et al., 2023) and therefore proposed marketing strategies mainly in terms of price discounts and weakening consumers’ negative perceptions toward produce. No research has been conducted to examine the conditions under which the ugly appearance can be a positive attribute such that consumers prefer ugly (vs. typical) produce instead and the underlying psychological mechanisms by which this process occurs. Thus, our research question is: when does this negative appearance feature instead become a positive advantage for it? If so, what would be the psychological mechanism that explains such consumer behavior?

To fill this research gap and address our research questions, we will examine a novel marketing communication strategy: applying naturalness cues to ugly produce so that in this case the ugly appearance becomes a positive attribute of the produce. We build on schema congruity theory to predict the joint effect of ugly appearance and naturalness cues on consumer preferences. We predict that applying naturalness cues to ugly produce can facilitate consumers to resolve schema incongruity evoked by ugly appearance through subtyping resolution and further bolster consumer preferences. Ugly appearance is the incongruous feature of ugly produce compared to typical produce (Loebnitz et al., 2015). However, consumers will favor

incongruent products over congruent products if they can make sense of the incongruent features (Noseworthy et al., 2018). In addition, consumers can resolve incongruous features by exploring the presence of other semantically related features—what the literature refers to as enablers (Noseworthy et al., 2014; Rehder, 2015). Moreover, people inherently hold that there are causal associations between product features (Ahn and Kim, 2000). In line with these insights, consumers associate the ugly appearance with the naturalness of produce (Yuan et al., 2019; Mookerjee et al., 2021). Therefore, we predicted that naturalness cues might act as an enabler corresponding to ugly appearance, which facilitates consumers to resolve schema incongruity and further boosts consumer preferences. This process occurs because the combination of semantically relevant features can improve consumers’ perception of the category typicality of ugly produce. This enables consumers to subtype the ugly produce as a subcategory of the corresponding produce category, thus resolving the schema incongruity triggered by the ugly appearance. Further, according to the schema congruity theory, consumers’ evaluations of ugly produce will not only be elevated but even higher than typical produce, thus making a negative feature of ugly produce instead become an advantage for it. Our findings provide practical implications and cost-effective management strategies for a more sustainable solution to the waste problem caused by ugly produce.

In the remainder of this article, we will first establish the theoretical background for our hypotheses by drawing on literature about ugly produce and consumer preferences, resolving schema incongruity through subtyping, the impact of “Enablers” on product category typicality, as well as the combination of naturalness cues and unattractive appearance. Then, the two experiments use different product categories to provide consistent empirical evidence. We discussed the theoretical and practical implications in the end.

2 Theoretical background and conceptual development

2.1 Schema incongruity and subtyping resolution

Schemas may be construed as organized cognitive structures that link a network of concepts (Magnusson et al., 2014). The activation of a particular object’s schema leads to various related concepts in the schema being active, making it easier for the individual to process new information that matches the active concept, and when the object does not match the activated schema, schema incongruity occurs (Meyers-Levy and Tybout, 1989). The ugly produce deviates from the corresponding schema of produce stored in the consumer’s mind, thus triggering schema incongruity for the consumer compared to typical produce (Loebnitz et al., 2015).

Consumers have psychological arousal to objects that elicit schema incongruity and will try to resolve the schema incongruity (Noseworthy et al., 2014). Thus, for ugly produce, consumers will also try to resolve the schema incongruity caused by ugly appearance. Previous research has shown that consumers can resolve schema incongruity through subtyping resolution (Noseworthy et al., 2018). The subtyping resolution refers to consumers’ integration of object stimuli into the existing category structure, thus treating object stimuli as exceptional cases or subcategories within the corresponding product category (Noseworthy et al., 2018). Namely, the subtyping

effect appears in consumers' categorical inferences about incongruent objects (Meyers-Levy and Tybout, 1989). In the subtyping process, individuals automatically categorize those incongruent target objects using a distinct set of beliefs, and subtyped instances are treated as exceptions and placed into a subcategory (Sujan and Bettman, 1989). For example, when consumers perceive green vitamin-enhanced coffee as a subtype of coffee, such as a healthier type of coffee, it leads to positive product evaluations (Noseworthy et al., 2018). Another example, the rarity of the product-harm crises can lead consumers to excuse an otherwise well-regarded brand by considering the crisis event an exception that is unrepresentative of the brand's normal behavior, thus, the subtyping effect emerges in the context of consumers constructing attributions of product-harm crises (Lei et al., 2012). From these examples, we know that the subtyping process can increase the evaluations of certain things that would otherwise be considered unfavorable. Likewise, people tend to disfavor ugly produce that elicit schema incongruity due to atypical appearance. Then, based on the aforementioned discussion of the subtyping effect and schema incongruity, we hold that if consumers can resolve the schema incongruity and make the subtyping effect arise in consumers' category inferences about ugly produce, this process will increase consumers' evaluations of ugly produce. So, along this line of thought, in the next section, we will expound on how to make the subtyping effect appear in consumers' category inferences about ugly produce.

2.2 Enablers and product category typicality

The emergence of the subtyping effect requires external enablers that correspond to the incongruent features of the stimulus objects (Noseworthy et al., 2018). Enablers are semantically related to product incongruent features and facilitate the understanding of the presence of incongruent features (Cheng and Novick, 1991). For example, if consumers were told that the transparent Pepsi was made from natural spring water, then they may regard transparent Pepsi as a special subtype of Pepsi, that is, the subtype effect arises in consumer's category inferences toward colorless and transparent Pepsi (Noseworthy et al., 2018). This process occurs because of the semantic association between the "natural spring water" and "transparent" features, where the product made from natural spring water are enablers corresponding to transparent color features, and the combination of the incongruent features and enablers enhances the consumers' perceptions of the category typicality of the product, thus contributing to the subtyping effect (Noseworthy et al., 2018). In addition, the typicality of the incongruent entity has been identified as crucial to determining whether a subtyping category is created (Noseworthy et al., 2018). Therefore, we predict that if the enablers provided to ugly produce make the combination of enablers and ugly appearance improve consumers' judgments of the category typicality of ugly produce, then the subtyping effect may arise in consumers' category inferences about ugly produce.

Products' enablers can have considerable impacts on the product category typicality judgments (Noseworthy et al., 2018). To improve product category typicality judgments, enablers do not have to be causal, they only need to preserve semantic associations with incongruent features of the product (Cheng and Novick, 1991). On the one hand, this is because consumers inherently believe that there is a natural causal relationship between product features, where one

feature naturally induces another feature (Ahn and Kim, 2000). These linked features enable consumers to make causal inferences through conjunctions (Rehder, 2015). On the other hand, and more importantly, enablers are features that are semantically associated with product incongruent features, and semantic associations provide a more coherent and consistent representation of object stimuli, stimulating more category consistency in combinations of features of object stimuli (Hayes and Rehder, 2012), thus improving consumer judgments of product category typicality (Noseworthy et al., 2018). Following these lines, we predicted that applying an enabler semantically associated with the ugly appearance might improve the typicality judgments of produce.

Then, combined with the above, in the case of ugly produce, the ugly appearance of produce triggers schema incongruity among consumers (Loebnitz et al., 2015). If the external enablers corresponding to the incongruent feature of ugly produce are provided as marketing communication cues, we can expect them to enhance consumers' judgments of the category typicality of ugly produce.

This, in turn, contributes to the subtyping effect on consumers' category inferences about ugly produce and helps resolve the schema incongruity caused by its unattractive appearance.

2.3 Combination of naturalness cues and ugly appearance

Naturalness cues of ugly produce can influence consumers' feature inferences and consumption choices about produce (Yuan et al., 2019; Qi et al., 2022). Consumers associate the semantic meaning of cues indicating the naturalness of food with natural-related attribute inferences (Berry et al., 2017). Furthermore, consumers spontaneously associate the ugly appearance of produce with the naturalness of the produce (Yuan et al., 2019; Mookerjee et al., 2021). Thus, naturalness cues that are semantically associated with ugly appearance can be enablers corresponding to ugly appearance features of produce. The combination of an enabler with a corresponding incongruent feature can improve consumers' judgments of the category typicality of a product and lead to the product being perceived as more typical of the category than if the features were shown independently. Higher product category typicality is more likely to enable consumers to filter out incongruent features of products and makes the object stimulus more likely to be perceived as a special case in the corresponding product categories, which in turn enables products that trigger schema incongruity to be integrated by consumers into the existing corresponding product category, thus prompting consumers to subtype incongruent product into a subcategory of the corresponding product category (Sujan and Bettman, 1989). That is, the subtyping effect appears in consumers' category inferences about products that trigger schema incongruity (Noseworthy et al., 2018). Thus, when the enablers corresponding to the incongruent features of ugly produce—the naturalness cues discussed above—are provided as marketing communication cues, this will facilitate consumers to resolve the schema incongruity triggered by ugly appearance through the subtyping resolution. This is, the subtyping effect emerges in consumers' category inferences about ugly produce. Whereas, when the enablers are absent, and since consumers subtype an object that triggers schema incongruity requires the external provision of the corresponding enablers (Noseworthy et al., 2018), then it can be predicted that the subtyping effect will not arise in the consumers' category inferences about ugly produce in the absence of the enablers situation.

Incongruent object stimulus disrupts existing knowledge structures to some extent, and people will attempt to cope with this discrepancy by resolving the incongruity (Noseworthy et al., 2018). Similarly, the appearance of ugly produce triggers schema incongruity (Loebnitz et al., 2015), and consumers will try to resolve the schema incongruity. In this case, presenting naturalness cues, which are enablers corresponding to the appearance features of the ugly produce, prompts consumers to subtype the ugly produce into a subcategory of the corresponding agricultural product category, thus resolving the schema incongruity caused by the ugly produce. Then, according to schema congruity theory (Meyers-Levy and Tybout, 1989), if consumers can resolve the schema incongruity, which can be a satisfying experience and may activate positive affections, they will have higher product evaluations than the corresponding schema congruity product—that is the typical produce in our context. However, when consumers are unable to resolve the schema incongruity caused by the ugly appearance through subtyping resolution, they will have negative feelings and product evaluations (Jhang et al., 2012). Therefore, we propose that when the naturalness cues are absent, consumers evaluate ugly produce as lower than typical produce. Nonetheless, when the naturalness cues are present as a marketing communication cue, consumers evaluate ugly produce higher than typical produce.

In conclusion, we propose that naturalness cues, as enablers corresponding to the incongruity features of the ugly produce, enable consumers to resolve the schema incongruity triggered by the ugly appearance. Hence, this process not only improves consumers' evaluations of ugly produce but even brings about higher consumers' evaluations of ugly produce than typical produce according to schema congruity theory. The mechanism by which this process occurs is that the combination of enablers and the appearance of the ugly produce allows consumers to perceive the ugly produce as a subcategory of the corresponding produce category. That is to say, the subtyping effect emerges in consumers' category inferences about ugly produce, resolving the schema incongruity caused by the ugly appearance and further boosting consumers' evaluation of the ugly produce.

Based on the foregoing, the following three hypotheses are proposed for this article:

H1: When the naturalness cues are absent, consumers' evaluations of ugly produce are lower than that of typical produce. However, when the naturalness cues are present, consumers' evaluations of ugly produce are higher than that of typical produce.

H2: When the naturalness cues are absent, the subtyping effect is not significantly different between ugly produce and typical produce. However, when the naturalness cues are present, the subtype effect of consumers' category inferences about ugly produce is higher than that of typical produce.

H3: The subtyping effect mediates the interaction of appearance (typical vs. ugly) of produce and naturalness cues (present vs. absent) on produce's evaluations.

3 Overview of the studies

We conducted two experiments to support our hypotheses (Supplementary Table 1). In experiment 1, we chose ugly and typical

carrots as stimuli adapted from Chen et al. (2021), primarily testing the interaction effect between the appearance of the produce and the naturalness cues on the produce's evaluations (H1). To expand the external validity of experiments, we expanded our produce category and selected the fruit for experiment 2. Based on replicating the findings of experiment 1 (H1 is again supported), we first successfully developed stimuli through a pretest, then supported H2 and the mediation role of the subtyping effect (H3). Experiment 2 further increases the generalizability of our findings.

4 Experiment 1

The primary purpose of this experiment was to support H1. As we predicted, the combination of naturalness cues and the ugly appearance of produce boosted consumers' evaluations of ugly produce. In this experiment, we used typical and ugly carrots as stimuli adapted from Chen et al. (2021) to support H1 initially.

4.1 Participants and procedure

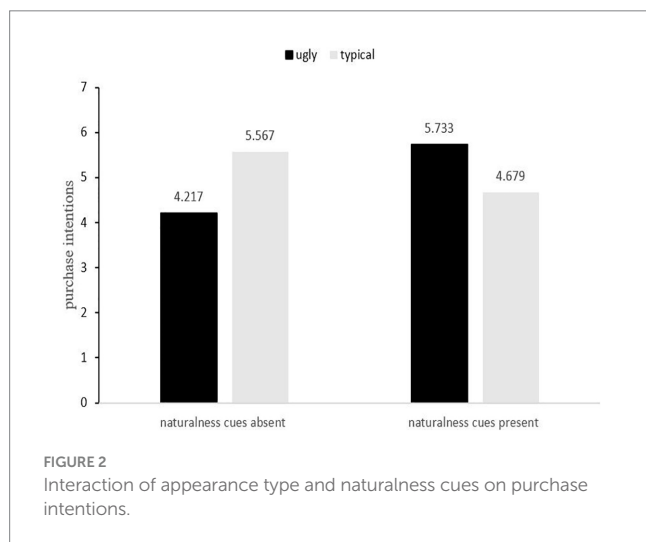
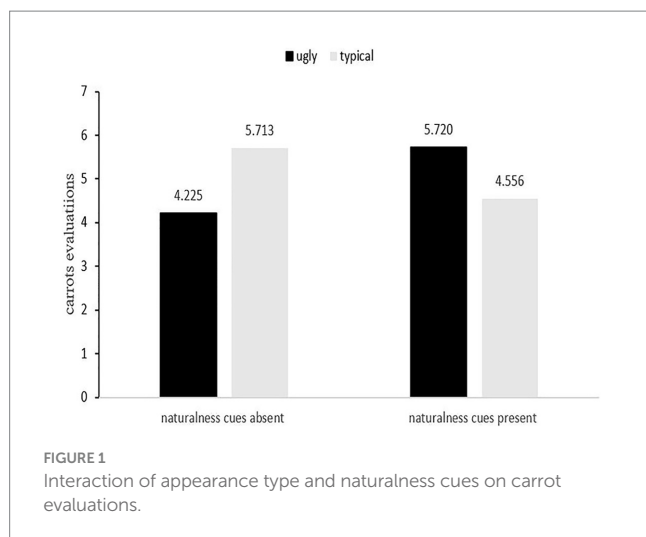
Two hundred participants were recruited through the online questionnaire survey platform: <https://www.credamo.com>.¹ Twenty-seven participants who failed the attention check were removed, leaving us with a valid sample of 173 participants ($M_{age} = 29.86$, $SD = 7.153$; female 63.0%).

Participants were randomly assigned to one of 2 (produce appearance: ugly vs. typical) \times 2 (naturalness cues: present vs. absent) between-subjects design conditions. Participants were asked to imagine themselves shopping in a fresh food supermarket and then seeing some carrots in the vegetable aisle. The manipulation of ugliness was limited to their natural shape variation consistent with Grewal et al. (2019). Thus, under typical conditions, participants were shown an image of a carrot shelf filled with typical-shaped carrots. Correspondingly, under ugly conditions, participants were shown an image of a carrot shelf filled with abnormal-shaped carrots. We manipulated naturalness cues adapted from Berry et al. (2017). Specifically, in the naturalness cues present groups, participants in the ugly conditions saw ugly carrots on the vegetable shelf with the words “naturally grown, all-natural” written on the vegetable shelf. Accordingly, participants in the typical conditions saw typical carrots on the vegetable shelf and the same naturalness cues. There were no naturalness cues on the vegetable shelf in the naturalness cues absent groups, and then participants were randomly assigned to the ugly conditions and the typical conditions (Appendix A).

4.2 Measures

After being shown random scenario stimulus information, participants indicated their carrots evaluations on three seven-point items anchored by “unfavorable/favorable,” “unappealing/appealing,” and “bad/good,” with higher values indicating more positive evaluations (Cronbach's $\alpha = 0.900$; Jhang et al., 2012). We measured purchase intentions with three items: “I would consider buying some of these carrots,” “I would like to

¹ The <https://www.credamo.com> is one of the most popular online survey platforms in China.



try some of these carrots,” and “I would not be inclined to buy some of these carrots” (reverse encoded; 1 = “completely disagree,” and 7 = “completely agree,” Cronbach’s $\alpha = 0.868$; Cooremans and Geuens, 2019). For the manipulation check, participants were asked to rate the ugliness on a seven-point Likert scales (i.e., “ugly,” “unattractive”; 1 = “completely disagree” and 7 = “completely agree”). To check the awareness of the presence of the naturalness cues, participants were asked: “Did the carrots that you viewed point that the carrots were natural?” with endpoints of “definitely not/definitely yes” (seven-point scale; Berry et al., 2017). To rule out the confounding factor, participants indicated their perceived health risk with two items: “these carrots are unhealthy/risky,” (1 = “completely disagree,” and 7 = “completely agree,” $r = 0.855$; Chen et al., 2021). At the end of the experiment, all participants answered demographic information.

4.3 Results

4.3.1 Manipulation check

The one-way ANOVA results showed a significant difference between the ugly conditions and the typical conditions rating of

ugliness, with the ugly conditions scoring significantly higher than the typical conditions [$M_{\text{ugly}} = 4.578$, $SD = 1.626$; $M_{\text{typical}} = 2.494$, $SD = 1.188$; $F(1,171) = 88.590$, $p = 0.000$, partial $\eta^2 = 0.341$]. Furthermore, we found no significant effect of ugliness manipulation on perceived health risk [$F(1,171) = 1.516$, $p = 0.220$, partial $\eta^2 = 0.009$]. These results suggest that ugliness manipulation was effective. These results suggest that ugliness manipulation was effective.

For naturalness cues, the one-way ANOVA revealed a significant difference in awareness of the presence of the naturalness cues. Participants exposed to naturalness cues indicated greater awareness of the cues than participants who were not ($M_{\text{present}} = 6.180$, $SD = 1.364$; $M_{\text{absent}} = 3.320$, $SD = 1.744$; $F(1,171) = 138.737$, $p = 0.000$, partial $\eta^2 = 0.448$), suggesting naturalness cues manipulation was successful.

4.3.2 Carrots evaluations

The two-way ANOVA results showed a significant interaction between appearance and naturalness cues [$F(1,169) = 50.162$, $p = 0.000$, partial $\eta^2 = 0.229$]. Simple effect analysis showed that in naturalness cues absent groups, those in the ugly conditions reported lower carrots evaluations than those in the typical conditions [$M_{\text{ugly}} = 4.225$, $SD = 1.744$; $M_{\text{typical}} = 5.713$, $SD = 0.987$; $F(1,169) = 37.374$, $p = 0.000$, partial $\eta^2 = 0.181$]. However, a notable point is that, in naturalness cues present groups, those in the ugly conditions reported higher carrots evaluations than those in the typical conditions [$M_{\text{ugly}} = 5.720$, $SD = 0.733$; $M_{\text{typical}} = 4.556$, $SD = 1.059$; $F(1,169) = 16.733$, $p = 0.000$, partial $\eta^2 = 0.090$; Figure 1]. This result offers support to H1 (Supplementary Table 1).

4.3.3 Purchase intentions

The two-way ANOVA results showed that the interaction effect between appearance and naturalness cues was significant [$F(1,169) = 34.086$, $p = 0.000$, partial $\eta^2 = 0.168$]. In naturalness cues absent groups, simple effect analysis showed that those in the ugly conditions reported lower purchase intentions than those in the typical conditions [$M_{\text{ugly}} = 4.217$, $SD = 1.788$; $M_{\text{typical}} = 5.567$, $SD = 1.230$; $F(1,169) = 25.419$, $p = 0.000$, partial $\eta^2 = 0.131$]. However, in naturalness cues present groups, it is noteworthy that simple effect analysis revealed participants in the ugly conditions reported higher purchase intentions than those in the typical conditions [$M_{\text{ugly}} = 5.733$, $SD = 0.794$; $M_{\text{typical}} = 4.679$, $SD = 1.259$; $F(1,169) = 11.358$, $p = 0.001$, partial $\eta^2 = 0.063$; Figure 2]. This result is consistent with H1, indicating that when ugly produce and naturalness cues are combined, consumers instead have higher choice preferences (produce evaluations and purchase intentions) for ugly produce compared to naturalness cues are absent.

4.4 Discussion

The result of experiment 1 offered initial support for H1. The results showed that when naturalness cues were absent, consumers’ evaluations and purchase intentions for typical carrots were higher than those for ugly carrots. However, when naturalness cues were present, consumers’ evaluations and purchase intentions of ugly carrots were even higher than those of typical carrots. In the following experiment, we changed the agricultural product category to increase the experiment’s external validity. We first successfully developed

pears as a stimulus for the main experiment through the pre-experiment. Then we supported H2 and H3 and replicated the findings of experiment 1 at the same time.

5 Experiment 2

The purpose of experiment 2 was 2-fold. First, experiment 2 aims to support H2 and H3 based on replicating the findings of experiment 1. We attempt to support the mediating role of the subtyping effect in this experiment. Secondly, equally important, experiment 2 aims to increase the external validity of our studies by changing the categories of agricultural products and further improving the generalizability of our findings.

5.1 Pre-experiment

Before the main experiment, we conducted a pretest to develop the stimuli for the main experiment. We chose pears as the stimuli and ugly pears were processed using photo-editing techniques with a typical pear photo as the base image. The pretest was a 2 (pear appearance: ugly vs. typical) between-subject design. We recruited 70 participants ($M_{\text{age}} = 29.99$ years, $SD = 7.414$, 55.7% female) from credamo.com. Participants were asked to imagine being in a fruit supermarket and then seeing some pears in a fruit basket on the fruit shelf (Appendix B-1). Then, participants rated the ugliness of the pears using the same measurement items as in experiment 1. A one-way ANOVA revealed that participants in the ugly pear conditions significantly perceived pears as being more ugly than participants in the typical conditions [$M_{\text{ugly}} = 4.118$, $SD = 1.402$; $M_{\text{typical}} = 2.375$, $SD = 0.751$; $F(1,68) = 39.579$, $p = 0.000$, partial $\eta^2 = 0.368$]. The results of the pretest indicated that the ugly pears were successfully developed. Therefore, we selected the pears successfully developed in this pretest as the stimuli for the main experiment.

5.2 Main experiment

5.2.1 Participants and procedure

Three hundred and eighty participants were recruited from the same online survey platform as in experiment 1. Thirty-two participants who failed the attention check were removed. This left us with a valid sample of 348 participants ($M_{\text{age}} = 29.13$, $SD = 6.718$; female 66.1%).

Participants were randomly assigned to one of 2 (produce appearance: ugly vs. typical) \times 2 (naturalness cues: present vs. absent) between-subjects design conditions. Participants were asked to imagine that they were shopping in a fresh produce supermarket and then seeing some pears in a fruit basket on the fruit shelf. Consistent with experiment 1, in naturalness cues present groups, consumers in the ugly conditions saw some ugly pears in the basket with a sign saying “Naturally grown, all-natural” on the side of the fruit basket facing the participants. In contrast, consumers in the typical conditions saw some typical pears and signs with the same naturalness cues. In naturalness cues absent groups, consumers in the ugly

conditions only saw some ugly pears in the fruit basket. Relatively, consumers in the typical conditions saw only typical carrots (Appendix B-2).

5.2.2 Measures

We used the same measurement items as in experiment 1 to measure the ugliness manipulation check, the naturalness cues manipulation check, produce evaluation (Cronbach's $\alpha = 0.845$) and purchase intention (Cronbach's $\alpha = 0.820$), and participants' perceived health risk ($r = 0.810$) of pears. In addition, for the measurement of the subtyping effect, we use the item: “Regarding the appearance of the pears in the fruit basket, you feel that the pears in the fruit basket look like a subcategory of the pears” (1 = “strongly disagree,” and 7 = “strongly agree”; Meyers-Levy and Tybout, 1989). All participants answered demographic information at the end of the experiment.

5.3 Results

5.3.1 Manipulation check

The one-way ANOVA results revealed a significant difference between the ugly conditions and the typical conditions rating of ugliness, with the ugly conditions scoring significantly higher than the typical conditions [$M_{\text{ugly}} = 3.087$, $SD = 1.329$; $M_{\text{typical}} = 2.743$, $SD = 1.190$; $F(1,346) = 6.442$, $p = 0.012$, partial $\eta^2 = 0.018$]. In addition, equally important, we did not observe a significant effect of ugliness manipulation on perceived health risk [$F(1,346) = 0.000$, $p = 0.993$, partial $\eta^2 = 0.000$]. These results suggest that ugliness manipulation was effective. These results suggest that ugliness manipulation was effective.

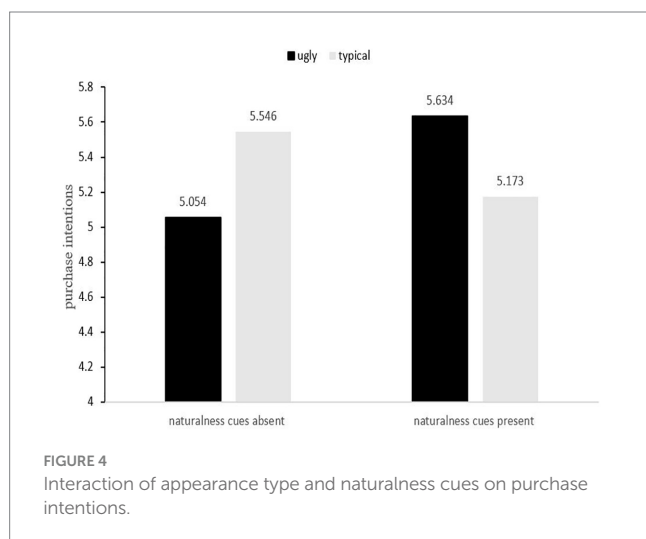
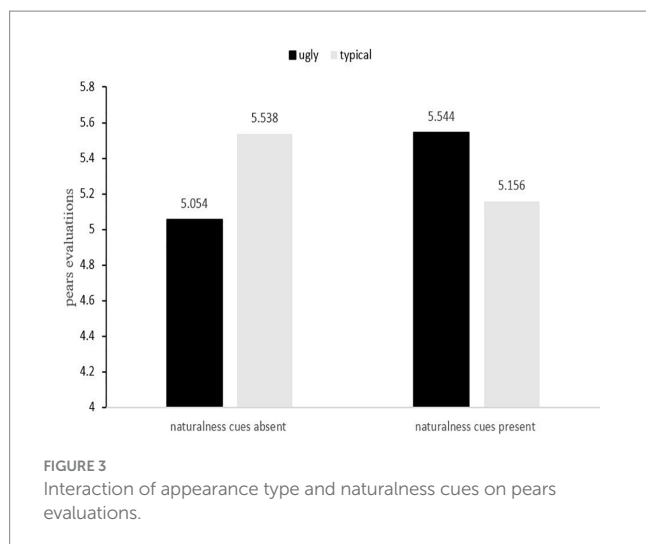
For naturalness cues, the one-way ANOVA results showed a significant difference in awareness of the presence of the naturalness cues. Participants exposed to the naturalness cues indicated greater awareness of the cues than participants who were not [$M_{\text{present}} = 6.380$, $SD = 1.127$; $M_{\text{absent}} = 3.270$, $SD = 1.510$; $F(1,346) = 470.479$, $p = 0.000$, partial $\eta^2 = 0.576$], suggesting naturalness cues manipulation was successful.

5.3.2 Pears evaluations

The two-way ANOVA results showed that the interaction effect between appearance and naturalness cues was significant [$F(1,344) = 17.200$, $p = 0.000$, partial $\eta^2 = 0.048$]. In the naturalness cues absent groups, simple effect analysis showed that participants in the ugly conditions reported lower pears evaluations than those in the typical conditions [$M_{\text{ugly}} = 5.054$, $SD = 1.326$; $M_{\text{typical}} = 5.538$, $SD = 0.837$; $F(1,344) = 10.707$, $p = 0.001$, partial $\eta^2 = 0.030$]. However, it is noteworthy that, in the naturalness cues present groups, participants in the ugly conditions reported higher pears evaluations than those in the typical conditions [$M_{\text{ugly}} = 5.544$, $SD = 0.626$; $M_{\text{typical}} = 5.156$, $SD = 1.010$; $F(1,344) = 6.737$, $p = 0.010$, partial $\eta^2 = 0.019$; Figure 3]. Consistent with the results of experiment 1, this result once again supports H1 (Supplementary Table 2).

5.3.3 Purchase intention

The two-way ANOVA results showed that the interaction effect between appearance and naturalness cues was significant [$F(1,344) = 18.337$, $p = 0.000$, partial $\eta^2 = 0.051$]. In the naturalness



cues absent groups, simple effect analysis showed that participants in the ugly conditions reported lower purchase intentions than those in the typical conditions [$M_{\text{ugly}} = 5.054$, $SD = 0.838$; $M_{\text{typical}} = 5.546$, $SD = 1.295$; $F(1,344) = 9.843$, $p = 0.002$, partial $\eta^2 = 0.028$]. However, in the naturalness cues present groups, it is worth noting that, simple effect analysis revealed participants in the ugly conditions reported higher purchase intentions than those in the typical conditions [$M_{\text{ugly}} = 5.634$, $SD = 0.930$; $M_{\text{typical}} = 5.173$, $SD = 1.036$; $F(1,344) = 8.523$, $p = 0.004$, partial $\eta^2 = 0.024$; Figure 4]. Once again, this result showed that when ugly produce and naturalness cues are combined, consumers instead have higher choice preferences (produce evaluations and purchase intentions) for ugly produce compared to naturalness cues are absent.

5.3.4 Subtyping effect

The two-way ANOVA results indicated that the interaction effect between appearance and naturalness cues was significant [$F(1, 344) = 8.236$, $p = 0.004$, partial $\eta^2 = 0.023$]. In the naturalness cues absent groups, simple effect analysis revealed that there were no significant differences in subtyping effect between participants in the ugly conditions and those in the typical conditions [$M_{\text{ugly}} = 4.460$,

$SD = 1.531$; $M_{\text{typical}} = 4.500$, $SD = 1.493$; $F(1,344) = 0.035$, $p = 0.853$, partial $\eta^2 = 0.00$]. Consistent with our expectations, In the naturalness cues present groups, simple effect analysis indicated that participants in the ugly conditions produced significantly higher subtyping effect than those in the typical conditions [$M_{\text{ugly}} = 4.620$, $SD = 1.374$; $M_{\text{typical}} = 3.780$, $SD = 1.313$; $F(1,344) = 14.887$, $p = 0.000$, partial $\eta^2 = 0.041$; Figure 5]. These results support H2.

5.3.5 Moderated mediation analysis

To further examine the psychological mechanism underlying the above-reported effect of appearance type of produce and natural cues on consumer preferences (produce evaluations and purchase intentions), we performed a moderated mediation analysis following (Hayes, 2013) model 8 with the subtyping effect as the mediator, appearance type as the independent variable, naturalness cues as the moderator, and product evaluations as the dependent variable. A 10,000 resample bootstrap analysis revealed that the 95% confidence interval did not contain zero, indicating a significant moderated mediation effect ($\beta = -0.088$, $SE = 0.046$, 95% $CI = [-0.191, -0.014]$). Similarly, replacing the dependent variable with purchase intention and repeating the above analysis process, again reveals a significant moderated mediating index ($\beta = -0.092$, $SE = 0.052$, 95% $CI = [-0.209, -0.009]$). These findings further supported H3 and provided novel insights regarding the psychological mechanism underlying the joint effect of the appearance of produce and naturalness cues.

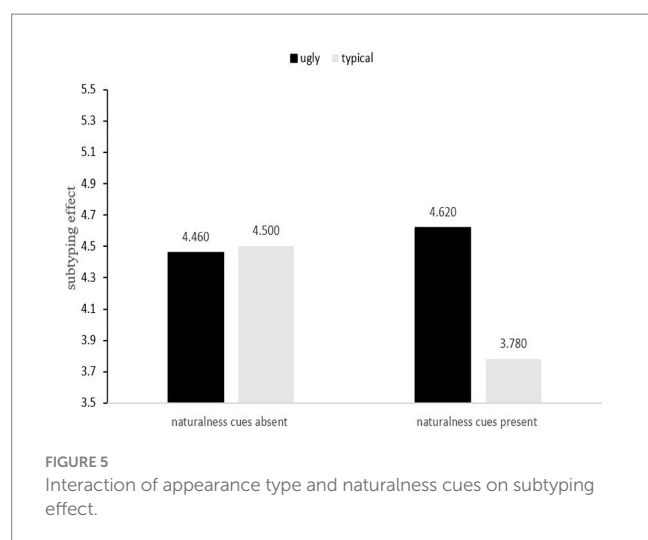
5.4 Discussion

The results of experiment 2 confirmed all our hypotheses using a different product category from experiment 1. Consistent with our hypotheses 1 and 2, the results indicated that when naturalness cues and ugly appearance are combined, this not only bolsters consumers' evaluation of ugly pears but even makes consumers generate higher evaluations than typical pears. This process occurs because the combination of the ugly appearance of pears and naturalness cues—the enabler corresponding to the ugly appearance that we have elaborated on in the previous section—facilitates consumers to subtype the ugly pears as a subcategory of the pear category and thus resolving the schema incongruity triggered by ugly appearance. This is, consistent with our hypothesis 3, the subtyping effect arises in consumers' category inferences for ugly pears. Further, consistent with schema congruity theory (Meyers-Levy and Tybout, 1989), this process not only elevates consumers' evaluation of ugly pears but even reverses consumers' preferences for typical pears, instead favoring ugly produce, so that the inherent negative feature of the ugly appearance of produce become a "positive" advantages. Experiment 2 increases the external validity of our studies and the generalizability of our findings.

6 General discussion

6.1 Theoretical implications

The theoretical implications of this research are as follows: Firstly, we tap into a condition that reverses consumer preferences for typical



produce, showing that consumers are more likely to favor ugly produce when naturalness cues are present as opposed to when they are absent. We bridge the gap of previous studies focusing only on the negative effects of ugly appearance. We illustrated that combined with the ugly appearance of the produce and naturalness cues, consumers will instead prefer ugly produce. In this case, the ugly appearance instead plays a “positive” advantage. Secondly, we demonstrate that naturalness cues are an enabler corresponding to the appearance of ugly produce, and their combination facilitates consumers to resolve the schema incongruity triggered by the ugly appearance of produce through subtyping resolution. These findings extend our understanding of the role of naturalness cues communication in the marketing of ugly produce. Finally, we examined the mediating mechanisms that bolster consumer preferences for ugly produce. The findings suggest that the subtyping effect mediates the interaction between the appearance of produce and naturalness cues on the produce evaluations, this elucidates and validates a novel consumer psychological cognitive mechanism that explains why consumers prefer ugly produce instead.

6.2 Practical implications

The findings of our research can have clear implications for retailers who wish to sell ugly produce without offering steep discounts, as we propose an easily implemented, low-cost intervention that may be more sustainable over the long term than discounting. First, ugly produce, combined with naturalness cues, could boost consumers’ preferences and help to create value for the farmers or retailers selling it. Second, the findings of the study could help to reduce food waste, which is a significant social dimension issue due to raising serious concerns about food security and economic and environmental pressures (Talwar et al., 2022). The avoidable food waste of produce due to their ugly appearance is currently very serious, which is not conducive to long-term sustainable social development. Our findings have theoretical implications and offer cost-effective management strategies for addressing the waste problem associated with ugly produce. By understanding and promoting consumer acceptance of esthetically imperfect produce, the research

contributes to sustainable consumption practices and offers a potential solution to reducing food waste. Overall, our findings provide coping strategies to promote consumer preferences (product evaluations and purchase intentions) for ugly produce, which in turn will help the stakeholder sector to reduce food waste due to the rejection of ugly produce and achieve more sustainable development of society in the long term.

6.3 Limitations and future research

We elaborated on how to boost consumers’ preference for ugly produces and provide coping measures to alleviate the major social problem of food waste caused by ugly produce. However, we also have limitations. First, we only focus on the categories of fresh produce. Future research can be extended to non-fresh food categories to further provide management measures for solving the problem of food waste at the social level, such as processed foods. Second, we only used a sample of participants from China. However, different countries have different cultural backgrounds and consumers have different consumer psychologies. So, future research could test whether our findings hold in the United States or other countries.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the (patients/participants OR patients/participants legal guardian/next of kin) was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

MX: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. YJ: Investigation, Methodology, Resources, Supervision, Writing – review & editing. BC: Investigation, Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2023.1313814/full#supplementary-material>

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Expanding recognition and inclusion of animal-free organic agriculture in the sustainable agriculture movement

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Animal-free organic agriculture resides at the margins of sustainable agriculture discourse, practice, and imaginaries, which center animal-based forms of farming. However, the concerns and goals of sustainable agriculture are overwhelmingly consistent with those of many forms of animal-free organic agriculture (AFOA), described as organic farming sans animal production, labor, and byproducts. Despite this sidelining, AFOA has great potential to contribute to a more robust sustainable agriculture movement. In order to emphasize the continuities between animal-based and animal-free sustainable agriculture, this Perspective identifies a number of key similarities between animal-free and animal-based sustainable farming, including mutual foci on soil health and shared opposition to intensive animal agriculture. It contends that beyond being compatible with sustainable agriculture, AFOA holds answers to some of the difficult questions currently and potentially confronting animal-based agriculture, such as projected impacts of climate change on animal agriculture and stability of supply chains for animal-based soil amendments. Barriers to greater inclusion of AFOA into the sustainable agriculture movement exist as well; this piece suggests potential ways to address some of these challenges, including the integration of AFOA into formal sustainable agriculture education.

KEYWORDS

sustainable agriculture, animal-free agriculture, stockfree organic, biocyclic vegan, vegan organic, veganic

1 Introduction

Calls for agriculture to abate the climate crisis, conserve natural resources, reduce agricultural pollution, ensure access to healthy affordable food, improve farmer livelihoods, and generally respond to the deleterious ecological and social impacts of industrial agriculture, are answered by a diversity of forms of sustainable agriculture. Agroecology, organic agriculture, regenerative agriculture, permaculture, conservation agriculture, and sustainable intensification are among these forms, in their concerns for environmental, social, and economic viability (Gomiero et al., 2011; Oberč and Arroyo Schnell, 2020; Kassam A. and Kassam L., 2021). While there are both key similarities and marked differences between these and additional sustainable agriculture approaches, one notable commonality is the normativity of domesticated or farmed animals. Farmed animals are enmeshed in sustainable farming systems in a multiplicity of ways, including as food animals (e.g., dairy cows and broiler chickens); as sources of fiber and skin (e.g., goose down and sheep wool); as sources of fertility for crops (e.g., manure and feather meal); as providers of ecosystem services (e.g., sheep and cattle in rotational grazing systems); as labor (e.g., oxen and draft horses); as attractions (e.g., heritage livestock breeds in agritourism

experiences); and as consumers of farm products (e.g., straw bedding and corn-based feed).

Forms of animal-based agriculture are centered in sustainable agriculture discourse and practice. Meanwhile, approaches to sustainable agriculture that are exclusive of farmed animals sit at the margins of conversations about sustainable agriculture futures—despite their actual and potential roles in sustainable agrifood systems (Hagemann and Potthast, 2015; Kassam L. and Kassam A., 2021; Hirth, 2022). Nobari (2021) recently observed that “From First-World urban gardening enthusiasts to indigenous movements, the push for a more sustainable way of growing food—one that works with ecosystems instead of against them—comes from a diverse set of voices. Within this diversity, one common denominator is the validation of small-scale, traditional forms of animal agriculture. This ranges from implicit to explicit. Even where not a central focus, animal husbandry is usually accepted as default in a sustainable agricultural system” (p. 381). They further assert that, “As awareness spreads that industrialized corporate agriculture is the problem, so does the notion that animal-based agriculture is the only possible alternative. When presented with the idea of veganic [an approach to organic agriculture that involves no farmed animals or animal byproducts], it’s like it can’t possibly be done” (p. 382). The status of animal-based agriculture as an unquestioned or a vital component of sustainable agrifood alternatives to industrial agriculture likely stems from a combination of factors, including European colonial legacies; community norms around animal husbandry; societal norms around meat and animal product consumption; the “logic of the larder;” and a general lack of knowledge around alternatives to animal-based fertility (Arcari, 2017; Weis and Ellis, 2020; Nobari, 2021).

Despite the marginal position of animal-free agriculture in sustainable agriculture discourse, practice, and imaginaries, animal-free organic agriculture (AFOA) is a set of approaches that evinces clear alignment with sustainable agriculture, and that is positioned to contribute meaningfully to the broader sustainable agriculture movement. As used in this piece, AFOA refers to organic plant agriculture systems that exclude domesticated or farmed animal bodies and byproducts (e.g., manure, blood meal, bedding litter) from the production of food, fiber, and fuel, instead using plant- and rock-based materials to enhance soil fertility. Three forms of AFOA have been codified as agricultural standards. In the following section, the Stockfree Organic Standards (based in the United Kingdom), the Biocyclic Vegan Standard (based in Germany), and the Veganic Standard (based in Canada) are used as touchstones for brief observations about continuities between AFOA and animal-based sustainable agriculture. Next, the piece outlines some of the challenges that animal-based agriculture may face in the near and midterm future, to which AFOA can respond. Finally, I identify some possible paths to effecting a more wholesale inclusion of AFOA in the sustainable agriculture movement. The intent of this Perspective is to draw greater attention to the existence and value of AFOA, with an eye to strengthening the sustainable agriculture movement.

2 Similarities between AFOA and animal-based sustainable agriculture

The three codified approaches to AFOA share numerous values, practices, and perspectives with forms of animal-based sustainable

agriculture. Acknowledging similarities that span the animal-based/animal-free divide is a useful way to counteract a narrow and divisive focus on the outstanding difference of the place of animals and animal byproducts in the respective forms of sustainable agriculture. The continuities outlined below are illustrative, not exhaustive.

A deep concern for soil health is perhaps the most fundamental shared value, even as this may manifest through different sets of practices (i.e., relative to the use of animals and animal byproducts). For instance, the Veganic Standard recognizes soils as “the essence of all life,” and emphasizes the importance of monitoring and building soil organic matter (NAVCS, n.d.), as does organic agriculture (Rodale Institute, n.d.-a). Improved soil health is foundational to the Biocyclic Vegan Standard, given that “... soil fertility is the basis of any sustainable and successful economic activity. All production techniques used in agriculture should therefore serve the aim of creation and maintenance of a diverse and active soil life ...” (Adolph Hoops Society, 2020), just as it is the most common desired outcome among regenerative agriculture practitioner organizations (Newton et al., 2020). Viewing agriculture as an instrument of climate change mitigation is another common value. The Biocyclic Vegan Standard, for instance, emphasizes the possibility for transformation of farmland into carbon sinks based in the application of carbon-heavy humus soil (Adolph Hoops Society, 2020). Meanwhile, over two-thirds of regenerative agriculture practitioner organizations view increased carbon sequestration as a desirable outcome of regenerative agriculture (Newton et al., 2020).

Practically speaking, commitments to growing without chemicals and genetically modified organisms (GMOs) articulated in the three sets of AFOA standards (Adolph Hoops Society, 2020; NAVCS, n.d.; Stockfree Organic Services, n.d.-a) are also common to many forms of animal-based sustainable agriculture. Cover cropping, minimal tillage, and crop rotations are other techniques implemented by some animal-free and some animal-based sustainable agriculture forms. Green manure application, an integral part of the Stockfree Organic and Biocyclic Vegan Standards, is a notable commonality, with animal-based plant agriculture also often implementing this plant-based technique to improve the soil. The United States Department of Agriculture (USDA) guidelines for organic crop producers, for instance, discuss green manuring as one of the primary soil-building activities on certified organic farms (Coleman, 2012). The integration or creation of natural landscape elements in and around farm ecosystems is another practice common across the animal-free/animal-based sustainable farming spectrum. Hall and Tolhurst (2007) detail numerous landscape design techniques that Stockfree Organic-certified farmers can implement to enhance biodiversity; attract predatory insects and mammals; and reduce wind speed and erosion. Similarly, Wezel et al. (2014) describe the agroecological practice of (re)integrating elements like vegetation strips and hedges as conferring benefits including habitat for pollinators; protection against erosion; and biodiversity conservation.

Finally, the problematization of intensive livestock production is common across almost all animal-free and animal-based sustainable agriculture approaches, though of course ultimately the proposed solutions differ. Intensive livestock farming is recognized in the Biocyclic Vegan Standard as a leading cause of greenhouse gas emissions (Adolph Hoops Society, 2020). While materials associated with the Stockfree Organic Standards tend not to focus on intensive production in particular, charges such as livestock production’s contributions to food

insecurity, greenhouse gas emissions, fossil fuel dependence, and waterway pollution apply (e.g., Hall and Tolhurst, 2007; Stockfree Organic Services, n.d.-b). From an agroecological perspective, Gliessman (2007) emphasizes that conventional animal husbandry techniques contribute heavily to the unsustainability of conventional agriculture, including via air and water pollution from confined animal feeding operations; monopolization of arable land by feed production; and risks to human health from zoonotic diseases and diets high in animal fat. The Soil Association connects intensive production of various types of livestock to animal welfare violations, antibiotics resistance, farmworker health, and ecological challenges (e.g., Soil Association, n.d.-a,n.d.-b).

These similarities are perhaps not surprising, given the importance of organic and/or regenerative agriculture as bases for the three AFOA standards. They demonstrate that in many important ways, AFOA and animal-based sustainable agriculture proponents are “on the same team.” They also offer common ground on which deeper understandings of AFOA could be built, as a step toward greater acceptance of AFOA approaches in the broader sustainable agriculture community, which would be to its benefit.

3 AFOA as an asset to the broader sustainable agriculture movement

AFOA is positioned to make a key contribution to the sustainable agriculture movement, in offering a more diversified path forward in the face of numerous environmental, scientific, and social shifts that could present substantial challenges to animal-based plant agriculture and animal agriculture (both industrial and alternative varieties) at various sites and scales. The developments described below suggest the vulnerabilities of a heavily or exclusively animal-based sustainable agriculture movement. In the worst cases, they may entail steep challenges to obtaining animal-based fertility for crops, and may render animal husbandry untenable or undesirable.

Animal-based approaches to plant agriculture rely on soil amendments such as manures, blood meals, and feather meals. These wastes and waste products originate from sources including industrial animal agriculture, small local farms, and on-site in mixed crop-livestock operations. As various threats to animal agriculture arise and escalate, including those outlined below, there is reason to expect that the reliability of access to animal-based inputs will destabilize.

The intensification of climate change is expected to yield considerable impacts on livestock production. Reduced and variable feed quantity and quality; diminishing water availability; shifting disease dynamics; and the effects of heat stress on animal reproduction, health, and mortality are among the ways in which climate change is expected to increasingly affect animal agriculture (Nardone et al., 2010; Rojas-Downing et al., 2017; Bernabucci, 2019). Livestock producers may need to prepare to implement appropriate adaptation strategies or to consider alternative livelihoods, and the scaling down or termination of vulnerable operations will have implications for growers dependent upon animal wastes or waste products from those sources.

The numerous environmental and social impacts of animal agriculture and animal-based foods have led to a growing scientific consensus that the production and consumption of animal-based foods must be substantially reduced. Impacts including the contribution of livestock production to global greenhouse gas

emissions; the vast resource requirements of livestock production, including land and water; and the relationship between intensive animal agriculture and potential zoonotic pandemics are oft-cited in these discussions (e.g., IPCC, 2019; Willett et al., 2019; Ripple et al., 2020). Relatedly, food security strategies that rely heavily on plant-based foods are emerging in discussion and design, typically with an eye either to peak meat production or to scaling back animal agriculture (e.g., Day, 2013; Sabaté and Soret, 2014; Jimenez-Lopez et al., 2020). These discourses all put pressure on livestock-based industries and animal farmers, raising serious questions about the environmental and social sustainability of animal agriculture. Farmer transitions out of animal production due to these developments will likely have downstream impacts on animal byproduct supplies.

The market for animal-based food products is changing, sometimes in ways unfavorable to animal agriculture. For instance, per-capita cow's milk consumption has been declining in the United States for decades, and consumer demand for plant-based milks is now a contributor to the decline in sales of cow's milk in the U.S. (Stewart et al., 2020). Cellular agriculture is another sector to consider. If lab-based animal agriculture scales up in coming years, production costs will drop, consumer interest in multiple “traditionally-produced” animal products may decrease, and challenges may arise for feed producers and “traditional” livestock and dairy producers (Burton, 2019; Saavoss, 2019; Newton and Blaustein-Rejto, 2021). As these pressures lead to some farmers exiting the meat, dairy, and other industries, operations that once fed the animal agricultural byproduct supply chain will cease to do so.

These and additional factors that threaten animal husbandry will not manifest uniformly around the world, and the degree to which they impact animal agriculture in any given region or place will be dependent upon complex configurations of industry, climate, geography, culture, and policy. As they do emerge or intensify, though, a trickle-down effect of diminished supplies of animal-based soil amendments might be expected to result from altered and reduced livestock production. The degradation of animal byproduct supply chains would create instability for growers reliant on inputs from impacted regions and economies. Sustainability-minded farmers will need to be aware of and open to animal-free avenues in the face of potential shortages of animal agricultural byproducts.^{1,2}

There is also the question of the desirability of animal-based fertility sources, in addition to that of availability. Recognition of the potential transfer of pathogens from animal waste materials to organic plants such as berries and vegetables drives concerns about food safety in animal-based organic crop production systems (Sorensen and Thorup-Kristensen, 2011; Alsanus et al., 2019). In Europe, the place in organic agriculture of animal-based inputs specifically from

1 The organic transition in some parts of Europe similarly necessitated implementation of plant-based fertility systems, particularly in certain arable regions that were managed sans livestock and thus lacked access to animal manure (Hall and Tolhurst, 2007; Løes et al., 2011). This situation eventually informed the development of the Stockfree Organic Standards in the United Kingdom.

2 Of course, some farmers may opt to use synthetic fertilizers to replace animal-based fertilizers; this would be consistent with approaches such as conservation agriculture.

conventional agriculture has been a topic of ongoing discussion (Schmutz et al., 2020). For instance, the decision that Danish organic farmers must eliminate conventional manures and straw from their systems was made to better align organic agriculture with the ideal of an agricultural system with minimal negative effects on environment, animals, and society; and in order to prevent importing manures containing residue from GMO feeds (Oelofse et al., 2013). In addition to calling into question the desirability of animal-based inputs, these considerations serve as a reminder that farming practices are to some degree constrained by regulations and standards, which can shift toward limiting animal inputs into plant agriculture. AFOA represents a way around contamination concerns as well as tightened regulations.

Furthermore, as previously noted, the climatic, environmental, social and marketing challenges to animal agriculture described above may entice or force livestock farmers to consider alternative means of supporting themselves. These farmers may consider paths including leaving agriculture altogether, diversifying their household incomes or their farming operations, or making a full transition to plant agriculture. AFOA approaches represent a promising alternative for farmers wishing to pursue partial or full transitions to plant agriculture, in their ability to circumvent potential shortages in animal-based soil amendments that may transpire. Additionally, difficult emotions related to acknowledgment of animal sentience and concern about the environmental impacts of livestock production can lead to changes of heart about animal production among farmers and ranchers (Hirth, 2021; Salliou, 2023). AFOA approaches allow growers to avoid reliance on products from livestock industries or operations that they find environmentally irresponsible or morally reprehensible.³

AFOA, including and beyond the three codified approaches introduced above, is a viable (e.g., Pimentel et al., 2005; Cormack, 2006; Eisenbach et al., 2019; Kakabouki et al., 2021; Kaniszewski et al., 2021; Hefner et al., 2022; Niether et al., 2023), less resource-intensive (Hirth, 2022) path forward in the face of numerous changes that may make animal-based plant agriculture and animal agriculture more tenuous or less enticing enterprises. The AFOA standards provide sets of agricultural principles and practices that sidestep these issues, particularly including methods for building soil fertility that do not rely on animal inputs. Other AFOA-compatible approaches, such as Shumei Natural Agriculture and the Grow Biointensive method, similarly offer soil-building techniques with no or minimal animal-based amendments. As such, they are valuable assets to a heavily animal-based sustainable agriculture movement. How, then, to move forward, toward a sustainable agriculture movement more inclusive to AFOA?

4 Toward fuller inclusion of AFOA in the sustainable agriculture movement

An embrace of AFOA faces numerous barriers. Firstly, AFOA will face challenges similar to some of those identified above for animal agriculture, which may invite skepticism. For instance, climate change threatens not only livestock production but also crop yields in some regions (Kang et al., 2009; Lobell and Gourdji, 2012), and animal-free

sustainable farming is not a silver bullet for this. Supply chain disruptions for plant-based inputs such as soybean meal could feasibly arise due to phenomena such as major weather events and shifting trade agreements, creating a parallel situation to that suggested for animal-based plant agriculture. These and other limitations do not diminish the overall value of AFOA to the sustainable agriculture movement, though. AFOA approaches are simply several of many forms of sustainable agriculture, optimal in some contexts and not in others. Indeed, neither animal-based nor animal-free approaches are appropriate for every circumstance, and neither should be recommended or defaulted to without consideration of relevant conditions, from the macro (e.g., climate) to the micro (e.g., a farmer's financial resources).

The fundamental difference in position on animal production, byproducts, and labor is another glaring barrier. Proponents of animal-based sustainable agriculture may hold deep-seated beliefs about the value and necessity of livestock to sustainable agriculture, be members of communities in which animal husbandry is a normal and desirable practice, and lack familiarity with animal-free sustainable methods (Weis and Ellis, 2020; Nobari, 2021). AFOA challenges these cultural beliefs and community norms, and information about animal-free organic farming systems is not nearly as widely available as is information about animal-based systems. One way in which this scarcity of information manifests is in the inadequacy of resources available to farmers who might wish to implement AFOA. There is support available on behalf of the organizations offering the three agricultural standards for AFOA, as well as from other grassroots actors. However, in the US for instance, there appear to be no opportunities for students enrolled in sustainable agriculture majors, minors, graduate degree programs, certificate programs, and farmer training programs to learn the principles and practices associated with various forms of animal-free farming (Seymour and Utter, 2021). The situation is likely similar in other world regions. New and experienced farmers interested in adopting AFOA must seek out information and instruction, sometimes internationally, from grassroots organizations and other farmers; this can be time-consuming and burdensome. This is a practical issue that absolutely must be resolved in order for AFOA to become a viable approach for more farmers, and for AFOA to be taken more seriously by the movement. There are a number of actions that may be taken in response to the knowledge-based and cultural barriers to lay a foundation for a broader sustainable agriculture movement.

First and foremost, better support for AFOA will be critical for expanding acceptance of AFOA in the sustainable agriculture movement and for rendering AFOA a more realistic pursuit for new and transitioning farmers. The integration of animal-free organic approaches into formal sustainable agriculture education is one key path forward. Expanding the agricultural curricula of two- and four-year colleges and universities, as well as of education-oriented agricultural non-profit organizations, to include AFOA would entail structural or programmatic changes that might be hard-won and challenging to implement. Cultivating institutional will and easing the burden of implementation might require investment on behalf of grassroots AFOA organizations, perhaps in terms of building relationships with sustainable agriculture program faculty and administrators, or even supplying funding or instruction for pilot courses. Some precedent for this exists. Glyndwr (now Wrexham) University in Wales once integrated the Stockfree Organic Standards into its organic horticulture management degree with involvement of the Vegan Organic Network (VON), the originator

³ Seymour and Utter (2021) report on a wider range of additional reasons for farmer adoption of AFOA.

of the standards (VON, 2010). Generally though, this sort of work is difficult to suggest, given the limited resources of even the most prominent AFOA-oriented organizations. Challenges aside, this would be a deeply meaningful shift, in providing platforms for raising awareness about the existence and viability of AFOA approaches in the minds of future sustainable agriculture practitioners and leaders, and in giving them the practical tools to farm animal-free.

Another productive form of support for AFOA is expanded research, particularly into soil fertility systems. While there is a small research literature on plant-based fertility, more extensive coverage of fertilizers, crops, and soil types would facilitate more comprehensive and precise formal education on AFOA. It would also assist farmers who are starting out or transitioning outside of the support offered by AFOA certifying organizations, as there is reportedly a strong element of experimentation with soil fertility as part of the AFOA learning curve (Seymour and Utter, 2021). An interesting research example, focused on a variety of management practices and outcomes including and beyond fertility, is the US-based Rodale Institute's Farming Systems Trial (FST). The FST incorporates both organic manure systems, fertilized by leguminous cover crops and composted manure, and organic legume systems, fertilized only by leguminous cover crops (Rodale Institute, n.d.-b). The FST is conceptually significant in its positioning of sustainable animal-based and animal-free systems contra a conventional, synthetically-fertilized system. In doing so, it points to some of the common ground between animal-based and animal-free agriculture, and is perhaps a model for research that could increase collaboration and understanding across the animal-based / animal-free divide. It is also significant that the Rodale Institute, a respected organization in organic agriculture, has incorporated AFOA into its FST; this is an important signal of the value of AFOA to the sustainable agriculture movement.

Events designed to bring together animal-based and animal-free practitioners and advocates can raise the visibility of AFOA to animal-based communities of practice and offer opportunities to identify and discuss common ground in practices, values, critiques, and goals. An example of this occurred in 2022, when the UK-based charity Viva! organized a panel of experts to speak to the question "Is the future of sustainable farming animal-free?" Animal agriculture supporters and vegan farming advocates engaged in a respectful discussion on the topic, identifying meaningful similarities and differences between animal-based and animal-free agriculture as they spoke to their respective concerns, goals, experiences, and visions for agrifood futures (Viva!, 2022). Conferences can be fruitful grounds for exchanges as well. For instance, Soil Not Oil, an annual grassroots gathering in the US around organic, regenerative, and agroecological farming, has been welcoming veganic agriculture activists, academics, and practitioners. This has allowed AFOA proponents valuable opportunities to both inform and learn from conference participants who align with animal-based production yet share the larger goal of a sustainable agrifood system.

Finally, highlighting the financial prospects for organic produce grown without animal byproducts may enhance acceptance of AFOA in the sustainable agriculture movement. Vegan and vegetarian consumers in Germany, for instance, have been found to express interest in stockfree organic products based on animal welfare attitudes (Jürkenbeck and Spiller, 2020), and US veganic farmers have reported enthusiastic responses to their produce from vegan customers (Seymour and Utter, 2021). This suggests that there may be nearly-untapped marketing opportunities for farmers who decide to adopt AFOA.

5 Conclusion

Though AFOA is indisputably aligned with sustainable agriculture and shares many practical similarities, values, and goals with animal-based forms of sustainable agriculture, it resides on the sidelines of the sustainable agriculture movement. Approaches to animal-free organic plant agriculture represent opportunities to address how farmers and other stakeholders might navigate in a sustainable manner the range of challenges that may affect livestock farming, mixed crop-livestock farming, and animal-based plant agriculture now and in the coming decades. A more prominent position in the array of sustainable agriculture approaches is therefore suitable for AFOA, and its current marginal status is a disservice to the strength and future of sustainable agriculture. As McGreevy et al. (2022) recently observed, "We no longer have the luxury of ignoring viable, successful options when it comes to agrifood system sustainability .. While there might be strong positions held for or against certain types of solutions, the challenges of sustainability in general and agrifood systems sustainability in particular are so complex and urgent that all types of solutions with real potential .. are needed" (p. 1015). Indeed, it is time to open discursive and material spaces in the sustainable agriculture movement to a currently-marginal(ized) set of perspectives, practices, and participants, and to think beyond normative practices, values, and visions relative to farmed animals in order to work earnestly and vigorously toward sustainable agrifood systems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MS: Conceptualization, Writing – original draft, Writing – review & editing.

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Cultivating a greener plate: understanding consumer choices in the plant-based meat revolution for sustainable diets

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The implementation of sustainable food systems on a global scale is of utmost importance in order to effectively achieve sustainable diet goals on a world level. Plant-based meat alternatives offer potential replacements for meals derived from animals and serve as a means to transition toward more environmentally sustainable dietary choices. Therefore, in the quest for sustainable diets, comprehending consumer behavior and preferences within the context of the plant-based meat revolution is crucial. The current study is planned to examine the factors that influence the acceptance of plant-based meat alternatives among Chinese people. For this purpose, data collected from 610 individuals through an online survey was analyzed using the partial least square structural equation model. The findings reveal that consumer perceptions, particularly regarding taste, nutrition values, and texture, were found to have a significant impact on the acceptance of plant-based meat alternatives. Effective promotional strategies, availability, and accessibility also play a vital role in influencing consumer preferences for plant-based meat alternatives. The outcomes regarding the significance of health perception and environmental concern in transforming consumer preferences for plant-based meat alternatives are also highlighted. Consumers prioritize plant-based meat alternatives due to their perceived health benefits and favorable environmental impact. Moreover, consumer satisfaction, rooted in meeting or exceeding expectations, signifies the mediating role in the relationship between consumer perceptions and the acceptance of plant-based meat alternatives, which boosts the plant-based meat alternatives' acceptance. Furthermore, the findings underline the mediating role of environmental attitude in the relationship between environmental concerns and plant-based meat alternatives' acceptance, emphasizing the importance of sustainable dietary choices. In general, these findings provide valuable insights into the promotion of sustainable dietary choices, the alignment of consumer behavior with environmentally conscious decisions, and transforming the food systems in light of changing consumer behavior and ecological concerns.

KEYWORDS

sustainable diets, sustainable food systems, consumer behavior, plant-based meat alternative, healthy nutrition

1 Introduction

Food systems possess the capacity to foster human well-being and uphold ecological sustainability, yet their present state poses a dual jeopardy to these objectives. The immediate challenge lies in ensuring that a burgeoning global population is afforded access to nutritious diets through the implementation of sustainable food systems. The lack of established scientific objectives for attaining nutritious meals within sustainable food systems has impeded widespread and coordinated endeavors to revolutionize the global food systems. A considerable body of research indicates that current global food systems and eating practices are not sustainable in terms of both human and ecosystem well-being (Willett et al., 2019). The food systems are responsible for 21–37% of global GHG emission and world agriculture is responsible for 70% of freshwater usage (Food and Agriculture Organization, 2013; Shukla et al., 2019). Furthermore, it is important to note that there are multiple leverage points within the global food systems, encompassing various aspects such as agricultural production and waste management. These leverage points possess the capacity to bring about significant transformative impacts. Nevertheless, it is improbable that the agriculture sector in isolation will be capable of achieving global climate targets without a simultaneous and substantial modification in consumer food habits (Theurl et al., 2020).

Meat has long been recognized as a significant constituent of the healthy diets, serving as a valuable reservoir of vital nutrients necessary for the processes of human development. Meat farming and processing contribute to employment and revenue creation in addition to their nutritional significance. In the past few years, there has been a growing focus on the sustainability of meat production and the potential negative impacts of animal husbandry and meat intake on the natural world and the well-being of humans. This has led to greater concern about the negative effects of meat production on the environment and human healthiness (Riley, 2010). The production of traditional meat through animal husbandry has been linked to various significant environmental issues, such as emissions of greenhouse gases, forest loss, and freshwater usage (McMichael et al., 2007).

The production of livestock is responsible for a significant proportion, ranging from 14 to 30%, of GHG emissions caused by human activities (Reisinger and Clark, 2018). Additionally, it is the primary source of methane emissions resulting from human activities. Meat farming also necessitates a disproportionate allocation of land and precious resources in comparison to other food sources (Alkon, 2014). Certain methods of cow production, such as those under consideration, necessitate the use of around 25 kg of animal feed and 15,000 L of water in order to yield 1 kg of meat (Mekonnen and Hoekstra, 2010). With the growing demand for meat, there is a mounting imperative to adopt intensive agricultural methods, such as feedlots, instead of relying on pastoral grazing. The rise in demand for animal feed, primarily sourced from extensively cultivated grain crops like maize and soy, has been identified as a significant factor in the occurrence of deforestation in regions such as the Amazon (Food and Agriculture Organization, 2013).

Numerous credible organizations have advocated for meat reduction for wholesome and sustainable food systems, acknowledging the related harms. In order to keep global warming due to human activity below 2°C, the IPCC has urged for a global food systems response that includes significant dietary changes as well as decreases

in meat production and consumption (IPCC, 2018). An estimated 10.9 to 11.6 million fatalities annually might be avoided by switching to a nutritious and environmentally friendly diet that includes less meat and switching to a meat alternative such plant-based meat alternative (PBMA) (Willett et al., 2019).

It is anticipated that the worldwide market for PBMA will experience significant growth, with a predicted value of \$85 billion (USD) by the year 2030 (Gordon et al., 2019). The promotion of PBMA is frequently advocated as a way to address the sustainability issues, animal welfare concerns, as well as in certain instances, public health issues linked to the farming and consumption of traditional meat. This approach aims to attract consumers by utilizing established supply chains. There is an increasing recognition among scientists that it is crucial for nations with a high intake of meat to make significant transitions toward sustainable diets that prioritize PBMA. This is necessary in order to effectively achieve climate change mitigation targets (Bajželj et al., 2014; Bryngelsson et al., 2016) and stay inside the limits of what the planet can sustain (Willett et al., 2019). Collectively, these apprehensions have motivated endeavors to diminish the use of traditional meat and enhance PBMA consumption.

PBMA provide a possible answer to the issues involved with shifting dietary patterns away from animal products worldwide. These dietary modifications frequently entail changes in meal composition and the acquisition of new cooking skills, which might be seen as barriers to a PBMA transition (Macdiarmid et al., 2016). PBMA is designed to closely replicate the sensory characteristics, particularly flavor and texture, of their animal-based meat.

The future implementation of large-scale sustainable meat production, which does not involve the use of animals, has the potential to address numerous ethical, environmental, and health-related issues that are now linked with the raising of animals (Bryant and Barnett, 2018). In recent years, there has been a growing acceptance of PBMA as a feasible substitute for traditional meat due to advancements regarding quality and its rising popularity among consumers (Wild et al., 2014). Nevertheless, the advantages of these products can only be fully realized if they effectively replace the need for traditional meat. A substantial 73% increase is projected in global meat demand by the year 2050 with a significant portion of this growth expected to originate from emerging nations. However, it is disconcerting to note the limited extent of studies conducted on consumer attitudes toward PBMA in developing countries.

China and India have been recognized as key nations for conducting consumer research on PBMA (Bryant and Barnett, 2018). These countries possess the largest populations globally and are anticipated to experience a surge in their meat consumption in the forthcoming decades due to the growth of their economies, enabling a greater number of people to afford meat. Moreover, it is important to acknowledge that there are significant cultural disparities between the developed and developing countries, which has been the primary focus of consumer acceptance research. Consequently, it is likely that consumer acceptance in China may exhibit distinct characteristics. There is a dearth of scholarly investigations pertaining to the level of consumer acceptance of PBMA in the Chinese market. Thus, this study aims to explore acceptance of PBMA for sustainable diet and identify the factors associated with their acceptance.

Understanding and viewpoints from consumers will be crucial for a PBMA's future market acceptability, even though customers may give less priority to the matter when the PBMA is unavailable and its

availability duration is uncertain (Goodwin and Shoulders, 2013). Consumers may not be as excited about developing agro-food technologies during their research and deployment stages, as seen in numerous recent examples such as biotechnology and nanotechnology (Verbeke et al., 2015). Consumers are receptive to non-invasive processing technologies that enhance the health and taste of meat, as reported by De Barcellos et al. (2010). However, strong opposition is shown to interventions and changes in the meat production chain that are viewed as excessive, invasive, or otherwise departing from natural processes.

This study is one of a few that explores consumer behavior related to the acceptance of PBMA for sustainable diets and food security in developing countries. PBMA can greatly contribute to addressing sustainable dietary intake and transitioning toward sustainable food systems that fulfill food security requirements worldwide. Additionally, exploring the potential of plant-based meat alternatives can enable individuals to meet their food security demands. This study looks into how consumer behaviors related to meat consumption have changed in favor of PBMA. What factors shape the consumer behavior in favor of PBMA. Thus, the current study is planned to examine the factors that influence the acceptance of PBMA among Chinese people. This research offers insightful information for decision-makers looking to observe consumer behavior in support of sustainable diets and food consumption. This study makes a substantial contribution to the expanding body of scientific literature that aids in our comprehension, prediction, and avoidance of possible adverse effects on people's future environmental inspirations and behavioral patterns brought on by conventional meat consumption. The findings of this study have significant ramifications for health professionals and legislators who prioritize sustainable food systems and sustainable diets. Government agencies, parties involved in the food supply chain, and nutritionists, who are largely in charge of guaranteeing sustainable diets, are among the study's possible beneficiaries.

2 Hypothesis development

The way that consumers view foods has a big impact on whether or not they are accepted. A number of elements, such as sensory qualities, esthetic appeal, flavor, texture, freshness, and safety, influence how consumers perceive a particular food. Customers' willingness to accept a food may be adversely affected if they believe it to be inferior to alternatives (Lim et al., 2014). The appeal of meals and consumers' opinions of their perceived safety and quality affect their purchasing decisions. PBMA and their analogs in processed meat are viewed similarly (Michel et al., 2021). This study also states that customer perception plays a major role in determining PBMA acceptability as sustainable diets and transition toward sustainable food systems.

H1: Consumer perception significantly affects the acceptance of PBMA.

Only a small percentage of consumers regularly purchase and consume PBMA products (Hagmann et al., 2019; Siegrist and Hartmann, 2019). On the other hand, a great majority of individuals do not take PBMA seriously (Lemken et al., 2019). According to a

study by Hoek et al. (2011), people who regularly eat PBMA are largely responsible for the positive results related to the acceptance of PBMA. Participants were asked to rate the flavor, texture, look, and aroma of both meat and PBMA in this study. The results showed that PBMA scored higher than meat among regular consumers. However, those that used PBMA moderately gave more balanced scores, leaning slightly more in favor of traditional meat. However, when compared to PBMA, those without access to meat substitutes gave meat a far higher quality rating (Hoek et al., 2011). Thus, we assume that

H2: Consumer satisfaction positively affects the acceptance of PBMA.

H3: Consumer perception significantly mediate between consumer satisfaction and the acceptance of PBMA.

The production and consumption of animals have been identified as significant contributors to various environmental challenges that pose a threat to sustainability. These challenges include GHG emissions, land use and degradation, water consumption, soil pollution, and food waste at the consumer level throughout all stages of the food supply chain (Magkos et al., 2020). The contemporary food system exhibits a notable environmental footprint, often linked to heightened levels of livestock farming and over consumption (de Boer and Aiking, 2011; Hoek et al., 2011). Curiously, notwithstanding this apparent disinterest, scholarly investigations indicate that a considerable proportion of individuals who partake in meat consumption recognize the possible advantages associated with adopting a vegan or vegetarian dietary regimen, particularly in relation to the well-being of cattle and the promotion of environmental sustainability (Bryant, 2019). The increasing recognition of the known environmental advantages associated with reducing the use of animal-sourced food has resulted in a surge in the acceptance of plant-based alternative food, particularly in industrialized countries (Fresán and Sabaté, 2019). According to Saerens et al. (2021), PBMA has a lesser negative impact on the environment compared to most forms of meat production. This is mostly attributed to the reduction in refining losses that occur within the animal production process. According to Alae-Carew et al. (2022), the concept of PBMA holds significant potential in the context of climate change mitigation, particularly in relation to the establishment of a sustainable food system and sustainable diets. According to Smetana et al. (2023), individuals who express a preference for the importance of environmental stewardship are more inclined to engage in pro-environmental behavior. Hence, it is postulated that:

H4: Consumer environmental concerns significantly affect the acceptance of PBMA.

H5: Consumer environmental concerns significantly affect consumer environmental attitude toward PBMA.

Further we hypothesize that

H6: Consumer environmental concerns mediated between consumer environmental attitude and acceptance of PBMA.

Over the course of recent decades, health organizations have issued recommendations advocating for the augmentation of whole plant food consumption (Rock et al., 2020). Adhering to this dietary recommendation is linked to decreased chances for diabetes, cancer, cardiovascular disease, and overall mortality to differing extents (Aune et al., 2017). In recent times, there has been an increased emphasis on the health advantages associated with substituting animal protein with (Abdelhamid et al., 2018). PBMA are commonly regarded as having a higher level of healthiness compared to meals derived from animals (Schiano et al., 2020; Profeta et al., 2021). The acceptance of plant-based diets is imperative in order to achieve a sustainable dietary pattern that can effectively contribute to beneficial outcomes in terms of environmental preservation, human health, and public health (Springmann et al., 2018). There is evidence to suggest that PBMA are frequently considered to be comparatively healthier than meals derived from animal sources (Michel et al., 2021). Alae-Carew et al. (2022) provide evidence indicating that a decrease in the intake of traditional meat would be in line with priorities for promoting health. Consequently, we postulate that

H7: Health perception significantly affect the acceptance of PBMA.

The role of marketing is crucial in shaping consumers' views and fostering their acceptance of sustainable diets. The marketing strategies employed for promoting products have the potential to shape consumers' perceptions and willingness to adopt novel food items, such as PBMA (Sucapane et al., 2021). Consequently, marketing practices significantly impact customers' choices when it comes to purchasing food. The marketing mix encompasses a variety of elements that are taken into account during the marketing of a product, such as the assessment of consumer preferences, the perception of the product, and its differentiation from competing products. In the context of food goods, several elements contribute to their marketability, including product descriptors and images shown on the packaging, pricing, as well as in-store placement and promotional strategies (Brooker et al., 2022). Therefore, it is assumed that

H8: Promotion strategies of PBMA can positively influence the acceptance of PBMA.

The potential for altering consumption patterns appears promising through the enhancement of the relative accessibility of PBMA in comparison to animal-derived meat (Raghoobar et al., 2020). There is a growing recognition that the arrangement of physical food environments significantly influences the shift toward more sustainable and nutritious dietary patterns, rather than solely attributing responsibility to consumers and focusing solely on conscious factors that influence behavior (Bianchi et al., 2018). Research has demonstrated that the physical attributes of environments have a significant impact on individuals' meal choices within these specific dining contexts. In-store availability of food has been consistently recognized as a significant determinant of food selection, as evidenced by the findings of Pitt et al. (2017). The concept of in-store food availability pertains to the frequency of product occurrences within the tangible retail setting (Pechey et al., 2020). Numerous studies have examined the relationship between

food availability and consumption, specifically focusing on the effects of increasing the availability of low-calorie foods while reducing the availability of high-calorie foods in order to promote the selection of healthier food options (Hollands et al., 2019). Insufficient scholarly focus has been devoted to comprehending the factors that determine the impact of food availability on the consumption patterns of more sustainable food options. Based on our hypothesis, it is postulated that

H10: Availability and accessibility of PBMA in food markets can positively influence its acceptance.

3 Materials and methods

3.1 Questionnaire design

Researchers studying the acceptance of new food products among consumers have frequently used questionnaire surveys to collect primary data. We first conducted a thorough assessment of the relevant scholarly literature and then solicited the feedback of academic and research specialists familiar with the subject area to construct the survey instrument for this study. An approach consisting of two stages was used to determine whether the questionnaire was suitable for the survey and whether it could be relied upon. At first stage, a group of five academic professionals, including professors, associate professors, and researchers, conducted an in-depth review and analysis of the questionnaires. These people were expert in the field of consumer behavior. The purpose of the study was to determine the extent to which the questionnaire included all relevant information and to assess how understandable the technical terminology was. In addition, a sample group consisting of twenty-five individuals was used for the initial evaluation. Consequently, changes were made to the questionnaire after it had already been completed. These changes were incorporated into the final questionnaire, and a well-designed questionnaire was used to collect the data for the study.

Eight constructs were measured in this study: (i) Consumer perceptions about PBMA (CPE), (ii) promotion strategies of PBMA (SFP), (iii) health perceptions (HPE), iv) environmental concerns (ENC), (v) acceptability and availability of PBMA (AAA), (vi) consumer satisfaction (CS), (vii) environmental attitude of consumers (ENAT), and (viii) PBMA acceptance. The first section of the questionnaire measured PBMA-related consumer perceptions using seven statements. The second section of the survey instrument included five queries related to PBMA promotion strategies. The third and fourth parts of the questionnaire measured the health perception and environmental concerns of consumers through nine and eight statements, respectively. The next two sections measured the accessibility, availability, and consumer satisfaction about PBMA. The seventh section examines the environmental attitude of consumers by using five questions. The acceptance of PBMA was measured through seven well-designed questions. The last section of the questionnaire focused on the socio-demographic characteristics of the consumers. A five-point Likert scale was used to evaluate responses to all questions in the survey instrument, with the exception of the first socio-demographic section.

3.2 Data collection

A questionnaire survey was undertaken utilizing an Internet-based platform to gather responses from individuals representing diverse socioeconomic characteristics in response to the COVID-19 regulations in China. An additional rationale for employing online surveys as a means of gathering data is the cost and time constraints associated with conducting in-person surveys, which may also yield a sample that is not representative of the population under study (Cooper et al., 2012). According to Frankfort-Nachmias and Nachmias (2008), questionnaire surveys require the involvement of skilled interviewers who can pose questions and gather unbiased information. Consequently, substantial investments in training are required to cultivate a proficient team that incurs both temporal and financial expenses. As a result, the decision was made to utilize online data collection methods to enhance the scope of the survey and encompass a more diverse range of participants from various cultural backgrounds.

Thus, information was gathered using an online survey presented to a sample of people recruited in China. Participants were given a link to the survey, which was developed using Google Forms. The samples were screened to evaluate the level of meat consumption. Participants who stated that they did not consume meat” and/or failed the attention and quality check questions were excluded from the study. 4.6% of the respondents stated that they did not consume meat. It was deemed necessary to incorporate a particular level of meat consumption to assess the consumer evaluation and acceptability of PBMA. Following the completion of these tests, the study included 610 questionnaires that were declared complete and acceptable for the analysis.

3.3 Statistical methods

The collected data were analyzed using the structural equation model (SEM) amalgamates the advantageous features of factor and path analysis, thereby resulting in a potent multivariate statistical instrument. The application of Structural Equation Modeling (SEM) is an approach to statistics that facilitates the analysis of the interrelationships among various effects, various influences, and latent variables. It integrates various analytical methods such as analysis of variance, factor analysis, regression analysis, and path analysis (Hair et al., 1998; Byrne and Stewart, 2006; Hair et al., 2006). All variables examined in this study exhibited interrelatedness, either as latent variables or through their interaction. The PLS-SEM methodology is a type of multivariate structural equation modeling that is classified as a second-generation approach. According to research, the use of non-parametric methods in studies with limited sample sizes can eliminate distribution assumptions and yield greater statistical power compared to other methods (Hair et al., 2012). The process of reducing and validating constructs prior to constructing the ultimate structural equation for each obvious variable enables the simple verification of item validity through the use of PLS. Previous literature has established that a minimum of 100 respondents is required to achieve impartial results when utilizing this particular model (Reinartz et al., 2009). Moreover, the adequacy of the respondents for this model was established through Hair et al.’s (2017) ten times rule and G*power. The present study heavily relied on the analytical approach put forth

by Hair et al. (2017). As Chin (2009) indicates, the PLS-SEM methodology consists of a measurement model and a structural model.

4 Results

4.1 Background of respondents

Table 1 shows the respondents’ sociodemographic characteristics. The average age of the respondents was more than 42 years, and a large majority of the respondents were aged between 26 and 50 years. Similarly, a large majority of the respondents had an education level between 10 and 16 years. The average family size was greater than three members in the study area. More than half the respondents participating in this study were married. More than two-fifths of the respondents resided in the rural areas of China. The mean monthly income of respondents was estimated to be more than 12,000 yuan.

4.2 Descriptive analysis of latent variables

Supplementary Table 1 describes the results evaluating various aspects related to the acceptance of plant-based meat alternatives (PBMAA) among consumers for sustainable diets. Regarding PBMA, the findings signify that, on an average, respondents perceived a moderate level of acceptance, with a mean score of 3.72. Notably, a mode score of 4 indicates that most respondents perceived a moderately high level of PBMA acceptance. The results are generally optimistic, with a mean score of 3.98 regarding consumer perception (CPE). This implies that consumers hold positive perceptions of PBMA. A mode of 4 supports this, which describes that most of the respondents indicated positive perception about PBMA. The mean score of 4.50 of strategies for promotion (SFP) signifies the effectiveness of promotional strategies for PBMA as sustainable diets. With a mode of 5, mostly respondents rated SFP with “strongly agree,” which indicates their potential impact on consumer choices for

TABLE 1 Respondents’ background.

Variables	Frequency/Mean
Age	
<25 years	177
26–50	352
>50	81
Mean	42.32 (11.23)
Education	
<10 years	149
10–16 years	442
>16	19
Mean	12.28 (3.21)
Family size (members)	3.57 (0.87)
Marital status (1 = Married)	307
Residential area (1 = Rural)	270
Monthly income (Yuan)	12230.76 (3287.16)

Values in parenthesis are standard deviation.

PBMA. The HPE associated with PBMA are generally positive, with a mean score of 4.06. The mode of 4 and 5 signifies that majority of respondents held optimistic views about the health aspects of PBMA, which highlights the perceived health benefits. Respondents, on average, indicated a moderate level of environmental concern regarding PBMA, with the mean score of 3.28. The responses show notable variation, and the standard deviation indicates that there is some diversity of opinion. AAA had a mean score of 3.68, describes those consumers found modest level of accessibility and availability. The mode of 4 indicates that the majority of respondents rated AAA positively.

4.3 Instruments internal consistency, reliability, and convergence validity

As usual, we used the standard procedure in PLS-SEM to look at a number of factors, such as factor loadings, composite reliability (CR), and average variance extracted (AVE), to find out the convergence validity (CV). The process of conducting a CV involves evaluating the level of agreement among various measurements, primarily through the utilization of factor loadings (FL). Factor analyses (FL) play a crucial role in the field of SEM by providing quantitative assessments of the associations between observable variables and latent factors. Higher factor loadings mean that the measurement is more valid, which makes it easier to figure out how latent variables affect the observed data and find out if the model is good enough. Prior studies have demonstrated that FL values greater than 0.70 are suggestive of a good CV (Bentler and Bonett, 1980; Cheung and Rensvold, 2002). The CV of the items in the current study was confirmed, as all of them had FL greater than the threshold of 0.70. When the mean explained variance is 0.80 or higher, compared to the variance resulting from measurement error, the construct effectively explains a sizable portion of the variance (Steiger, 1989). This shows strong loadings and CV. The statistical importance of each individual statement's FL is shown in [Supplementary Table 2](#). Given that all items displayed factor loadings above 0.70, it is reasonable to infer the existence of CV.

Cronbach's alpha is a statistical measure used to evaluate the internal consistency of a set of items by quantifying the degree of connection among the items within a certain construct. Cronbach's alpha is a common statistical measure used to check the reliability of instruments, especially when measuring effective constructs (Kollmuss and Agyeman, 2002; Frick et al., 2004). According to previous studies (Davis et al., 2011; Levine and Strube, 2012), a minimum alpha value of 0.70 is typically seen as indicative of reliability when assessing latent variables. In the present investigation, it is seen that all constructs demonstrate Cronbach's alpha values are greater than the threshold of 0.70, hence suggesting robust internal consistency and reliability. The findings, as displayed in [Table 2](#), offer strong evidence about the appropriateness of the scale for further research.

Bentler and Bonett (1980), Cheung and Rensvold (2002), and Su et al. (2023) stated that composite reliability (CR) is a better way to measure internal consistency and reliability than Cronbach's alpha because it takes factor loadings for accuracy into account. A CR coefficient of at least 0.60 ensures construct validity (Fornell and Cha, 1994; Cohen, 2013), while CR scores above 0.70 indicate adequate

model fit (Preacher and Hayes, 2004). Model validity is confirmed with a CR value of 0.80 or higher (Steiger, 1989). All constructs in the current study have CR values greater than 0.80, supporting the continuation of the research.

Carlson et al. (2009) came up with Average Variance Extracted (AVE), which is used to find convergent validity. This is similar to how it is measured by observing how well a construct can capture variance as compared to error. To demonstrate a strong CV, AVE values should exceed 0.50. In this study, all AVEs exceed 0.50, indicating robust CV and a substantial amount of variance explained in the observed variables. Consequently, all constructs exhibit strong internal consistency and reliability, which confirms the presence of CV.

4.4 Discriminant validity of measurement model

Discriminant validity (DV) in PLS-SEM distinguishes between constructs, ensuring statements within the model reliably differentiate one construct from others. The Fornell-Larcker criterion (FLC) and the Heterotrait–Monotrait ratio (HTMT) were used to check the DV, as shown in [Table 3](#). To find the Fornell–Larcker criterion, correlation scores between constructs and the square roots of the AVE for each construct are used. According to Rahman et al. (2021), DV is present when the square root of AVE for a construct is higher than its correlation scores with other constructs.

Additionally, HMR values confirm discriminant validity. HMR values below 0.90 indicate strong discriminant validity (Henseler et al., 2015; Rouf and Akhtaruddin, 2018). [Table 3](#) results confirm DV through both the FLC and HTMT analysis. This underscores the need for separate measurement of each construct, as indicators within each construct have stronger associations with their respective construct.

4.5 Goodness of fit of structural model

[Table 4](#) depicts goodness-of-fit parameters' scores for the structural model and compares them with their threshold values. The Chi-Square to Degrees of Freedom ratio is 2.73, indicating an acceptable fit. The GFI is 0.921, indicating a good fit, while the CFI stands at 0.916, supporting a good fit. The AGFI and NFI values above 0.90 signify improvements over the null model. The RMSEA is 0.071, which also ensures an excellent fit. Overall, the structural model aligns well with the data, confirming that the variable relationships are adequately represented.

4.6 Results of structural model

First, the structural model's ability to predict was tested by looking at the coefficient of determination (R^2), which measures how much variation can be explained. [Table 2](#) displays the R^2 values, with all values exceeding 0.63, indicating the strong predictive powers of each hypothesis. We used the nonparametric bootstrapping method described in Wetzels et al. (2009) to test the hypotheses about the relationships between latent variables. This showed that all of the hypotheses were true.

TABLE 2 Direct impact without mediation.

Path	Beta-value	Std. Err.	t-value	f^2	Q^2	R^2	Decision
CPE → PBMAA	0.503	0.084	6.011	0.668	0.446	0.686	Accepted
SFP → PBMAA	0.385	0.065	5.934	0.771	0.464	0.704	Accepted
HPE → PBMAA	0.432	0.103	4.194	0.992	0.287	0.736	Accepted
ENC → PBMAA	0.295	0.084	3.528	0.309	0.473	0.685	Accepted
AAA → PBMAA	0.309	0.048	6.505	0.942	0.316	0.786	Accepted

PBMAA, Plant-based meat alternatives acceptance; CPE, Consumer perception; SFP, Strategies for promotion; HPE, Health perceptions; ENC, Environmental concerns; AAA, Accessibility and availability.

TABLE 3 Discriminant validity of measurement model.

Fornell-Larcker criterion								
	PBMAA	CPE	SFP	HPE	ENC	AAA	CS	ENAT
PBMAA	0.821							
CPE	0.473	0.800						
SFP	0.284	0.184	0.806					
HPE	0.475	0.382	0.473	0.834				
ENC	0.372	0.463	0.298	0.184	0.840			
AAA	0.563	0.392	0.284	0.284	0.284	0.826		
CS	0.281	0.372	0.184	0.285	0.483	0.483	0.826	
ENAT	0.382	0.294	0.382	0.194	0.382	0.362	0.374	0.836
Heterotrait-Monotrait Ratio (HTMT)								
	PBMAA	CPE	SFP	HPE	ENC	AAA	CS	ENAT
PBMAA								
CPE	0.385							
SFP	0.285	0.483						
HPE	0.285	0.385	0.294					
ENC	0.363	0.248	0.195	0.295				
AAA	0.285	0.362	0.483	0.395	0.392			
CS	0.436	0.483	0.364	0.298	0.294	0.385		
ENAT	0.285	0.184	0.274	0.375	0.194	0.294	0.483	

PBMAA, Plant-based meat alternatives acceptance; CPE, Consumer perception; SFP, Strategies for promotion; HPE, Health perceptions; ENC, Environmental concerns; AAA, Accessibility and availability; CS, Consumer satisfaction; ENAT, Environmental attitude.

The coefficient ($\beta=0.503$, $p<0.01$) signifies the strength and direction of the association between consumer perception (CPE) and PBMAA, with a magnitude of 0.503. According to Cohen's categorization (Cohen (2013)), the f^2 value of 0.668 indicates a medium effect size. This suggests that the CPE can account for about 66.8% of the variance in PBMAA. The coefficient score pertaining to the SFP demonstrates a noteworthy beneficial impact on the PBMAA, with a value of 0.385. The f^2 value of 0.771, which indicates the effect size of the SEP in relation to the PBMAA, is significant. The study revealed a favorable and significant impact of the HPE of consumers regarding PBMA on plant-based meat alternative acceptance. The f^2 value indicates a progressively strong effect size. The coefficient ($\beta=0.295$, $p<0.0$) indicates that there is a positive and significant relationship between ENC and the PBMAA. The study evaluated the significant and favorable impact of AAA on the PBMAA, with a beta coefficient of 0.309. The calculated f^2 value for the AAA variable, which is equivalent to 0.942, suggests a substantial and statistically significant

impact on the PBMAA. The predictive validity of all hypotheses has also been confirmed. In order to achieve our objective, we have employed the approach proposed by Fornell and Cha (1994). Q^2 values greater than zero imply considerable predictive relevance.

Table 5 presents the results regarding the mediation effect of consumer satisfaction between CPE and PBMAA and of ENAT between ENC and PBMAA. The direct impact of CS on PBMAA was significant, and the impact of CPE on PBMAA is also significant. Similarly, the impact of ENAT and ENC on PBMAA is also significant, while CS and ENAT are incorporated as mediators. Therefore, the findings signifies that the direct path is significant, and inclusion of mediators are meaningful.

Hence, including consumer satisfaction (CS) and environmental attitude (ANAT) as mediators proves to be meaningful. We needed to find out how important indirect pathways are in order to confirm whether CS and ENAT act as mediators between CPE and PBMAA and ENC and PBMAA. To assess the significance of these indirect paths, we extracted

TABLE 4 Goodness of fit parameters of structural model.

Parameters	Critical values	Computed values
χ^2/df	<3.0	2.830
GFI	>0.90	0.943
CFI	>0.90	0.918
AGFI	>0.90	0.930
NFI	>0.90	0.926
RMSEA	<0.08	0.061

TABLE 5 Mediation effect.

	Beta-value	Std. Err.	t-value	Decision
CS → PBMAA	0.428	0.094	4.540	Accepted
CPE → PBMAA	0.073	0.015	4.893	Accepted
CPE → CS	0.463	0.124	3.734	Accepted
ENAT → PBMAA	0.372	0.048	7.702	Accepted
ENC → PBMAA	0.165	0.032	5.156	Accepted
ENC → ENAT	0.375	0.074	5.061	Accepted

PBMAA, Plant-based meat alternatives acceptance; CPE, Consumer perception; ENC, Environmental concerns; AAA, Accessibility and availability; CS, Consumer satisfaction; ENAT, Environmental attitude.

the bootstrapping sample data and imported it into MS Excel. In this process, we calculated the standard deviation to derive the t-values for the indirect paths. The t-value for the indirect path (CPE → CS → PBMAA) is 3.049 (indirect effect/standard deviation = 0.198/0.065), with a value of $p < 0.01$, supporting the conclusion that CS indeed mediates the relationship between CPE and PBMAA. Similarly, the t-value for the indirect path (ENC → ENAT → PBMAA) is 4.354 (=0.139/0.032), with a value of $p < 0.01$, signifying the meaningful inclusion of ENAT as a mediator between ENC and PBMAA.

Determining the strength of mediation holds significance in our analysis. We use the variance accounted for (VAF) method, which Hair et al. (2012) advise, to assess this. Based on Table 6, the influence of CS can account for 56.436% (VAF = indirect effect/total effect * 100) of the effect of CPE on PBMAA. Given that the VAF surpasses 20% and is less than 80%, it is concluded that CS serves as a partial mediator in this scenario. Furthermore, Table 6 also shows that 45.78% of the effect of ENC on PBMAA is accounted for by ENAT. With the VAF value within the range of 20 to 80%, it indicates that CS partially mediates the relationship between ENC and PBMAA.

5 Discussion

In the pursuit of sustainable diets, understanding consumer choices in the plant-based meat revolution holds significant importance. As society progresses toward a greater emphasis on environmentally sustainable food choices, it becomes evident that consumers significantly influence the transformation toward sustainable food systems. Through an in-depth exploration of the determinants that drive consumer acceptance of PBMA, we acquire significant insights into how to promote and encourage sustainable dietary choices on a broader scale.

The consumer perception has crucial role in influencing the acceptance of PBMA. The way in which consumers perceive these alternatives has a direct impact on their willingness to incorporate them into their diets. Therefore, findings reveals that the consumers perceive PBMA as delicious, high-quality, and satisfying substitutes for traditional meat, they are more likely to adopt them. Thus, the positive perceptions regarding taste and quality play and important role in breaking down initial resistance to trying PBMA as sustainable diets. It is widely recognized among marketers that the manner in which customers perceive the characteristics of an invention can have a significant impact on its rate of acceptance (Pan and Fesenmaier, 2000; Christou and Kassianidis, 2002). Previous studies have identified a notable barrier in the acceptance of PBMA diets among individuals who consume meat, which centers on their perception of substandard taste (Hoek et al., 2011; Pohjolainen et al., 2015; Bryant, 2019). There is a prevailing view among individuals that meat-based goods possess a more desirable taste in comparison to PBMA. This perception remains consistent even in the situation where consumers are provided with evidence indicating that all products have a similar taste (Van Loo et al., 2020; Michel et al., 2021). In spite of subjective taste preferences, individuals who regularly consume meat often perceive plant-based diets as comparatively less satisfying and nutritionally complete in comparison to meals that include meat (Kildal and Syse, 2017; Michel et al., 2021).

The findings of the study also revealed that promotional techniques have a significant influence on the adoption and acceptability of PBMA. There are various promotion strategies that can affect the acceptability of PBMA and transition toward sustainable food systems. The strategies include measures such as enhancing the availability of PBMA in restaurants and fast-food chains, adopting discounts and promotional offers on PBMA products, carrying out educational campaigns to emphasize the benefits of PBMA, and employing effective packaging and labeling strategies that will positively affect consumer behavior. These promotional strategies align with consumer preferences and their decision-making processes, and they also reflect their level of awareness and perception of credibility. According to study findings, it can be inferred that an effectively designed promotional strategy holds the capacity to considerably accelerate the adoption and uptake of PBMAA. Consequently, this can play a pivotal role in fostering the acceptance of more environmentally sustainable dietary choices on a broader scale. The utilization of price promotion as a marketing tactic has been extensively employed to enhance consumer usage experiences and attract new customers during the initial phase of product introduction (Zhang et al., 2020). This approach involves a temporary reduction in the unit price of a certain product. Price markdown is a prevalent strategy employed in the field of price promotion. The enactment of nutrition labeling on food products has been a major strategy for promoting healthy dietary choices (Cowburn and Stockley, 2005). According to Feunekes et al., 2008, required nutrition labels serve as a health education intervention that has a wide scope of influence. These labels are prominently displayed at the moment of purchase and also during food preparation and consumption. Previous studies have demonstrated that the utilization of simplified labels has a positive impact on enhancing the precision of individuals' nutrition assessments of unhealthy items (Finke, 2000). Nutrition labels are commonly perceived as a reliable and authoritative means of obtaining information, and a considerable portion of

TABLE 6 Mediation analysis.

Path	Coefficient	Indirect effect	Sta. Dev.	Total effect	VAF (%)	t-value
CS → PBMAA	0.428	0.428*0.463 = 0.198	0.065	0.152 + 0.198 = 0.351	(0.198/0.351) *100 = 56.436	3.049
CPE → PBMAA	0.153					
CPE → CS	0.463					
ENAT → PBMAA	0.372	0.372*0.375 = 0.139	0.032	0.165 + 0.139 = 0.304	(0.139/0.304) *100 = 45.780	4.354
ENC → PBMAA	0.165					
ENC → ENAT	0.375					

PBMAA, Plant-based meat alternatives acceptance; CPE, Consumer perception; ENC, Environmental concerns; CS, Consumer satisfaction; ENAT, Environmental attitude.

consumers depend on them to guide their decision-making process when purchasing food items. The existing body of evidence consistently indicates a favorable correlation between the implementation of successful promotional methods and the adoption of healthy food patterns (Campos et al., 2011).

The perception of a person's health significantly impacts the acceptance of PBMA. The inclination toward PBMAA among individuals who prioritize their health is substantiated by its perceived positive impact on health, which encompasses lower levels of saturated fats and cholesterol, alongside a rich content of essential nutrients. The attractiveness of PBMAA is strengthened by the perceptions that it contributes to general health, aids in weight management, is easily digestible, and has a good impact on heart health. The importance of acknowledging PBMAA as a preferable alternative for mitigating foodborne illnesses cannot be overstated, particularly for customers who prioritize safety. The general perception of PBMA as a more sustainable diet alternative, as shown by the scale, highlights its potential for widespread acceptance, especially among individuals who prioritize their health and nutritional needs in their eating habits. Over the past five decades, there has been a growing emphasis on the significance of health in relation to consumers' selection of food. Studies examining consumer perceptions of food quality reveal that both health and sensory factors hold approximately similar significance (Grunert, 2006). According to Bucher et al. (2015), a research investigation was conducted to examine the perception of the nutritional value of soft drinks. The study revealed that the presence of fruit in soft drinks was positively correlated with the perception of healthiness, however higher levels of sugar concentration and fat contents were negatively linked with healthiness perception.

The acceptance of PBMA is notably influenced by environmental concern. Consumers conscientiously take into account the environmental consequences of their dietary decisions, which encompasses the contribution of PBMA in transition toward sustainable food systems. Moreover, consumers are swayed by overarching ENC, such as the greenhouse gas emissions stemming from the food business. The users' inclination to actively seek information regarding the environmental advantages of PBMAA and their willingness to pay a premium for sustainable alternatives highlights the significance of sustainability. The conviction on the positive impact of PBMA on the preservation of natural resources serves to strengthen their attractiveness. Furthermore, it is evident that consumers exhibit a proactive approach in their quest of ecologically sustainable products when engaging in grocery shopping, so emphasizing their dedication to making eco-conscious decisions.

In conclusion, the consideration for the environment significantly influences the acceptance and desire for PBMA, particularly among persons who prioritize sustainability and choose to match their dietary choices with eco-conscious behaviors. The literature suggests that there is a connection between ENC and consumers' pro-environmental actions aimed at protecting the environment (Cruz and Manata, 2020; Molinillo et al., 2020; Kumar et al., 2021). Additionally, it has been observed that consumers are motivated to choose products that incorporate natural elements, as indicated by their preference for natural content (Molinillo et al., 2020). The findings of our study align with the research conducted by Cheung and To (2019), which demonstrated that individuals who are environmentally concerned tend to engage in natural consumption habits as a result of their ENC. It is anticipated that consumers who possess an increased consciousness of environmental concern will exhibit a preference for products that are environmentally friendly (Essoussi and Zahaf, 2008). According to the findings of Lin and Huang (2012), there exists a positive relationship between individuals' level of environmental concern and their inclination toward selecting and adopting green products.

The acceptance and preference for PBMA are greatly influenced by the factors of AAA. The influence of PBMA's availability in local grocery stores on purchase decisions highlights the significance of retail accessibility. The presence of plant-based menu options in restaurants serves as a catalyst for the increased selection of PBMA, when individuals choose to dine out. The convenient availability of PBMA in local retail establishments is indicative of its easy accessibility. The deliberate pursuit of plant-based eating alternatives and their favorable consequences in preferred restaurants highlights the significance of accessibility in influencing individual preferences. The criteria associated with AAA play a critical role in determining the acceptance of PBMA, hence emphasizing the need for their widespread availability. There is an increasing body of evidence suggesting that the availability of healthier food options plays a significant role in influencing individuals' eating choices (Delva et al., 2007). The interconnection between food accessibility, availability, and choice is undeniable. The purchasing options for consumers are limited to the products that are both accessible and available to them. Consequently, regardless of an individual's level of nutrition knowledge or income, the selection of food is ultimately determined by the availability of food items. The significance of "food selection" outweighs that of "food choice" due to the limited options available to consumers, who can only select from the products offered in the accessible stores (Furey et al., 2001; Bustillos et al., 2009).

The mediating role of consumer satisfaction in the relationship between consumer perception and acceptance of PBMA is highly significant. Consumer perceptions about PBMA have a significant effect on consumer attitudes and choices toward PBMA. Positive perceptions regarding taste, nutrition, and sustainability enhance the likelihood of PBMA's acceptance (Hoek et al., 2011). Simultaneously, consumer satisfaction plays a pivotal role because it is rooted in post-purchase experiences (Oliver, 1980) and alignment with expectations. Therefore, when PBMA meets or exceeds the expectations of consumers, it fosters their satisfaction and ultimately reinforces the acceptance process. These findings highlight the significant impact of consumer perception and their satisfaction in driving the acceptance of PBMA, with extensive implications for sustainable diets and the food industry.

The research has identified the noteworthy mediation function of environmental attitude in the relationship between consumers' ENC and their acceptance of PBMA. The significance of one's environmental attitude, including personal beliefs and concepts related to ecological sustainability, is pivotal in influencing one's desire for accepting PBMA. Consumers that possess a favorable environmental attitude are more likely to choose PBMA owing to their less ecological impact as compared to traditional meat products. Furthermore, the acceptability of PBMA is influenced by environmental concern, which is rooted in an increased knowledge of pressing environmental issues and a personal dedication to minimizing one's carbon footprint. As the level of environmental consciousness among individuals increases, there is a greater propensity for them to select sustainable dietary options such as PBMA. The study conducted by Sadiq et al. (2020) has demonstrated that dietary habits, which are impacted by environmental considerations, have the potential to contribute to climate change (Carlsson-Kanyama and González, 2009). The prior research by De Boer et al. (2014) emphasized the importance of changing Western meat consumption patterns for better health outcomes and address environmental issues (Sarigöllü, 2009; Pavalache-Ilie and Cazan, 2018). Similarly, studies have reported that individuals with higher ENC are more likely to develop positive environmental attitudes. This positive attitude toward environment can influence their food choices (Verain et al., 2015). Collectively, these characteristics underscore the crucial significance of environmental attitudes and concerns in facilitating the acceptance of PBMA. This alignment of consumer behavior with eco-conscious dietary choices and the promotion of sustainable food practices is emphasized.

Although this study presents valuable insights for policymakers and meat consumers, it is not without limitations. First, sampling bias may arise due to an online data collection method, which can be a complex task to address when attempting to obtain a representative sample of the Chinese population owing to its extensive and heterogeneous demographic composition. Second, it is important to consider the potential impact of the social desirability bias on respondents' answers. This tendency may lead individuals to submit responses that they perceive as socially acceptable, rather than expressing their genuine beliefs. Consequently, this could result in overestimation of the reported levels of acceptance of PBMA. Finally, the ever-changing nature of consumer preferences and swiftly growing culinary trends in China may result in the data soon becoming outdated, thus restricting its long-term applicability of study

findings. The future studies may conduct comprehensive face to face interviews to gain a deeper understanding of the cultural and contextual elements that influence the reception of PBMA in different areas of China.

6 Conclusions and policy recommendations

In today's pursuit of sustainable dietary choices and a sustainable food system, comprehending the consumer behaviors and preferences in the context of the plant-based meat revolution is of paramount importance. The transformation toward sustainable food systems toward more environmentally conscious and sustainable practices significantly depends on the consumers behavior and their dietary choices. Hence, a comprehensive exploration of the factors influencing consumer acceptance of PBMA not only elucidates the factors driving this transformation but also offers valuable insights into how we can promote and encourage sustainable dietary choices on a broader spectrum.

This study highlights the significant impact of consumer perceptions, particularly regarding taste, texture, nutritional value, and prices, on the acceptance of PBMA. It is imperative to address the problems associated with taste and nutritional value in comparison to conventional meat. Effective promotional strategies significantly influence the acceptance of PBMA. The convenient availability and accessibility of PBMA play a crucial role in shaping individual dietary cultures. Moreover, this study sheds light on the importance of health consciousness and environmental concern in forming consumer preferences for PBMA, highlighting the role of HPE and sustainability in dietary decision-making. Additionally, the mediating role of consumer satisfaction and connecting consumer perception reinforces PBMA acceptance. Moreover, the study underscores the mediating role of environmental attitude, which establishes a connection between ENC and the acceptance of PBMA, underscoring the importance of sustainable dietary choices. Therefore, comprehending these aspects is essential for promoting sustainable dietary choices and transforming the food industry to align with evolving consumer preferences and ecological concerns.

In order to facilitate the widespread acceptance of PBMA and encourage sustainable dietary choices, a multifaceted approach is essential. Food manufacturers should emphasize improving the sensory attributes and nutritional value of PBMA while using effective promotion strategies that highlight aspects including taste, texture, health benefits, and sustainability. Widespread availability of plant-based meat alternatives in fast-food chains, restaurants, and grocery stores, along with clear and comprehensive nutrition labeling, can increase accessibility and enable individuals to make well-informed decisions. It is recommended that educational campaigns be initiated, particularly those promoting the environmental benefits of PBMA, in order to reshape consumer perceptions. The acceptance of PBMA will be driven collaboratively by collaboration among industry stakeholders, environmental organizations, and governments, as well as through consumer engagement and research and development activities. In essence, this collaborative effort has the potential to enhance the sustainability of the food system by aligning consumer behavior with environmentally conscious decisions and transforming

the food industry to accommodate evolving consumer behavior and ENC.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Wuhan Business University, Wuhan, China. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

SE: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. SQ: Conceptualization, Formal analysis, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. LW: Data curation, Formal analysis, Methodology, Writing – review & editing. MD: Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

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The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2023.1315448/full#supplementary-material>

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