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Current practices and key challenges associated with the adoption of resilient, circular, and sustainable food supply chain for smallholder farmers to mitigate food loss

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Introduction: In response to increasing global food insecurity, resilient, circular, and sustainable practices hold significant potential to enhance food supply chain performance and reduce food loss. This study examines the current practices and key challenges faced by Peruvian smallholder farmers in managing a resilient, circular, and sustainable food supply chain, proposing a hybrid model that integrates ancestral agricultural knowledge with modern innovations.

Methods: Using a qualitative approach, in-depth interviews were conducted with 16 smallholder farmers from various regions of Peru. Participants were selected through purposive sampling, focusing on farmers who apply organic agricultural techniques. Data were analyzed using content analysis techniques supported by ATLAS.ti 23 software to identify patterns in practices and challenges.

Results: The findings reveal that farmers operate within short supply chains, without intermediaries, applying intuitive practices aligned with circular economy principles, including Rethink, Redesign, Reduce, Replace, Reuse, Repurpose, and Recycle, but excluding Recovery. While social and economic dimensions are prioritized, current practices are insufficient to ensure long-term sustainability. Key challenges include technological limitations, restricted market access, and low consumer awareness.

Discussion: A hybrid model is proposed, combining resource-efficient technologies with culturally rooted practices, fostering multi-stakeholder collaboration. This approach addresses identified gaps and contributes to food security, environmental sustainability, and the achievement of Sustainable Development Goals 1 (No Poverty), 2 (Zero Hunger), and 12 (Responsible Consumption and Production).

KEYWORDS

resilience, circular economy, sustainability, hybrid model, food loss, food supply chain, smallholder farmers, ancestral agricultural practices

1 Introduction

The convergence of climate change, pandemics, and geopolitical conflicts is continuously straining vital resources, including food, water, material, and energy, placing the agricultural system at significant risk (Galanakis et al., 2022; Farooq et al., 2022; Saxena et al., 2018). Global crises, such as COVID-19, have exposed vulnerabilities in the global food system, emphasizing the need for resilience through multi-level approaches that engage all stakeholders (Alam et al., 2023; Boyacı-Gündüz et al., 2021). Conflicts like the Russia-Ukraine war have exacerbated food insecurity since 2022 by disrupting global markets for fertilizers and agricultural commodities (Esfandabadi et al., 2022; FAO, 2022a,b).

These disruptions have intensified food prices and reduced access, especially in low-income, food-deficit countries (FAO et al., 2024). In parallel, food waste persists as a global issue: in 2022, 19% of food available to consumers was wasted, with Latin America and the Caribbean contributing 6% of this total [United Nations Environment Programme (UNEP), 2024]. Economic shocks and extreme weather events further heighten vulnerabilities [United Nations Environment Programme (UNEP), 2024]. In regions like Latin America and the Caribbean, where smallholder farmers form the backbone of the agricultural economy, these challenges are particularly acute, yet the strategies these farmers employ to mitigate them remain underexplored (Galanakis, 2023).

Smallholder farmers are critical to global food security. However, environmental, economic, and social disruptions exacerbate their vulnerability, leading to considerable food losses [FAO, 2019; United Nations Environment Programme (UNEP), 2021]. Ancestral agricultural practices, passed down through generations, emerge as alternative solutions by combining sustainable resource management with cultural values. These practices enhance resilience to climate change and environmental degradation, while ensuring ecological, cultural, and social sustainability (FAO, 2023). Nevertheless, these traditional methods alone are insufficient to address the complexities of modern food systems. A hybrid model that integrates ancestral knowledge with modern technologies can preserve cultural strengths while improving productivity, resource efficiency, and resilience (FAO, n.d.).

This highlights the urgent need to transform food systems toward greater sustainability and resilience (Galanakis et al., 2021; Seekell et al., 2017). Circular economy (CE) models for production and consumption offer a promising pathway (Weetman, 2019). Transforming food supply chains (FSCs) to reduce volatility and build resilience is especially crucial for traditional and transitional FSCs, which are disproportionately impacted by external shocks (FAO et al., 2024; Galanakis, 2023).

Despite extensive research on broader food loss challenges and CE models, a significant gap remains in understanding how smallholder farmers integrate resilient, circular, and sustainable practices to mitigate food loss, particularly involving all stakeholders in the FSC (Ume et al., 2023; Boyacı-Gündüz et al., 2021; Devereux et al., 2020). This gap is especially evident in countries like Peru, where agricultural practices are deeply rooted in local traditions.

This research addresses this gap by examining the current practices and challenges faced by Peruvian smallholder farmers in managing a resilient, circular, and sustainable FSC to mitigate food loss. The study proposes a hybrid model that integrates ancestral agricultural practices with modern innovations, offering a balanced approach to address these challenges effectively. The study offers actionable insights for policymakers and stakeholders to enhance food security and sustainability. A qualitative research approach is employed to provide a rich, contextual understanding of farmers' experiences.

The paper is structured as follows. Section 2 reviews existing research on resilient, circular, and sustainable supply chains in smallholder farming. Section 3 outlines the study's qualitative approach. Section 4 presents findings on current practices and key challenges. Section 5 discuss implications for policy and practice. Section 6 concludes with key insights, while Section 7 identifies limitations and directions for future research.

2 Literature review

2.1 The resilient, circular, and sustainable food supply chain

The resilience of FSCs refers to their capacity to maintain functionality by mitigating damages and adapting to disturbances (Galanakis, 2023). Resilience plays a critical role in reducing the impacts of major disruptions, such as climate change, pandemics, and conflicts. Discussions on resilience strategies emphasize the need for transformative, inclusive, and knowledge-based approaches (Leach et al., 2020), which allow for the identification of actions and initiatives to strengthen food system resilience (Agyemang and Kwofie, 2021). These strategies are categorized into proactive, reactive, and recovery approaches: proactive strategies focus on preparation and mitigation before disruptions, while reactive strategies aim to restore systems to their original state (Gunessee and Subramanian, 2020; Kumar et al., 2022).

The CE is an economic model designed to redefine the relationship between society and nature by curbing resource depletion, promoting energy efficiency, and closing material loops to foster sustainable development (Ormazabal et al., 2018). CE initiatives address externalities caused by resource loss and waste, ensuring that materials re-enter the economy or are used more efficiently (Gedam et al., 2021; UNCTAD, 2018). In the context of FSCs, circularity is operationalized through the 8R framework: Rethink, Redesign, Reduce, Replace, Reuse, Repurpose, Recycle, and Recovery (Vlajic et al., 2021), which aligns closely with the practices of smallholder farmers (Ali et al., 2021).

Sustainable agri-food systems integrate environmental, economic, and social dimensions to deliver food security and nutrition for both current and future generations (Neven, 2015). According to The Food and Agriculture Organization (FAO, 2021) five fundamental principles underpin sustainability: (1) increase productivity; (2) protect and enhance natural resources; (3) improve livelihoods and foster sustainable economic growth; (4) enhance the resilience of people, communities and ecosystems; (5) adapt governance to new challenges.

Carter and Rogers (2008) define sustainable supply chain management (SSCM) as the transparent integration of environmental, social, and economic goals into inter-organizational processes to enhance long-term performance. SSCM balances three interdependent pillars—environmental, social, and economic performance—known as the triple bottom line (Bressanelli et al., 2018; Ocicka and Razniewska, 2018). These pillars are supported by facets such as risk management, transparency, culture, and strategy, which are interconnected and essential for achieving sustainability. Additionally, fostering consumer education and promoting informed purchasing behaviors are crucial for reducing waste and driving sustainable (Schmitt et al., 2021). Collaborative strategies and collective efforts, especially during crises, are key to addressing vulnerabilities and fostering innovation (Tolotti et al., 2022).

The integration of CE and sustainability—known as Sustainable CE—delivers macro-level benefits, such as resource efficiency, energy recovery, continuous economic growth, and circularity in production systems (Elia et al., 2020; Sehnem et al., 2019). Resilient agri-food systems ensure access to safe, nutritious food while safeguarding the livelihoods of stakeholders, even in the face of disruptions (FAO, 2021).

Resilient, circular, and sustainable FSC systems may rely on both ancestral practices and modern technologies to address current challenges. For example, circularity practices inspired by natural systems enable nutrient management strategies that leverage eco-innovation, contributing to the sustainable transformation of the agricultural sector (Kuppan et al., 2024). Regional ancestral cultures embed sustainability as a guiding principle, offering a perspective that transcends the triple bottom line (Bravo et al., 2022). Products originating from ancestral agroforestry systems have high potential for access to specialized markets due to their cultural value, biodiversity, and sustainable practices (Salazar et al., 2023). The adoption of modern technologies and digitalization can promote the transition to a sustainable circular economy by closing material cycles, reducing resource consumption, and improving efficiency (Antikainen et al., 2018; Bressanelli et al., 2018; Kayikci et al., 2021; Zhang et al., 2019).

Resilience and sustainability efforts require localized and context-specific approaches, particularly in the context of small-scale food producers in developing countries such as Peru. Smallholder practices have demonstrated the capacity to improve family resilience through regenerative agriculture (Jezeer et al., 2018; Kristjanson et al., 2007), diversify agricultural production while balancing forest conservation (Andrieu et al., 2019), and alleviate poverty by increasing rural household incomes and enhancing their capacity to face climate change challenges (Jezeer et al., 2018; Kristjanson et al., 2007). These dynamics highlight how smallholder farmers effectively balance economic and ecological objectives in vulnerable environments, tailoring their efforts to specific contexts and available resources.

Organic agriculture is recognized as a promising sustainable agricultural system, particularly in developing countries, due to its significant positive impact on food security, regardless of market orientation (Ume, 2023). Ancestral practices such as the Peruvian ayni and minka, along with traditional agricultural techniques like terraces and crop rotation, strengthen social cohesion, foster community resilience, and promote sustainability in response to natural disasters and climate change. These practices integrate rituals honoring the Pachamama and revitalize indigenous knowledge to preserve cultural heritage while adapting to modern challenges (FAO, 2023; Zeballos-Velarde et al., 2023).

The integration of local knowledge with modern innovations—as suggested by FAO (n.d.)—emerges as a key solution to address the challenges of resilient, circular, and sustainable food systems. A hybrid model that combines resource-efficient technologies with culturally rooted, sustainable practices aligns with resilience strategies, circular economy principles, and sustainability dimensions. This approach not only mitigates external disturbances but also preserves cultural heritage and fosters long-term resilience across environmental, social, and economic dimensions.

2.2 Smallholder farmers supply chain and the food loss mitigation effort

The traditional supply chain presents problems and challenges in terms of the use of technical, biological, energy, and water resources (Weetman, 2019). However, by understanding the different stages and elements of the supply chain, it is possible to develop more successful and sustainable long-term solutions, which not only reduces waste (Vieira et al., 2018) but also contributes to the eradication of poverty (SDG 1), the end of hunger (SDG 2), and responsible consumption and production (SDG 12).

However, due to the complexity of the FSC, its study represents a great challenge for both researchers and practitioners (Raak et al., 2017). Then, in the management environment there is a growing trend to analyze the agri-food product cycle from production through the supply chain (Albisu, 2016), which includes the stages of production, post-harvest handling, processing, storage, trade, distribution, packaging, and wholesale and retail sale of food (FAO, 2014).

Smallholder farmers consist of households operating crop-based small-scale farming enterprises, whose operation experiences have greater constraints due to their limited access to markets and resources such as land, water, information, technology, capital, assets, and institutions (FAO, 2021). Therefore, management in the context of small-scale food producers requires adaptations related to the understanding of practices due to both their constraints and differences.

Food loss is represented by the decrease in the quantity or quality of food due to the decisions and actions of suppliers at all stages of the FSC (FAO, 2019). Therefore, to identify and model the food loss drivers in the different stages of the supply chain of smallholder farmers, it is relevant to consider aspects such as technological and environmental, improper practices, inadequate marketing systems and information insufficiencies, and insufficient infrastructure and governmental regulations (Ali et al., 2021; Herczeg et al., 2018)—as shown in Figure 1.

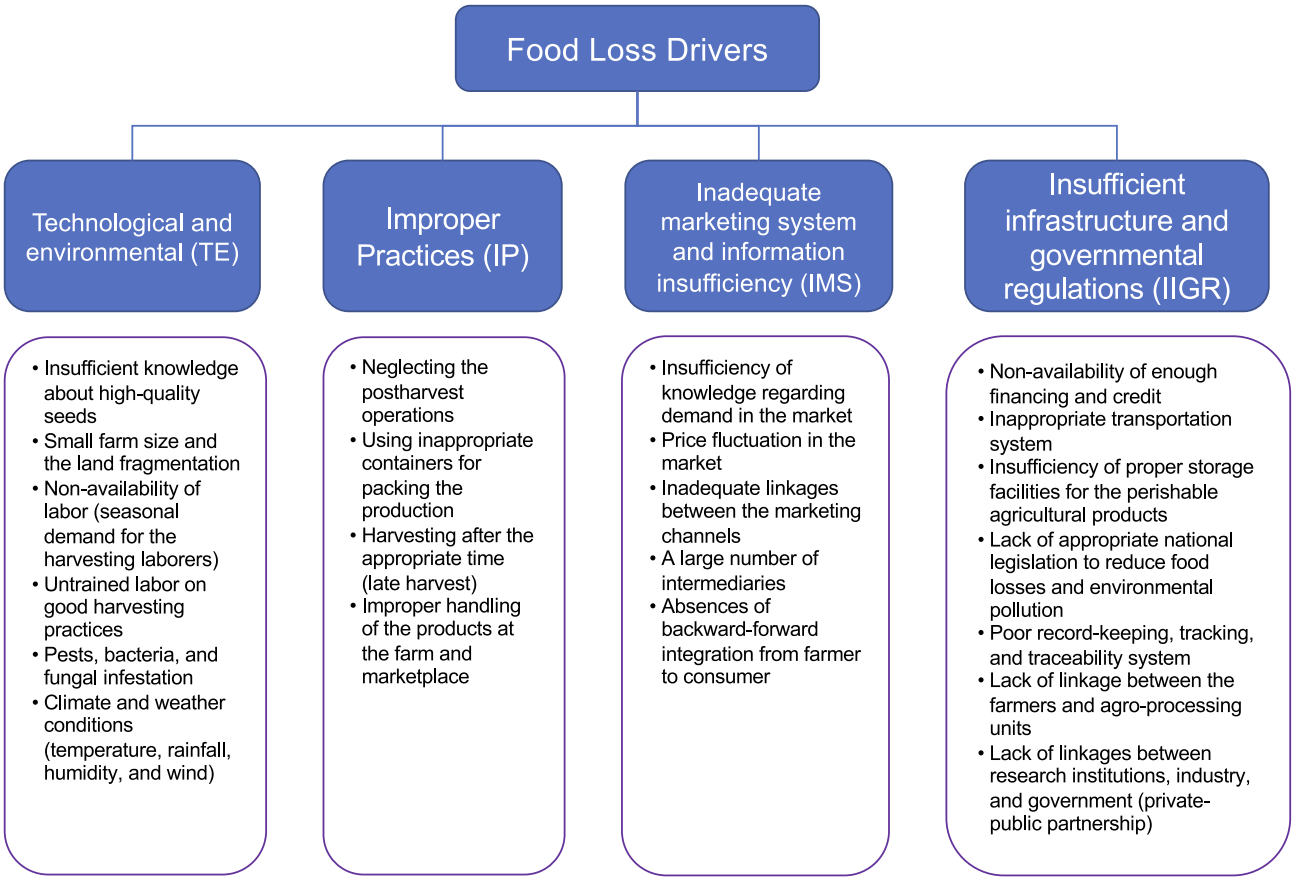

FIGURE 1
Food loss drivers in the food supply chain of smallholder farmers. Source: Adapted from Ali et al. (2021) and Herczeg et al. (2018).

3 Methods

3.1 Research design

This study adopts a qualitative research design with a descriptive and interpretative approach, aimed at understanding the experiences and perspectives of smallholder farmers (Creswell and Creswell, 2018; Hennink et al., 2020; Verd and Lozares, 2016). The choice of a qualitative design is grounded in the study's objective to explore complex, context-specific practices and challenges that are not easily captured through quantitative measures. Given the limited prior research on this topic, particularly within the Peruvian context, a qualitative approach is particularly well-suited for capturing the depth and richness of the farmers' lived experiences, which are essential for developing a nuanced understanding of the strategies they employ in managing resilient, circular, and sustainable FSCs.

3.2 Participants

The sample was selected using purposive sampling (Tracy, 2019) which involved 16 smallholder farmers who met specific inclusion criteria: (1) owners of farming businesses that sell their own produce, (2) aged over 18 years, and (3) willing to participate in the interview voluntarily. Exclusion criteria included family members not involved in agricultural production and sellers without ownership roles. These smallholder farmers represent diverse production units and were chosen from three different farmers' markets in Lima, Peru: Agroferias Campesinas, Ecoferia de Miraflores, and Feria de Barranco. These markets, collectively, group 110 smallholder farmers, of whom ~30% sell in more than one market. Farmers associated with these markets have been pre-verified as practitioners of organic and ecological agriculture techniques, although they do not hold formal certifications.

This purposive sampling approach ensured the inclusion of farmers from diverse regions of Peru, capturing a broad spectrum of agricultural practices and challenges. The selection reflects key characteristics of smallholder farming in Peru, such as reliance on ancestral techniques, short supply chains, and the integration of agroecological practices tailored to regional contexts. Additionally, the number of participants in this qualitative study was intentionally determined to facilitate an in-depth exploration of context-specific phenomena and to identify emergent patterns within complex agricultural systems (Creswell and Creswell, 2018; Hennink et al., 2020).

3.3 Data collection

Data were collected cross-sectionally at a single point in time, using in-depth semi-structured interviews. The interviews were conducted *in situ* at the farmers' stands during market hours, allowing for a naturalistic observation of their practices. The semi-structured format provided flexibility to explore emergent themes while ensuring coverage of key topics. Each interview lasted 45 min, and all interviews were audio-recorded with the participants' consent. Informed consent was obtained prior to the interviews, with assurances of confidentiality and anonymity.

The semi-structured interview guide was designed to ensure accessibility and comprehension by the participants. Complex terminology, such as circular economy, was deliberately avoided to minimize misunderstanding. Instead, the questions were framed in practical and accessible terms, focusing on participants' daily practices both on the farm and at the market stalls. For example, participants were asked: How do you handle leftover crops or materials from the farm to the market stall?, How do you manage unsold products at the end of the day?. What types of fertilizers do you use in your farming activities, and how do you decide which ones to apply?. Follow-up questions were used to explore emerging themes and ensure in-depth responses, capturing the participants' practices and experiences.

3.4 Data analysis

A total of 16 interviews were conducted; however, due to high levels of ambient noise in the market settings, four interviews could not be transcribed. To address this limitation, detailed notes taken during these interviews were incorporated into the analysis to ensure their inclusion and provide additional context. The remaining 12 interviews were fully transcribed and analyzed using content analysis techniques (Bardin, 2016; Kuckartz, 2019), facilitated by ATLAS.ti 23 software.

The analysis followed an iterative and systematic approach, aiming to identify recurring patterns and themes related to smallholder farmers' practices and challenges. Coding was conducted both inductively, allowing for the emergence of novel themes, and deductively, guided by predefined analytical categories (Babbie, 2021): (a) structure of smallholder farmers' supply chains, (b) current practices, (c) resilience initiatives, (d) application of CE through R principles, (e) sustainable practices, and (f) key challenges in adopting resilience, circularity, and sustainability. Data saturation was reached after analyzing 10 interviews, with two additional interviews included to ensure comprehensive thematic coverage. To enhance the validity and reliability of the findings, methodological triangulation was employed (Cypress, 2017; Yin, 2005). This included integrating data from transcribed interviews, field notes, and direct observations conducted during the interviews at the market stalls.

4 Results

4.1 Structure of smallholder farmers food supply chain

The structure of the FSC of smallholder farmers has several stages: planting in small farms, harvesting, transportation, direct sales in farmers markets and consumers. In addition, to diversify their products, a phase of collection of fruits and vegetables from other small-scale producers was identified.

4.1.1 Food in farm stage

The first stage is characterized by artisan production, without the use of pesticides or industrial fertilizers, following Andean ancestral practices passed down from generation to generation; hence farmers referred to their products as organic. The process begins with the selection of seeds, chosen and preserved by the producers themselves year after year, which are exchanged with the neighbors, and they agree not to plant the same ones and thus have a variety of products. The whole family group works in this process, serving as training for the younger ones as a way of transferring the ancestral cultural methods of planting. Live fences are used to protect crops from pests and adverse weather conditions. Irrigation is a critical issue for them because water availability is reduced in these areas. Compost is produced by themselves using the composting technique. However, sometimes some specific nutrients are needed but farmers do not have access or cannot afford it.

To preserve and not exhaust the land, crop rotation is practiced. The harvest is carried out with the intervention of the entire family group. Women work in the fields carrying the youngest children on their backs (a traditional practice in the region) and the older children stay close to their mothers. In general, small-scale producers do not have machinery, as such, all the work is done manually.

4.1.2 Food harvested

This stage consists of harvesting, handling, sorting and selecting products to meet consumer requirements in terms of size, appearance, shape, and freshness. For the disposal and storage of products, farmers use rustic containers, made by themselves, with materials available on their farms. Once harvested, the products are stored in barracks or small improvised warehouses on their farms. In some cases, between the second and third stages, the activity of incorporating food collected from other smallholders can be added, thus smallholders collect the products of other smallholders to have a variety of products. The harvesting process is manual and carried out by the family group.

4.1.3 Food transported

Once all the marketable production is sorted, trucks are used to take products from the farm to the urban area, and then taxis and small cars are used to take it to the farmers markets. In general, the types of transport available do not have adequate conditions to

protect the food from climatic conditions or the proper ventilation and refrigeration to transport delicate and perishable products.

4.1.4 Food sold

The FSC of small-scale producers is short and without intermediaries. Marketing is characterized by the producers selling their own products in farmers markets, organized on weekends in different districts of the city of Lima and located in strategic parks or crowded areas that are easily accessible to the public.

4.1.5 Consumers

The consumers are generally characterized by housewives or customers who buy for home consumption and live near the farmers markets. Consumers tend to appreciate organic products but are unaware of their benefits for healthy eating. They are also not familiar with the idea that organic products mature faster or may have different visual and aesthetic characteristics and cost more to produce.

4.2 Current practices in smallholder farmers food supply chain

4.2.1 Main drivers of food loss

Among the current practices of smallholder farmers, food losses are generated at all stages of the FSC, and the main drivers were identified using the framework stated in Figure 1. *The primary cause of food loss in farm stage* is the lack of technology and sustainability in the long term. Parents and older adults transfer ancestral knowledge to their young children thereby over time they learn to sow in the traditional way and to use natural repellents. Also, the crop fields are small plots that limit the use of machinery, equipment, and technologies.

Government support is lacking, hindering technified production and increasing production costs. Training programs for technified production are not developed and small-scale producers do not have access to loans. The costs of permits and sanitary registrations are the same for a small or large farmers and the small farmers cannot absorb these high costs because they are individual non-associated production units. Besides, climate affects the volume of production as crop fields are affected by frost and snowfall, rain, excessive heat, or landslides.

Additionally, farmers are mostly elderly, and it is difficult to find workers because young people prefer to work in informal activities to generate more income in the short term, to study a major in urban areas, and believe that migrating to the city improves their life and social status, configuring a potential risk to lose the ancestral knowledge.

Food loss during the harvest stage complicates the accurate estimation of yield due to variations in product weight resulting from different production processes and the impact of weather conditions. This issue is particularly pronounced for organic products, which experience higher levels of loss. Mistreatment during handling due to the use of traditional manual techniques or harvesting by people without proper training in the use of tools and technology. The rustic containers where they are stored do not offer adequate protection from weather conditions. Also, part of the harvested products do not meet the aesthetic standards to be marketed, generating a loss that is used for their own consumption, animal feed or compost.

The food loss in transportation occurs because small-scale producers face the following difficulties in transporting their products (a) in rural areas surrounding farms, there is neither adequate nor sufficient storage and transportation infrastructure, public or private; (b) farmers do not qualify for working capital loans or real estate; (c) procedures are cumbersome and costly; (d) many times, to avoid losing products, producers are forced to sell to the wholesaler, even when the latter pays them quite low prices. These situations mean that many small-scale producers prefer to sell their products to other small-scale producers to obtain a better price and reduce their losses.

In addition, the climate affects the quality of the products transported, causing them to lose weight and generating losses because when they are moved manually from one transport to another they are mistreated; farmers do not have warehouses in transit or in the farmers markets; farmers use rustic containers unsuitable for the shape or size of the product; the trip from the farm to the city takes long hours and is done in unsuitable vehicles for loading foodstuffs.

The losses at the stage of food sold by the producer are generated by making manual forecasts of the quantity of products to be sold in the farmers markets. In addition, organic products have the characteristic of requiring a shorter period between harvest and consumption and because food is stored in rustic containers precariously protected to avoid exposure to extreme weather conditions. Another difficulty is that these products are perishable and need to be sold before deteriorating and generating loss; however, the possibility to sell them is limited to only 2–3 times a week in the farmer markets; therefore, if it is not sold in time, the food is lost.

The losses at the consumer stage are generated by the lack of consumer knowledge about the implications of organic production, the search for products with an aesthetically perfect appearance and size and the short consumption period. Moreover, buyers are not willing to pay more for organic products that have higher production costs and selling prices than industrialized products, even less so when prices may increase due to climate changes and seasonality. In addition, producers may mention that their products are organic but generally cannot formally confirm this because certification costs are expensive and unaffordable.

The emerging findings, identified as novel themes beyond the predefined analytical categories, were categorized by the research team. These findings include the transfer of ancestral knowledge for family labor and shrinkage, which were classified as technological and environmental factors, respectively. Additionally, buyer rejection based on visual and aesthetic characteristics, as well as the mismatch between organic certification and profits, were identified by the research team as indicators of an inadequate marketing system and information insufficiency. Finally, insufficient infrastructure and the lack of alignment with governmental regulations were grouped under infrastructure and policy-related factors.

4.2.2 Resilience strategies

In contexts of crisis and amplified vulnerability, smallholder farmers adopt proactive and reactive resilience strategies throughout the FSC, many of which, as seen during the COVID-19 pandemic, remain in place post-pandemic.

Proactive actions include seed improvement and the use of excess food to generate new products. In the farming stage, proactive initiatives were to clean the farm, improve seeds and implement new grafting techniques; and in the selling stage, small-scale producers created new products to mitigate losses.

Reactive actions in the transportation stage, were smallholder farmers decided not to sell through wholesalers and transport their products by themselves. In turn, in the selling stage, farmers focused on: (a) implementing digital payments through digital wallets to reduce physical contact and facilitate customers purchasing; (b) creating digital content with their own cell phones and publishing it on social networks; taking orders by phone and making home deliveries; (c) starting to sell at farmers markets periodically.

4.2.3 Circular economy through R principles

Smallholder farmers are generally unaware of the formal concepts of CE. However, they intuitively adopt CE practices, with seven of the eight R's evident in their FSC processes, as described below:

a) *Rethink*. Is represented by actions aimed at educating consumers about their work on the farm, the process of growing organic products and their health benefits, as well as the importance of buying directly from the producer.
b) *Redesign*. Reflects the small-scale farmers' sense of connection and respect to the land, which is why they care for and protect it by: (i) rotating crops; (ii) using live fences to protect crops from insects and diseases and not using industrial pesticides; (iii) employing ancestral techniques to improve plant resistance to extreme weather conditions.
c) *Reduce*. Results from the awareness of small-scale producers about the need to use resources efficiently and apply ancestral techniques. By that, farmers improve the responsible use of water, the reduction of fire on the farm, the use of natural fertilizers from animals, the use of natural repellents and vitamins, the non-use of agrochemicals or products harmful to the environment, the concern about pollution and their decision to produce organically to protect the environment and preserve ancestral practices.
d) *Replace*. Is given by using food that cannot be sold to feed their animals, reduce the loss and feed their families. It also includes the improvement of seeds and the implementation of grafting techniques, as well as make compost in the farming stage.
e) *Reuse*. The products that do not have the desired aesthetic characteristics, that deteriorate, or that are not sold are donated to family members, neighbors, community kitchens, social organizations, workers and customers, and serve as food for their farm animals.
f) *Repurpose*. The products that were not sold are used to produce new products, with higher added value for selling, like cakes and drinks.
g) *Recycle*. The smallholder farmers make compost and decompose animal manure and leaves to be used as fertilizer. They also use the damaged products that cannot be sold to make compost as fertilizer for their next crops.

It is important to emphasize that farmers do not recognize the application of CE principles, specifically the R principles, during the transportation stage.

4.2.4 Sustainable practices

Sustainability practices were identified in the social, economic and environmental dimensions. The social dimension is observed in the farming stage where ancestral knowledge is transferred from generation to generation as a way of life to learn the whole productive process, the eco-efficient use of natural resources and techniques to protect the plants. In some cases, young farmers improve these processes by combining this knowledge with that acquired in formal studies. Also, as the family is the main source of labor, women can work and care for their children by bringing them to the farm while they work sowing and harvesting. In the selling stage, the work-family balance is achieved because women work a few days a week in the farmers markets and dedicate the other days to raising their children.

The economic dimension is observed in the transportation stage: small-scale producers sell their products to other small-scale producers instead of selling to wholesalers to obtain a fair price; and the selling stage: farmers sell their own products and those bought from other producers at the farmers markets to obtain higher profits by eliminating intermediaries.

The environmental dimension is observed at the farming stage when small-scale producers decide to plant organic products to preserve the land and not pollute the environment, thus contributing to the health of workers and consumers, directly or indirectly. Finally, it is crucial to note that farmers do not recognize any sustainable practices during the buyers/consumers stage.

4.3 The key challenges of smallholder farmers FSC in the adoption of resilience, circularity, and sustainability

Smallholder farmers play a pivotal role in fostering resilience, circularity, and sustainability within food systems. While their current practices often incorporate ancestral knowledge, which has proven inherently sustainable, these alone are insufficient to meet the challenges of modern agricultural systems or to strengthen their contribution to SDG 1 (No poverty), SDG 2 (Zero hunger), and SDG 12 (Responsible consumption and production). Addressing these challenges requires a holistic approach, which this study frames as a hybrid model—a balance between ancestral methods and modern innovations to optimize resilience, circularity, and sustainability. To address these challenges effectively, it is essential to strike a balance between traditional methods and modern innovations by integrating low-cost, resource-efficient technologies with existing ancestral practices in a hybrid model that combines both systems' strengths.

The adoption of these approaches requires technical support, infrastructure, and coordinated action from all stakeholders, including government, private entities, academia, civil society, and smallholder farmers themselves. Furthermore, the effective implementation of such initiatives relies on external support, including funding, partnerships, and supportive policies, to ensure impactful and long-term results.

a) *Government and policymakers* play a crucial role in addressing the absence of public policies and regulations at national and local levels. This includes promoting a hybrid model as a solution that integrates traditional and modern systems for increased resilience and sustainability. Key actions include:

- *Technical support and training programs*: Facilitate innovation by providing smallholder farmers with access to modern, low-cost technologies while recognizing the sustainability of traditional methods. Training programs should emphasize the complementarity between both systems to optimize outcomes.
- *Organic certification*: Simplify certification processes and reduce associated costs to encourage the continued adoption of organic production methods.
- *Infrastructure and logistics*: Invest in shared infrastructure, such as community storage centers and sustainable transportation systems, to enhance food preservation and minimize losses.
- *Financial support*: Allocate sufficient government budgets for small-scale agriculture and provide access to credits programs tailored to smallholder farmers' needs.

b) *Private entities*, including financial institutions and international organizations, play a critical role in supporting smallholder farmers. Key actions include:

- *Targeted financial support*: Develop innovative financing options, such as flexible credit schemes and microloans, to complement government efforts and support the adoption of sustainable and modern agricultural practices.
- *Capacity-building partnerships*: Facilitate training programs that integrate modern technologies with ancestral knowledge, demonstrating their hybrid benefits for increased productivity and resilience.
- *Food waste reduction initiatives*: Expand food bank collection programs to include smallholder farmers, minimizing waste, and improving food distribution.
- *Consumer education campaigns*: Promote awareness initiatives to highlight the benefits of purchasing from small-scale producers and supporting indigenous, sustainable products.

c) *The food industry*, including supermarket chains, wholesale markets, and the HORECA sector (hotels, restaurants, and catering), plays a complementary role in integrating smallholder farmers into inclusive and sustainable value chains, bridging traditional production methods with market demands. Key actions include:

- *Facilitating access to formal markets*: Adopt flexible quality standards, particularly regarding aesthetic attributes such as size, color, and shape, while maintaining food safety compliance.
- *Promoting fair trade programs*: Ensure equitable pricing and strengthen direct connections between smallholder farmers and consumers.
- *Increasing demand for local and sustainable products*: Prioritize sourcing from smallholder farmers who produce organic or traditional crops with distinctive attributes.
- *Preserving biodiversity*: Encourage direct purchasing practices that support diversified production, fostering the conservation of local crops and varieties within sustainable agricultural systems.

d) *Academia*, including educational and research institutions have the potential to drive sustainable agricultural systems by addressing key gaps in knowledge and innovation. Academia can serve as a catalyst for developing the hybrid model by combining empirical evidence and local knowledge. Key actions include:

- *Capacity-building programs*: Develop training initiatives that integrate ancestral knowledge with modern innovations, ensuring that traditional farming practices are preserved and adapted to address current challenges in agricultural productivity and sustainability.
- *Research and innovation*: Conduct research on low-cost technologies that complement traditional methods, focusing on areas such as postharvest management and water efficiency, while emphasizing the integration of both systems to create a hybrid approach.
- *Education programs*: Promote knowledge dissemination at all educational levels to highlight the value of ancestral knowledge and encourage its integration into modern solutions.

e) *Civil society*, including consumers, NGOs, and community organizations, plays a vital role in supporting sustainable food systems. Key actions include:

- *Raising awareness on food waste*: Promote knowledge of food waste collection opportunities and highlight its potential for composting, redistribution, and circular reuse.
- *Promoting smallholder farmers*: Emphasize the critical role of smallholder farmers in achieving food sustainability while showcasing the environmental and health benefits of locally produced organic food.
- *Consumer education*: Educate consumers about the unique attributes of organic products, including their visual diversity, production challenges, and environmental benefits.
- *Encouraging responsible consumption*: Highlight the societal and economic impacts of food loss and waste to encourage sustainable purchasing behaviors.

f) *Smallholder farmers* face significant challenges but are key actors in advancing sustainable agricultural practices and preserving cultural heritage. Key actions include:

- *Safeguarding ancestral knowledge*: Promote initiatives that engage younger generations in agriculture, ensuring the

preservation and transfer of traditional farming practices to maintain cultural continuity and biodiversity.

- *Access to technical support and sustainable innovations*: Facilitate access to technical support tailored to smallholder farmers' needs, focusing on low-cost technologies that enhance productivity and resource optimization while respecting and integrating ancestral methods. This support should include training programs on postharvest storage, composting techniques, and water-efficient irrigation.
- *Consumer awareness strategies*: Strengthen efforts to highlight the ecological, social, and cultural value of stallholder farmers' products, increasing market demand through direct consumer engagement and participation in sustainable value chains.

5 Discussion

Smallholder farmers in Peru face numerous challenges in maintaining resilient, circular, and sustainable FSCs. While they employ various intuitive practices aligned with CE principles and resilience strategies, these efforts are insufficient to ensure long-term sustainability or significantly contribute to SDGs (Ume et al., 2023). The study's findings highlight the need for a structured and multi-stakeholder approach to fully realize the benefits of these practices. Coordinated actions across government, private entities, academia, civil society, and smallholder farmers are essential to address systemic challenges and foster a sustainable food system. By addressing these challenges through the hybrid model—integrating modern technologies with ancestral practices—smallholder farmers can enhance productivity, resilience, and sustainability in their FSCs. Also, it is necessary to integrate strategy, culture, risk management and transparency to join sustainable management practices and systemic coordination of processes (Carter and Rogers, 2008).

The primary *drivers of food loss* identified in this study align with the findings of Ali et al. (2021), highlighting key challenges such as technological and environmental factors, improper agricultural practices, inadequate marketing systems and information insufficiencies, and deficient infrastructure and governmental regulations. Addressing these drivers requires coordinated interventions involving targeted technical support, infrastructure investments, and supportive policies. These actions are essential for advancing the objectives of SDG 12 (Responsible Consumption and Production).

From the producers' perspective, targeted training programs on proper postharvest handling techniques and resource-efficient practices are essential to reduce food losses effectively. From the consumers' perspective, there is an urgent need to disseminate comprehensive information about organic products, including their unique characteristics, production costs, consumption guidelines, and the associated health benefits. Bridging these knowledge gaps between producers and consumers, while fostering collaboration among government, private entities, and civil society, is vital for building a resilient, circular, and sustainable FSC grounded in the hybrid model.

Concerning *resilience strategies*, the study reveals that smallholder farmers engage in both proactive and reactive strategies (Gunessee and Subramanian, 2020). Proactive initiatives, such as seed improvement and direct consumer engagement, help to maintain ancestral practices connected to their cultural values (Salazar et al., 2023) and serve as business drivers (Agyemang and Kwofie, 2021; Kumar et al., 2022) to mitigate food loss and maintain operations. Reactive measures, such as adopting digital payment systems (Vieira et al., 2018) and adjusting sales strategies using social networks (Kayikci et al., 2021; Zhang et al., 2019) during crises and conflicts (Galanakis, 2023; Galanakis et al., 2021) showcase their adaptability and drive smart supply chains, as well as the efficient use of resources (Antikainen et al., 2018; Kayikci et al., 2021; Zhang et al., 2019). However, these practices are largely *ad-hoc* and lack the systematic support needed for sustained resilience. Integrating formal resilience frameworks could enhance the farmers' ability to cope with future disruptions, aligning with SDG 1 (No Poverty) and SDG 2 (Zero Hunger).

Regarding *CE practices*, smallholder farmers intuitively implement seven of the eight R principles (rethink, redesign, reduce, replace, reuse, repurpose, recycle) stated by Vlajic et al. (2021) with a commitment to the land, nature and society (Ormazabal et al., 2018) to minimize food loss and mitigate the social cost associated with waste (Sehnem et al., 2019). However, the absence of Recovery practices and limited application during transportation stages hinder the full potential of CE practices. Addressing these gaps could significantly reduce food loss and strengthen the environmental sustainability of FSCs, contributing to SDG 12 (Responsible Consumption and Production). Additionally, raising awareness and providing education on CE concepts could help farmers optimize their existing practices.

Referring to *sustainable practices*, sustainability in the FSCs is evident in the environmental, social, and economic dimensions. *Social sustainability* is reflected in the preservation of ancestral knowledge to ensure the continuity of farming practices across generations. However, the declining interest among younger generations to remain in rural areas and engage in farming poses a significant threat to long-term sustainability and food security (Ume, 2023). Additionally, the presence of children in production areas presents a complex issue. While it is culturally rooted and linked to survival, it raises concerns regarding child labor and the potential disruption of their education, highlighting tension between traditional practices and modern ethical standards.

Environmental sustainability is evident in the adoption of organic farming methods (Ormazabal et al., 2018; Ume et al., 2023), which are employed to limit greenhouse gas emissions (Farooq et al., 2022; Saxena et al., 2018) and thereby reduce the overall environmental footprint (Neven, 2015); however, most smallholder farmers lack organic certification, which negatively impacts the market positioning of their activities and products. Neven (2015) notes that this ecological approach, while environmentally beneficial, is often associated with lower labor productivity due to the reliance on low-cost family labor, which paradoxically contributes to increased poverty.

Economic sustainability is demonstrated through direct sales at farmers' markets, which maximize income by eliminating intermediaries. However, significant power asymmetries between smallholder farmers and larger producers were identified, highlighting the challenges faced by smaller operations in achieving equitable market access. However, the dominance of

economic considerations over social and environmental aspects indicates a need for a more balanced approach to sustainability. This imbalance poses a challenge to achieving comprehensive sustainability in the long term.

The study identifies several key challenges impeding the adoption of more resilient, circular, and sustainable practices. These challenges—such as inadequate government policies, limited access to technology and financial resources, and low consumer awareness of organic products—can be addressed through the hybrid model, which ensures an integrated and multi-stakeholder approach (Weetman, 2019). Government and policymakers must prioritize the design and implementation of policies that support smallholder farmers by facilitating access to organic certification, delivering technical training programs, and investing in infrastructure such as community storage centers and sustainable transportation systems. Private entities, including financial institutions and international organizations, should focus on enhancing market access, offering flexible financing schemes, and promoting technologies that optimize resource use while respecting traditional farming methods. The food industry can contribute by adopting flexible quality standards, promoting fair trade practices, and prioritizing direct sourcing from smallholder farmers to preserve biodiversity and strengthen local value chains. Academia must take an active role in research and innovation to develop low-cost, sustainable technologies and capacity-building programs that integrate ancestral knowledge with modern solutions. Civil society, including NGOs, must work to raise consumer awareness of the environmental, social, and health benefits of sustainable products, increasing demand for goods produced by smallholder farmers. Finally, smallholder farmers themselves play a critical role by adopting circular economy practices, safeguarding cultural heritage, and engaging consumers to highlight the ecological and cultural value of their products.

6 Conclusion

This article examined the current practices and key challenges among Peruvian smallholder farmers in managing a resilient, circular, and sustainable FSC to mitigate food loss. The findings highlight the strengths of ancestral practices and the limitations that arise when they are not systematically supported or combined with modern solutions. The hybrid model, rooted in the synergy between ancestral knowledge and modern innovations, emerges as a scalable and adaptable solution to ensure long-term sustainability, resilience, and circularity. It leverages the strengths of both systems to address systemic goals of sustainability.

6.1 Regarding the current practices

Smallholder farmers intuitively implement CE principles, such as Rethink, Redesign, Reduce, Replace, Reuse, Repurpose, and Recycle, demonstrating their deep-rooted connection to sustainable, low-cost ancestral methods. However, the absence of systematic recovery practices and limited implementation during transportation stages constrain the full potential of these efforts. The hybrid model addresses this limitation by systematically incorporating resource-efficient technologies and infrastructure improvements, enhancing both productivity and sustainability while respecting tradition.

Social sustainability is reflected in the preservation of ancestral knowledge, ensuring the intergenerational continuity of farming practices. Economically, direct-to-consumer sales maximize farmers' incomes by eliminating intermediaries, while organic production methods contribute to environmental sustainability by protecting natural resources and minimizing ecological impacts. Nevertheless, significant challenges persist, including declining youth engagement in agriculture, lack of organic certification, and power asymmetries in market access. The hybrid model bridges these gaps by integrating traditional farming systems with modern tools, enabling access to specialized markets and fostering productivity.

Resilience strategies in mitigating food loss and sustaining smallholder operations further underscore the potential of the hybrid model. Proactive initiatives such as seed improvement and direct-to-consumer engagement, preserve cultural practices while driving economic resilience. Reactive measures, including the adoption of digital payment systems and social networks, highlight smallholder farmers' adaptability to crises. However, these efforts are often fragmented and lack systematic support. By embedding technological innovations and digital platforms into resilience frameworks, the hybrid approach strengthens farmers' capacity to anticipate, adapt to, and recover from future disruptions while safeguarding cultural continuity.

6.2 Key challenges

Key challenges identified in this study—such as inadequate policies, limited access to technology and financial resources, and low consumer awareness—underscore the need for a multi-stakeholder effort. The hybrid model emerges as an integrated framework where actions from diverse actors converge to address these systemic gaps: Government and policymakers must prioritize supportive policies, infrastructure investment, and access to organic certification and training. Private entities should focus in offering innovative financing solutions, facilitating capacity-building, and creating market opportunities. The food industry can bridge traditional production systems with modern market demands by adopting flexible standards, promoting fair trade, and supporting biodiversity preservation. Academia must advance research that integrates ancestral knowledge with modern innovations, while developing training programs tailored to smallholder farmers' needs. Civil society can raise awareness of the ecological, social, and cultural value of sustainable products, driving consumer demand and supporting knowledge transfer. Smallholder farmers themselves are central to the hybrid model, combining ancestral practices with modern tools to showcase sustainable, high-value products.

In conclusion, the hybrid model—rooted in the synergy between ancestral knowledge and modern innovations—represents a transformative, scalable, and adaptable solution to the challenges faced by Peruvian smallholder farmers. By fostering collaboration among all stakeholders, this integrated approach enhances resilience, circularity, and sustainability across FSCs. The adoption of this model ensures that smallholder farmers play a transformative role in advancing food security,

economic resilience, and environmental sustainability, while contributing significantly to the achievement of SDG 1 (No Poverty), SDG 2 (Zero Hunger), and SDG 12 (Responsible Consumption and Production). In the face of ongoing economic, environmental, and social challenges, the hybrid model provides a comprehensive pathway to achieving long-term sustainability in agricultural systems.

7 Limitations and suggestions for future research

This study, while offering valuable insights is subject to several limitations that are categorized as follows:

Methodological Limitations: The qualitative approach and purposive sampling used in this study provide deep insights but limit the generalizability of the findings. Future research should consider employing a mixed-methods approach, integrating on-site observations of farming activities alongside interviews to complement the existing dataset and contribute to a more comprehensive understanding of agricultural practices.

Geographical Limitations: This study's focus on farmers operating in Lima's urban markets may not capture the full spectrum of practices and challenges across different regions of Peru. Future research should explore regional variations by conducting comparative studies in various rural and urban settings within Peru, as well as, in other countries with similar agricultural contexts.

Stakeholder Engagement: Although the study recognized the importance of collaboration among various stakeholders, it primarily reflected the perspectives of smallholder farmers. Future research should engage more extensively with other stakeholders, including government agencies, private sector entities, and NGOs, to explore collaborative approaches.

Data availability statement

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

Author contributions

JV: Writing – original draft, Writing – review & editing. MC: Writing – original draft, Writing – review & editing. VS: Writing – original draft, 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.

Generative AI statement

During the preparation of this work the authors used ChatGPT in order to improve language, as english is not our mother tongue. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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