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Building a Sustainable Circular Agri-Food Supply Chain For Rural Producer Organization

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ABSTRACT

The development of a sustainable circular agri-food supply chain for rural producer organizations is essential to address the challenges of food loss, agricultural waste management, and resource efficiency. This study explores the integration of circular economy principles within the vegetable supply chain of rural producer organization, emphasizing the utilization of waste as a resource through technologies. Using a mixed-methods approach, the research analyzes the current state of waste management practices, quantifies losses across production and post-harvest stages, and identifies opportunities for improvement. The findings highlight significant inefficiencies in waste utilization, revealing that daily losses result in financial losses amounting to 4-10% of potential revenue. A sustainable circular supply chain model is employed to analyze and coordinate the interdependencies and decision-making processes among stakeholders, ensuring efficient resource allocation, effective waste management, and the integration of circular economy principles to achieve sustainability outcomes. By aligning production processes with circular economy principles, rural producer organizations can reduce environmental impacts, improve economic resilience, and contribute to the long-term sustainability of the agri-food supply chain.

Keywords: *circular economy, sustainability, food loss, waste management*

BACKGROUND

The increasing global food waste poses significant challenges to sustainability, impacting economic, environmental, and social dimensions. According to Huang et al. (2020), almost 1.3 billion metric tons, or about one-third of the world's total food production, goes to waste every year. This not only represents a significant misuse of valuable resources but also exacerbates environmental degradation and undermines global food security (Corrado et al., 2019). According to statistical analyses, food waste results in an annual economic loss of nearly $750 billion, comparable to the gross domestic product of multiple nations (Gruber et al., 2016).

The Food Loss and Waste Study Report in Indonesia published by Bappenas (2021) states that the FLW generated in Indonesia reached 23-48 million tons/year in 2000 - 2019 or equivalent to 115-184 kg/capita/year. The estimated economic losses caused by FLW in Indonesia during this

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period ranged from 213 to 551 trillion rupiah annually, accounting for approximately 4-5% of Indonesia's Gross Domestic Product (GDP) (Bappenas, 2021). The horticulture sector, particularly vegetables, is the most inefficient sector, with losses amounting to 62.8% of the total domestic vegetable supply (Bappenas, 2021). According to Sagar et al., (2018) fruit and vegetable processing operations generate significant by-product waste, amounting to about 25-30% of the total production in this commodity group. Meanwhile, despite contributing only around 1.6% to GDP, the horticulture sector experienced significant growth during the COVID-19 pandemic, with exports of horticultural products increasing by 38.99% in 2020 (Kusnandar et al., 2021).

The concept of a circular agri-food supply chain (CASC) is increasingly recognized as an essential approach to enhancing sustainability, reducing waste, and improving resource efficiency in agriculture. For instance, the recycling of crop and animal waste can significantly boost soil fertility, reducing reliance on synthetic fertilizers (Nguyen et al., 2024; Rodino et al., 2023). By mitigating environmental impacts, this approach not only promotes healthier soils but also advances the overall sustainability of agricultural practices (Rodino et al., 2023). A key aspect of circular agriculture involves integrating local food systems, which helps simplify supply chains and lower transportation-related emissions, further supporting sustainable practices (Jurgilevich et al., 2016; Nguyen et al., 2024).

Food waste is increasingly recognized as a critical issue within the Sustainable Development Goals (SDGs), particularly Goal 12 on sustainable consumption and production. Recent studies on circular economy in agri-food supply chains provide valuable insights into how this concept can enhance sustainability, resource efficiency, and waste management. Schneider et al. (2021) emphasize the importance of circular economy methodologies in small-scale food production to ensure food security and sustainability in agricultural activities. Rodias et al. (2021) , in their research, conducted a deeper investigation into the interactions between water, energy, and nutrients within the agri-food industry. Their findings reveal that circular systems effectively reduce resource consumption while promoting the production of bioenergy and organic fertilizers, thereby making significant contributions to environmental preservation. These studies demonstrate that incorporating circular techniques in small-scale agriculture can yield substantial economic and environmental benefits.

Furthermore, research on circular supply chains examines a comprehensive optimization framework for effectively managing crop-livestock-biogas systems under conditions of uncertainty. This framework facilitates the efficient recycling of organic waste, thereby enhancing biodiversity and resource sustainability, particularly in small-scale farming systems (Yue et al., 2022). Analyses of the potential of circular agriculture for small-scale farmers highlight significant barriers, including technical and financial limitations, but emphasize its potential to improve sustainability (Boon & Anuga, 2020). In promoting the principles of circular economy (CE) among small-scale farmers, Perdana et al. (2023) argue that supply chain governance plays a crucial role. Their study on the vegetable and dairy product supply chains reveals that improved coordination between farmers and traders can help minimize surpluses and reduce food waste. Despite the growing body of research on CASC, significant gaps remain in understanding how these systems can be practically implemented at the micro-level. This study seeks to fill these gaps by focusing on a specific farmer organization, offering actionable insights for sustainable waste management and circular supply chain integration.

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This study will be conducted in Lembang Agri, a Rural Producer Organization (RPO), located in West Bandung Regency, West, Java, Indonesia. RPO is a community-based enterprise owned and governed by producers, primarily aimed at facilitating collective marketing and enhancing the economic opportunities of its members (Mwambi et al., 2020). This RPO is an excellent example of a strategic case study because of the impact it has on regional food production and its pivotal position in the supply chain for horticulture. Lembang Agri represents a microcosm of rural farming communities in Indonesia, where waste management practices are often underdeveloped, and the potential for implementing circular supply chain models remains largely unutilized.

This study is designed to address three key objectives related to waste management and circular supply chain implementation in Lembang Agri. First, it seeks to quantify the daily volume of waste produced and estimate the financial losses resulting from inadequate waste management practices. Second, it aims to analyze the current waste management practices within the organization, identifying inefficiencies and challenges in handling agricultural waste. Third, the research explores the potential for developing a tailored circular supply chain model, focusing on recycling organic waste into valuable resources. These objectives collectively aim to provide actionable recommendations for improving sustainability and resource efficiency in small-scale agricultural systems.

RESEARCH METHODS

The study was conducted in West Bandung Regency, a region renowned for its high productivity in vegetable farming, contributing significantly to the agricultural output of West Java (Septian & Judiantono, 2019). Within this regency, Lembang Agri was chosen as the study site due to its status as a diverse RPO consisting of eight farmer groups spread across Cikidang Village in Lembang District. Lembang Agri caters to various market types, including spot markets and contract farming arrangements, making it an exemplary case for analyzing agricultural supply chain dynamics and the integration of circular economy practices. Additionally, Lembang Agri is recognized as a large and well-established organization that has successfully developed an agribusiness cluster and operates its own packing house, which is independently managed by its members. This infrastructure and organizational capacity further enhance its role as a model for studying sustainable agricultural practices and innovative supply chain management.

This study focuses on analyzing and addressing key aspects of waste management and resource utilization within RPO, specifically Lembang Agri, to build a sustainable CASC using mixed methods approach. According to Creswell (2014), mixed methods research is particularly effective for providing a comprehensive and nuanced understanding by integrating both quantitative and qualitative data. According to Bryman (2012), for small populations (below 300), selecting around 30-40% of the population can be considered sufficient to produce representative data. In the context of 284 members, selecting a sample of 103 members (approximately 36%) aligns with these guidelines. The study employed a simple random sampling technique to select 103 respondents from the total 284 members of the RPO. These individuals were chosen based on their experiences with vegetable loss and waste generation.

Using a structured questionnaire and in-depth interviews, the study employed a multi-method approach to investigate waste management practices and food loss within the RPO. Two distinct

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surveys, supplemented by qualitative interviews, were conducted to gather comprehensive data from the organization's 103 members.

The calculation of vegetable losses focuses on the stages from farmers to the packing house. The measurement determines the weight loss at each stage of the supply chain, specifically at the farmer level and during transportation or processing at the packing house. The loss is calculated using the following formula (Rahmani et al., 2024):

$$VLHP = \frac{A - B}{A} \times 100\%$$

Explanation:
VLHP : Vegetable loss at harvest percentage (%)
A : Weight of vegetables at the initial stage (kg)
B : Weight of vegetables at the next stage (kg)

To quantify the economic loss in monetary terms, calculations are made based on the total weight of vegetables lost and their market value using the following formula:

$$TR = P \times Q$$

Explanation:
TR : Total Revenue loss from vegetables (Rp)
P : Price of vegetables per kg (Rp)
Q : Quantity of vegetables lost (kg)

After calculating vegetable losses at each stage, the next step involves adopting a governance approach to analyze and strengthen the management of the circular vegetable supply chain. Supply chain governance refers to the coordination of relationships, authority, and decision-making mechanisms within a supply chain to optimize resource allocation, foster collaboration, and address challenges such as sustainability and efficiency (Ryciuk, 2020). This approach emphasizes the roles and responsibilities of various stakeholders, including farmers, RPO, village-owned enterprises, and government agencies, in reducing losses and enhancing resource efficiency. Effective governance ensures proper coordination, decision-making, and accountability at every level of the supply chain, from production and post-harvest handling to waste processing and recycling.

RESULT AND DISCUSSION

Vegetable Supply Chain Dynamics in Rural Producer Organization

The selected RPO operates under two distinct supply chain governance models: contract farming arrangements and spot market supply chains, as illustrated in Figure 1. Spot markets are platforms where commodities are traded for immediate delivery, with prices determined dynamically based on current demand and supply conditions (Zhao et al., 2015). Whereas contract farming arrangements refer to institutional frameworks in which agribusiness firms establish formal or informal agreements with farmers to produce specific agricultural commodities under predetermined conditions (Mugwagwa et al., 2020). The contract farming supply chain (Figure 1) focuses on delivering high-quality produce that meets strict specifications to structured markets such as supermarkets and *r*estaurant. These markets demand premium standards in terms of product quality,

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size, and packaging, offering farmers price stability and consistent demand in exchange for adherence to these requirements.

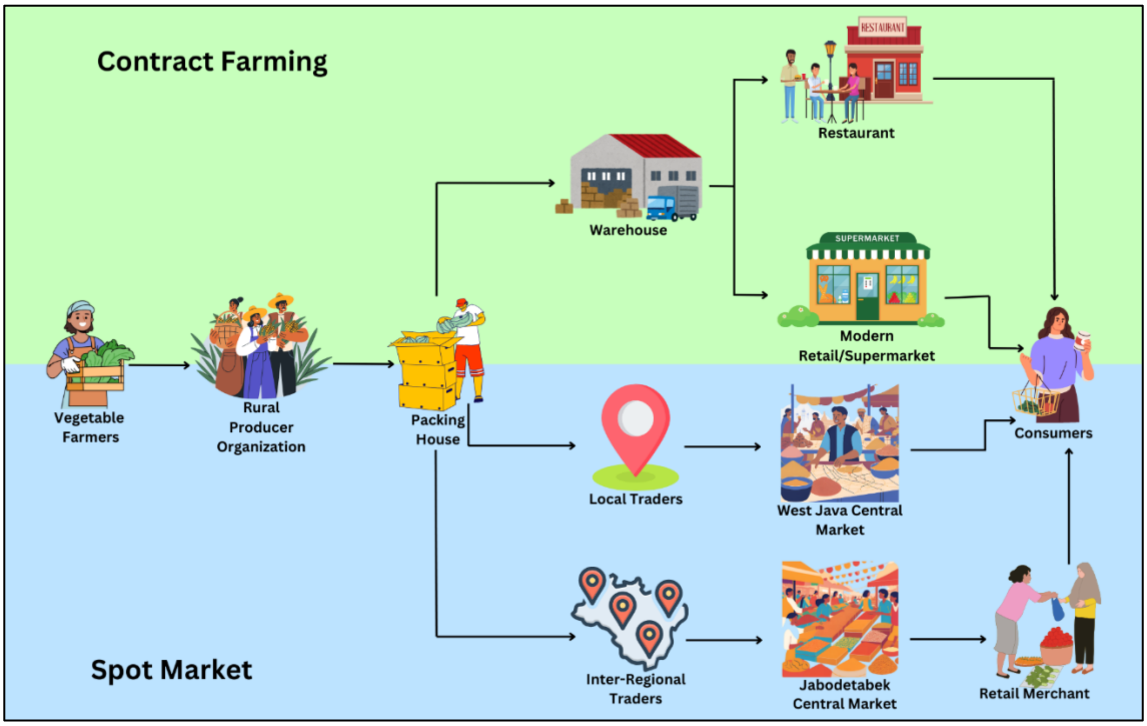

Figure 1. Structured Supply Chain (Contract Farming) and Traditional Market Supply Chain (Spot Market) in RPO

In contrast, the spot market supply chain (Figure 1) caters to traditional markets, where standard-grade or lower-quality produce is sold. This model provides farmers with greater flexibility, allowing them to quickly sell surplus or non-premium products without the need to meet strict specifications. However, it also exposes them to price fluctuations and inconsistent demand. Together, these two models reflect the RPO's efforts to connect farmers with diverse market opportunities while optimizing the value of their agricultural outputs.

Food Loss Quantification in Rural Producer Organization

Measuring food loss is essential for comprehending inefficiencies in the agricultural supply chain and formulating efficient waste reduction measures. Food loss transpires at multiple stages, including harvesting, post-harvest handling, and distribution, and can profoundly affect economic profitability and environmental sustainability (Perdana et al., 2023). Previous research conducted by Ningsih et al. (2024) examined food loss analysis on rice commodities in West Kalimantan. In addition, research conducted by Ariani et al. (2022) discussed a critical review of food waste, including the magnitude, causes, impacts and policy strategies on a macro scale. Systematic measurement of food loss enables the identification of critical inefficiency points, the calculation of financial repercussions, and the formulation of focused measures to reduce waste. This process not

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only highlights the extent of resource wastage but also provides valuable data for implementing sustainable practices and improving supply chain resilience.

Table 1. Loss at Farmer Level

No	Vegetable	Total initial weight (kg/day)	Weight loss (kg/day)	Percentage loss	Selling price (Rp/kg)	Economic loss
1	Red bell pepper	110.5	5.5	4.98%	Rp32.000	Rp176.000
2	Green bell pepper	135.8	15	11.05%	Rp21.000	Rp315.000
3	Tomato	402	20	4.98%	Rp7.000	Rp140.000
4	Romaine lettuce	74	4.5	6.08%	Rp11.000	Rp49.500
5	Green beans	36.4	1.8	4.95%	Rp8.000	Rp14.400
	Total	758,7	46,8	6,4%		Rp694.900

Table 2. Loss at Packing House Level

No	Vegetable	Total initial weight (kg/day)	Weight loss (kg/day)	Percentage loss	Selling price (Rp/kg)	Economic loss
1	Red bell pepper	105	4	3.81%	Rp43,085	Rp172,340
2	Green bell pepper	120.8	5	4.14%	Rp32,500	Rp162,500
3	Tomato	382	15.5	4.06%	Rp22,000	Rp341,000
4	Romaine lettuce	69.5	3.5	5.04%	Rp15,500	Rp54,250
5	Green beans	34.6	2.35	6.79%	Rp14,000	Rp32,900
	Total	711,9	30,35	4,77%		Rp762.990

The data in Table 1 shows that at the farmer level, a total of 758.7 kg of vegetables was handled, with a weight loss of 46.8 kg (6.4%), resulting in an economic loss of Rp694,900 per day. The highest percentage loss occurred in green bell peppers (11.05%, Rp315,000/day), while green beans experienced the lowest (4.95%, Rp14,400/day). A significant portion of this loss occurred during the post-harvest stage, primarily due to inadequate infrastructure, which affected storage, handling, and transportation, contributing to the overall weight and economic losses. In research Ningsih et al. (2024), yield loss in rice commodities during the post-harvest process reached 9,52%, primarily caused by scattered or damaged grains due to the use of manual labor or harvesting equipment. Meanwhile, in research Ariani et al. (2022), the largest macro-level yield loss was observed in horticultural commodities, reaching 62%. The main contributing factor was the consumption behavior of various actors and institutions in the food supply chain, including traders, transporters, restaurants, hotels, households, and household members.

Table 2 presents the packing house level, where a total of 711.9 kg was processed, with a weight loss of 30.35 kg (4.77%), causing an economic loss of Rp762,990 per day. Green beans had the highest percentage loss (6.79%, Rp32,900/day), while red bell peppers incurred the highest economic loss (Rp172,340/day) due to their high selling price (Rp43,085/kg). At the packing house,

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most of the losses occurred during the grading process, where vegetables that did not meet quality standards were discarded, contributing to the overall weight and economic losses.

When comparing the two stages, it is evident that the farmer level has a higher weight loss percentage (6.4%) compared to the packing house level (4.77%). On average, the estimated economic losses per week are approximately Rp4-5 million at both levels, demonstrating the significant financial impact of waste over a short period. These losses underscore the urgent need for enhanced waste management practices and strategies to minimize inefficiencies and optimize resource utilization across the supply chain. One major cause of food loss at the farming stage is the use of inefficient harvesting techniques and poor post-harvest handling practices. Smallholder farmers often lack access to modern technologies and adequate training, leading to significant losses during harvesting. The cost of processing waste at the farmer level is quite significant. Beyond the investment required for technology, there are also additional costs for human resources to manage the waste properly. Due to these high costs, farmers often opt to discard their waste directly or pay a waste collection fee of Rp10,000 per day rather than investing in waste management solutions. For example, research in Salatiga, Central Java, Indonesia found that pests, diseases, and human errors during manual harvesting were key factors contributing to farm-level food losses (Simamora et al., 2022). Similarly, in the citrus industry, post-harvest losses could be significantly reduced through the adoption of recommended technologies; however, many farmers remain unaware of these solutions (Hanif & Ashari, 2021). This gap in knowledge and resources frequently results in considerable crop losses, negatively impacting farmers' income and exacerbating broader issues of food insecurity. Food loss and waste at the farming stage is a complex problem influenced by factors such as inefficient harvesting methods, financial constraints, limited awareness, and inadequate infrastructure. Tackling these issues necessitates a holistic strategy involving education, improved access to technology, and enhancements in storage and transportation systems.

Waste Management Practices in Rural Producer Organization

Efficient waste management procedures among farmers and RPO are essential for enhancing agricultural sustainability and reducing economic losses. The survey results indicate significant deficiencies in the implementation of these principles. Based on the findings in Figure 2, the majority of respondents, 97,2%, answered No, indicating that most farmers do not utilize any form of technology to manage or reduce agricultural waste. Only 2,8% responded Yes, suggesting that only a small fraction of farmers are employing technology. For those who answered Yes, the technology is limited to basic tools, such as small-scale composting equipment or simple storage solutions, to prevent spoilage and repurpose waste.

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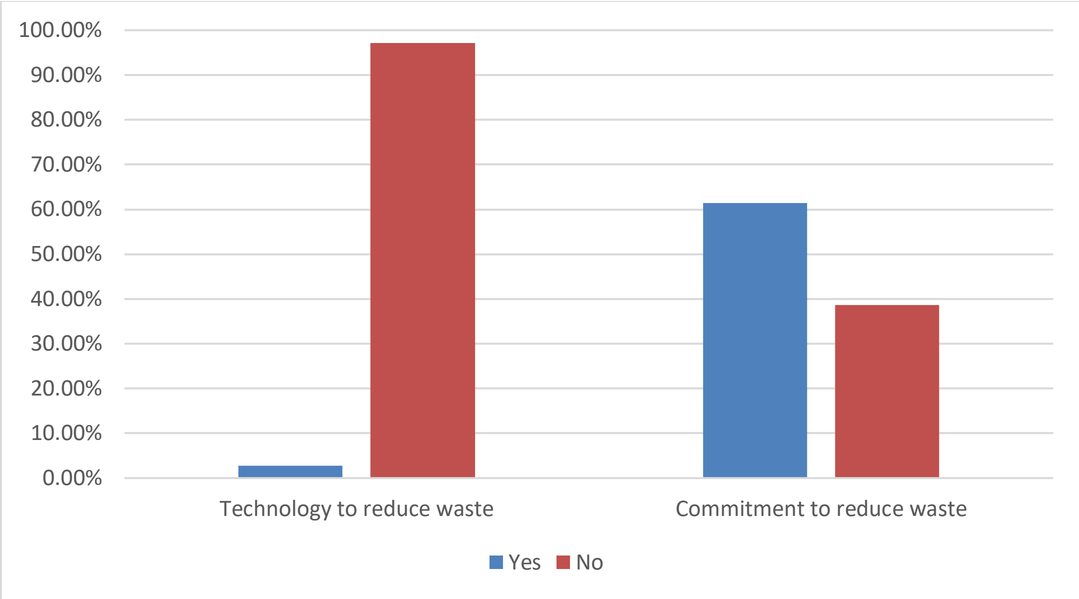

Figure 2. Current Waste Management Practices

The level of commitment among farmers to reducing agricultural waste on their farms. A majority, 61,4%, of respondents expressed a commitment to reducing waste, showing a positive attitude towards adopting practices that minimize agricultural waste and loss. However, 38,6% of respondents indicated a lack of commitment to waste reduction.

A significant challenge in managing rural waste is the absence of structured systems for disposal and recycling. In Bangladesh, for example, small-scale poultry farmers frequently discard waste in unregulated ways, such as dumping or using it as untreated fertilizer, which poses risks to the environment, including soil and water pollution (Begum et al., 2023). Similarly, in India, the widespread practice of burning agricultural residues contributes to severe air pollution and health concerns (Bhuvaneshwari et al., 2019). To tackle these issues, there is a need to adopt more sustainable practices, such as composting and biogas production, which can transform waste into valuable resources (Bhattacharjee et al., 2023; Rajpal et al., 2020).

Figure 2 depicts efforts made by farmers to minimize waste through sustainable farming practices. A large majority, 72,7%, of farmers reported utilizing sustainable practices, such as converting crop residues into organic fertilizers or practicing crop rotation to reduce waste and improve soil health. This indicates a strong inclination among farmers to adopt environmentally friendly methods that contribute to waste reduction. However, 27,3% of respondents stated that they do not currently implement sustainable practices. A key challenge faced by small-scale farmers is their limited access to resources and technology. Many smallholders work on marginal lands with inadequate access to modern agricultural inputs, such as fertilizers and irrigation systems, which restrict their ability to enhance production efficiency and reduce waste (Boza et al., 2024). For example, small-scale farmers often lack the financial capacity to adopt advanced waste management technologies or practices that could help minimize food loss (Yusof et al., 2023). This resource constraint not only hampers their productivity but also limits their ability to implement sustainable strategies for waste reduction.

There is a significant gap in the adoption of advanced technological solutions to improve waste management efficiency and reduce losses in agricultural production. This highlights a critical

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need for targeted interventions and investments in sustainable farming practices. The commitment of small-scale farmers to adopt sustainable waste management practices is increasingly seen as essential for advancing sustainable agriculture. Composting is an eco-friendly waste management method that enriches soil with essential nutrients, improves soil structure, reduces landfill waste, mitigates greenhouse gas emissions, and supports sustainable agriculture (Hajam et al., 2023). These methods not only reduce waste but also improve soil quality and fertility, supporting long-term agricultural productivity (Lal, 2015). Furthermore, the economic benefits of sustainable waste management are significant. By converting agricultural waste into valuable resources such as bioenergy or organic fertilizers, farmers can reduce reliance on external inputs and enhance profitability (Qu & He, 2024). For instance, biogas production from agricultural waste offers a renewable energy source that can meet the energy needs of rural communities while simultaneously addressing waste disposal issues (Dai et al., 2015). Sustainable waste management in agriculture thus holds the potential to mitigate environmental impacts, improve economic resilience, and promote social well-being, making it a vital component of modern agricultural practices.

Strategies to Mitigate Losses and Utilize Waste in the Vegetable Supply Chain within a Rural Producer Organization

To further understand the dynamics of waste management and its integration into a circular economy framework, Figure 3 represents the proposed model for a sustainable circular supply chain within rural producer organizations. This model highlights the flow of agricultural waste, the role of recycling centers, and the coordination required to align supply and demand for waste-derived products. It serves as a comprehensive representation of how agricultural and livestock systems can collaborate to enhance sustainability through effective waste recycling and resource utilization.

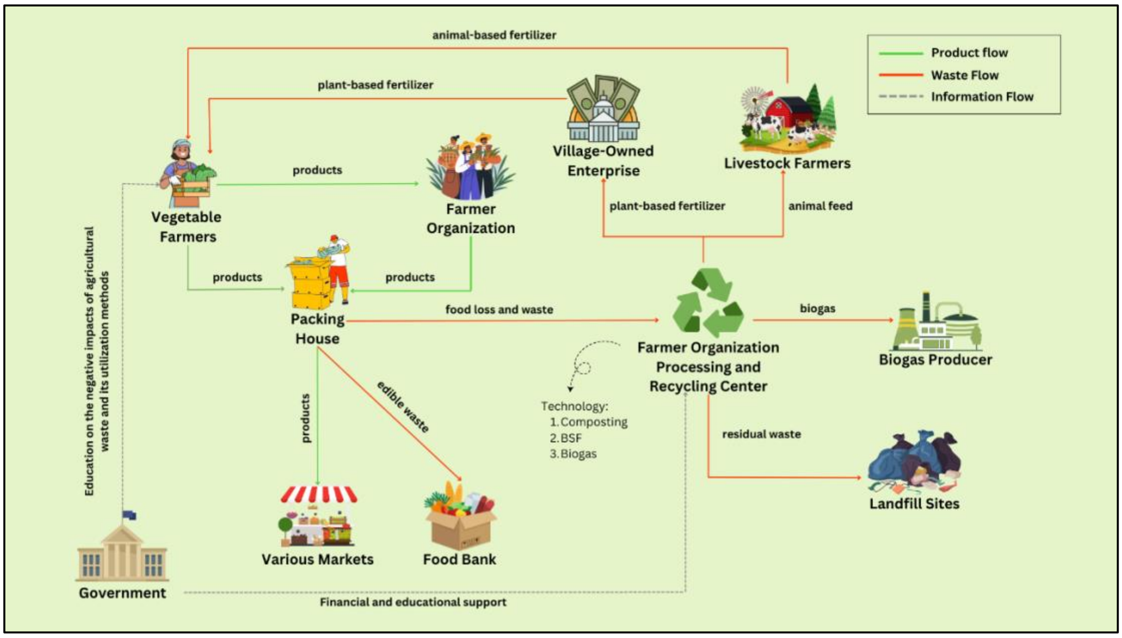

Figure 3. Circular Supply Chain Model for Fresh Vegetables in RPO

The diagram illustrates a circular supply chain model for fresh vegetables within RPO, emphasizing the integration of product, waste, and information flows to enhance sustainability. In the product flow, farmers deliver produce to the Farmer Organization or directly to the Packing House,

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where sorting and distribution to various markets occur. Edible waste generated at the packing house is redirected to Food Banks, minimizing food loss and benefiting the community.

The waste flow in a circular agricultural system addresses the management of agricultural waste by directing waste from farms and packing houses to the Farmer Organization Processing and Recycling Center. At this facility, advanced technologies such as composting, Black Soldier Fly processing, and anaerobic digestion are employed to convert waste into valuable outputs like plant-based fertilizers, animal feed, and biogas. Residual waste that cannot be repurposed is sent to landfill sites.

Each of these technologies plays a crucial role in advancing sustainable waste management practices. Composting is particularly effective in recycling nutrients and mitigating greenhouse gas emissions associated with organic waste decomposition in landfills (Poulton et al., 2018). This practice aligns with sustainable agricultural principles and supports the circular economy by returning essential nutrients to the soil (Yagüe et al., 2023).

BSF processing offers an innovative solution for food waste management and animal feed production. Black Soldier Fly larvae efficiently convert organic waste, including food scraps and agricultural by-products, into high-protein animal feed and organic fertilizers (Sari et al., 2022; Țucă & Cătălin, 2023). These larvae can process waste with up to 90% moisture content, making them suitable for handling a wide range of organic materials (Sari et al., 2022).

Anaerobic digestion further complements these efforts by transforming organic waste into biogas through microbial fermentation in an oxygen-free environment. This process reduces waste volume while generating biogas, a renewable energy source that can be used for cooking, heating, or electricity production (Orskov et al., 2014; Tsai, 2020). Additionally, the nutrient-rich digestate produced during anaerobic digestion serves as organic fertilizer, recycling nutrients back into agricultural soils and completing the nutrient cycle (Kang et al., 2021; Ries et al., 2023).

The information flow involves the Government providing financial and educational support to RPO. This includes training on the negative impacts of agricultural waste and effective utilization methods, encouraging sustainable practices. Recycled outputs, such as plant-based and animal-based fertilizers, are redistributed to local farmers and RPO, creating a closed-loop system. Surplus biogas can be supplied to biogas producers, contributing to energy sustainability.

The government plays a critical role in reducing food loss and waste in rural areas. By investing in facilities for composting, anaerobic digestion, and food processing, governments can transform agricultural waste into valuable resources such as organic fertilizers and biogas. A notable example is Taiwan, where the government has established anaerobic digestion and composting plants to recycle food waste, showcasing the significant benefits of such initiatives (Tsai, 2020). Additionally, governments can prevent food loss and waste by improving infrastructure, supporting food redistribution programs, implementing awareness campaigns, enforcing policies that promote efficient supply chains, and incentivizing sustainable agricultural practices (Nicastro & Carillo, 2021). They can also foster partnerships that utilize local knowledge and resources to create tailored solutions for managing food loss and waste (Pratama et al., 2021).

The circular supply chain model illustrated in Figure 3 provides significant practical, managerial, and policy implications. Practically, the model highlights the importance of implementing technologies to transform agricultural waste into valuable resources. At the managerial and policy levels, the model emphasizes the need for strong coordination among stakeholders,

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including farmers, RPO, and government agencies. Policymakers should prioritise investments in infrastructure to enhance community-level waste management. By integrating these flows, RPO can enhance sustainability, reduce environmental impact, and improve economic resilience. In summary, the circular supply chain model for fresh vegetables in RPO demonstrates how integrating product, waste, and information flows can lead to a more sustainable and resilient agricultural system. By adopting circular economy principles, these organizations can effectively manage resources, reduce waste, and contribute to environmental sustainability.

CONCLUSION AND SUGGESTION

This study underscores the critical importance of integrating circular economy principles within the agri-food supply chain of RPO. The study quantifies the daily volume of agricultural waste produced and estimates the financial losses associated with inadequate waste management, highlighting the economic impact of current practices on the organization and its members. Additionally, the analysis of current waste management practices reveals significant challenges, such as inefficient handling processes and the absence of structured systems for managing agricultural waste. The findings of this study emphasize the need for RPO to adopt strategies that foster a sustainable CASC. One essential step is the establishment of waste management and recycling centers to process agricultural waste into valuable products such as compost, animal feed, and biogas. Furthermore, implementing Standard Operating Procedures (SOPs) for production, post-harvest handling, and waste management is critical to ensuring consistency and minimizing inefficiencies throughout the supply chain.

This research possesses specific limitations. The investigation concentrates on a single RPO, thus constraining the applicability of the findings to alternative contexts or geographies. Future study may mitigate these constraints by broadening the scope to encompass various farmer organisations across different geographic and socio-economic circumstances. Furthermore, employing simulation models or optimisation methods may yield a more comprehensive examination of waste reduction strategies and the operational efficacy of suggested circular supply chain frameworks.

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