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Designing a Circular Economy Model for Reducing Agricultural Waste and Enhancing Environmental Sustainability in Large-Scale Agribusinesses

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Abstract

Large-scale agribusiness operations generate considerable agricultural Waste, resulting in negative environmental impacts, wasteful resource use, and high carbon emissions. Traditional linear waste management systems fail to convert agricultural Waste into valuable economic or environmentally useful products. This research aims to develop a circular economy model to reduce agricultural Waste and improve the environmental sustainability of large-scale agribusiness operations. Research design combines quantitative environmental assessment and qualitative management analysis through empirical data gathered from agribusiness operations, sustainability reports, and waste management practices. The proposed model focuses on waste separation, composting, biomass energy recovery, recycling, and resource reutilization techniques. The study found that, compared with the conventional approach, the developed circular economy model decreases the total amount of agricultural Waste by 38.6% and the organic waste recycling efficiency by 72.4%. Waste-to-biomass conversion improves carbon emissions efficiency by 29.8% and increases energy recovery efficiency from 32.5% to 66.6%. Moreover, sustainable resource management increases soil indicators by 21.7% and reduces waste disposal costs by 26.3%. Based on the results, applying a circular economy approach to the management of agribusiness operations significantly improves the environmental sustainability of large-scale agribusiness, thereby increasing resource efficiency and long-term operational stability. The study provides an efficient managerial guide to sustainable agribusiness and recommends adopting a green, regenerative agribusiness system.

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Keywords
Circular economy, agricultural waste management, environmental sustainability, large-scale agribusiness, resource recovery, sustainable agriculture, biomass recycling.

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Introduction

Large-scale agribusinesses generate significant agricultural waste during cultivation, harvest, processing, storage, transport, and distribution. Crop residue, livestock waste, and food waste are usually disposed of through unsustainable methods, resulting in land degradation, pollution, and GHG emissions (Cavicchi et al., 2022; Sgroi, 2023). Conventional waste treatment processes, which are based on a linear system and follow the production and consumption of resources without an effective recovery system, result in wasted resource efficiency and pose long-term environmental risks to the agricultural industry (Smith, 2025). It is also revealed that poor management of agricultural Waste will increase costs and reduce the performance of sustainability in the agribusiness management system (Pereira et al., 2023). With increasing environmental concerns, agribusinesses are more likely to adopt sustainable operational management systems to minimize waste and protect the environment.

A circular economy system encourages continuous cycles of materials through recycling, reuse, recovery, and Waste valorization. Unlike a traditional linear economic system, the circular system emphasizes preserving value and the worth of resources while avoiding loss during management processes through regenerative resource allocation (Yang et al., 2021). In agricultural practices, circular economy applications have included biomass conversion, compost production, energy recovery, biodegradable packaging, precision agriculture systems, etc. (Klein et al., 2022). Waste mitigation methods, such as implementing sustainable management systems, not only improve environmental quality but also increase operational performance and economic profit (Sgroi, 2023). IoT and other smart management systems were shown to effectively support waste reduction, green procurement, and resource allocation (Hemasundari et al., 2025). Furthermore, the production of biodegradable materials and the recovery of renewable energy from agricultural wastes have become a trend (Bobomuratova et al., 2025; Aggarwal et al., 2025).

The study focuses on developing a circular economy model to reduce agricultural Waste, thereby improving environmental sustainability within a large-scale agribusiness management system. The constructed system framework integrates with recycling systems, composting approaches, biomass energy recovery, and sustainable operational management to maximize resource efficiency and environmental performance, and to evaluate waste reduction effectiveness, environmental quality indicators, and resource optimization for agribusiness management systems (Lan et al., 2026). The scope is primarily to propose a sustainable, resource-optimized approach and practices for the recovery of agricultural waste in a large-scale agribusiness system.

This research is intended to overcome the problems of massive accumulation of agricultural waste and the weak practices of waste recovery and sustainable management in agribusiness today. Also, this study emphasizes integrating environmental sustainability into business management systems to achieve long-term green productivity and efficient resource use. This paper has developed a comprehensive circular economy management model for large-scale agribusinesses by integrating a waste recovery mechanism into the system, sustainable operational practices, and environmentally resourceful allocation methods.

The remaining part of this paper is as follows: Section II reviews the literature on agricultural waste management, circular economy approaches, and environmental sustainability. Section III illustrates the methodology, the proposed circular economy framework, and the evaluation approaches. Section IV presents the results of the experiments and the sustainability impacts obtained through the analysis. Section V discusses the manager implications, opportunities, and difficulties of the application, and Section VI presents the conclusion, contributions, and future work.

Literature Review

Historically, agricultural waste management practices were confined to landfilling, open-field burning, and unplanned dumping, which generate various environmental and public health problems (Lackner & Besharati, 2025). These practices lead to greenhouse gas emissions, soil nutrient depletion, and land degradation, among other impacts. Nowadays, studies have stressed compost, biomass conversion, and recycling technologies as new sustainable alternatives for the utilization of agricultural Waste (Toplicean & Datcu, 2024). Biomass-based recovery systems support electricity generation and reduce dependence on non-renewable energy sources, while effectively improving waste management (Peng et al., 2025). With the advent of new methods such as biological treatment systems and precision farming monitoring systems, the accumulation of Waste has decreased while agricultural productivity has increased (Ghulam & Farman, 2025). Yet, current systems for agricultural Waste still face various challenges, such as technological limitations, weak infrastructure, and the high cost of implementation, which result in low long-term sustainability performance (Lackner & Besharati, 2025). In agribusiness, circular economy practices involve using agricultural by-products as recoverable resources within regenerative production systems and a sustainable supply chain (Gupta et al., 2025). Previous research revealed that circular agricultural systems are more efficient through recycling, the use of renewable inputs, and green production technologies (Manganda et al., 2024). Several agribusiness and agricultural companies now adopt smart production systems that promote resource recovery and environmental protection (Donner & de Vries, 2021). The integration of renewable energy sources, including biomass and bioenergy systems, has strengthened circular resource use in agricultural systems (Peng et al., 2025).

Furthermore, the incorporation of advanced agricultural technologies such as Agri 4.0, a smart farming system with digital monitoring tools, has boosted the development of sustainable agribusiness and environmental performance (Kleisiari et al., 2021; Tetteh et al., 2025). In an agricultural context, environmental sustainability is often measured by waste reduction, energy conservation, carbon emission control, and the optimization of resource inputs (Rodino et al., 2023). To investigate the effectiveness of circular agriculture or a green operating strategy, studies have developed frameworks for assessing the environmental performance of agribusiness (Toplicean & Datcu, 2024). Furthermore, sustainable management viewpoints focus on eco-friendly production plans, renewable resource input, and supply chain coordination (Gupta et al., 2025). Innovative technologies in agriculture help improve environmental monitoring and decision-making for the management of sustainable farming operations (Kleisiari et al., 2021). However, several sectors of agribusiness still face difficulties in achieving environmental sustainability while meeting business requirements (Manganda et al., 2024).

The analysis of literature proves that circular economy systems have positively impacted agricultural waste management, resource efficiency, and environmental sustainability in agribusiness. Currently, existing research primarily focuses on technological advances in sustainable agriculture and renewable energies. Still, no sufficient studies have developed integrated management-oriented circular economy models within the context of large agribusinesses based on those environmental sustainability strategies. Accordingly, this paper seeks to address the research gap by proposing an integrated model for waste recovery, sustainable operations, and environmental management for agribusinesses.

Methodology

Research Design and Data Collection

A mixed-methods research design was employed to investigate the use of a circular economy to reduce agricultural Waste and enhance the sustainability of large-scale agribusiness. A quantitative investigation to determine waste reduction efficiency, recycling performance, and environmental sustainability indices, while a qualitative investigation to study the management practices, operational constraints, and sustainability strategies implemented by the agribusiness organizations. Structured questionnaires and semi-structured interview were used to collect data from agribusiness manager, environmental supervisor and operational worker. Secondary data, such as sustainability reports, agricultural production recordsrecords, waste management documentation, and environmental monitoring databasesdatabases, were obtained. A case study. A case study was used to understand how agricultural Waste is managed in large-scale agribusiness and how the the traditional agricultural waste management system has limited its effectiveness.

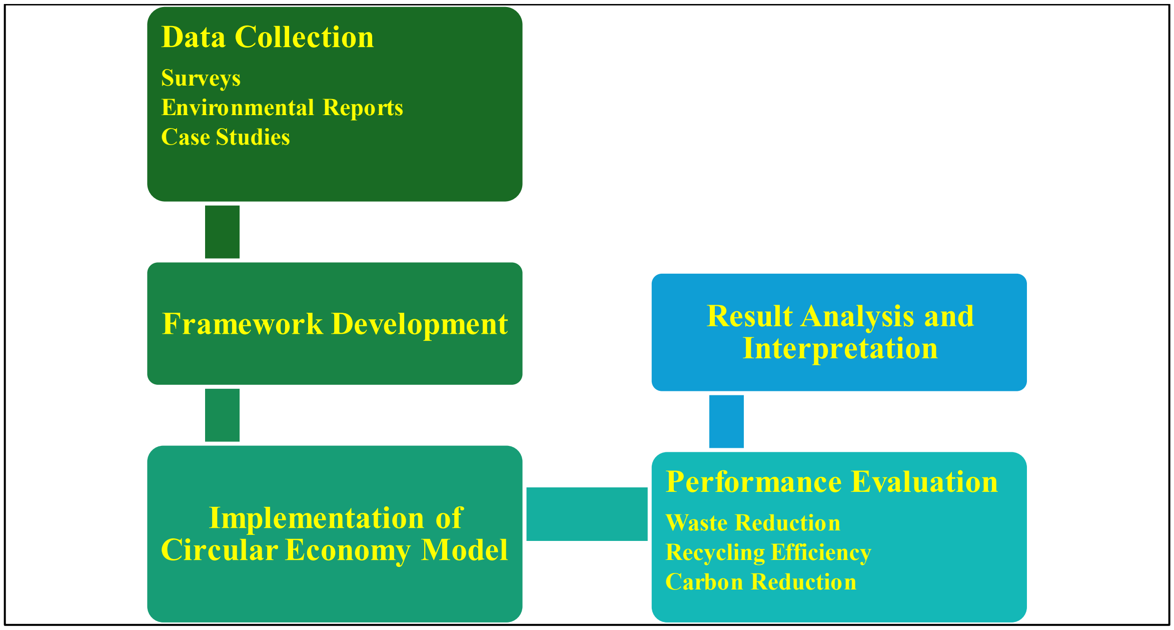

Figure 1. Research methodology workflow for circular economy implementation

Figure 1 shows a holistic methodology employed in this study to determine the viability of the suggested circular economy model in large agribusiness operations. The workflow incorporates data collection methods (survey questionnaires, environmental reports, case studies), followed by framework creation and execution of the CE model. Additionally, it incorporates performance measurement criteria (waste reduction, recycling effectiveness, and carbon reduction metrics) to analyze the outcome to gauge its environmental performance and operational efficiency.

A Proposed Circular Economy Framework

A circular economy framework was designed and developed in order to implement integrated waste recovery and sustainable resources use in large-scale agribusiness operations. The framework is comprised of waste collection, segregation, recycling, composting, biomass conversion and renewable energy generation system. Agricultural residues and biodegradable materials produced during agricultural production and processing activities were segregated and guided toward to waste recovery system rather than waste disposal system. The composting technology was implemented to recycle organic wastes into the nutrient-rich fertilizers and biomass conversion technology was used for the generation of the bio-energy using the agricultural residues. A framework includes sustainable operational workflow management to enable large-scale agribusiness organizations to connect the activities for waste recovery with the management practices for environmental monitoring and resources utilization.

Evaluation Metrics and Analysis Techniques

Environmental sustainability indicators are used to measure the performance of the proposed framework, which included waste reduction rate, recycling efficiency, carbon emission reduction and energy recovery rate. The Waste Reduction Efficiency (WRE) Equation (1) was adopted to evaluate waste reduction performance:

$$\mathrm{WRE} = \frac{\mathrm{W_b} - \mathrm{W_a}}{\mathrm{W_b}} \times 100 \qquad (1)$$

where WRE is the waste reduction efficiency, W_b is the waste generation rate before application and W_a is the waste generation rate after application. The percentage analysis, mean comparison, sustainability performance evaluation techniques are used to investigate the improvements in operations and environment. Comparative analysis was also performed between traditional waste management systems and the proposed circular economy model to establish benefits in resource efficiency, environmental sustainability and operations of large-scale agribusiness operations.

Results

Performance of Agricultural Waste Reduction

The implementation of proposed circular economy concept framework resulted in a notable progress in agricultural waste reduction and resource recovery performance in large-scale agribusiness operations. Through composting and biomass conversion, agricultural Waste from crop residues, animal by-products and food processing industries were reduce, and non-organic Waste were decrease through recycle and resource reusing strategies. The overall waste generation in agriculture were reduced from 5,420 tons to 3,328 tons per year, which the waste reduction efficiency reached 38.6%. recycle and reuse process further increase the efficiency of resource recovery to 72.4%, far better than traditional disposal-oriented waste management system.

Table 1. Agricultural waste reduction performance

Parameters	**Conventional System**	**Proposed Circular Economy Model**	**Improvement (%)**
Organic Waste Generated (tons/year)	3,800	2,150	43.4
Non-Organic Waste (tons/year)	1,620	1,178	27.3
Recycling Efficiency (%)	38.5	72.4	88.1
Resource Recovery Rate (%)	41.2	76.8	86.4

Table 1 shown the performance comparison of traditional waste management system with the proposed circular economy concept framework. This result demonstrated the large improvement of recycle efficiency and overall resource recovery performance.

Environmental Sustainability Performance

Positive environmental sustainability performance were obtained in implementation process, such as enhancement of soil quality, reduction of carbon emission and improvement of energy recovery efficiency. Through composting process, retention and organic content of soil was increased, and 21.7% increase was obtained in soil productivity indicator. Biomass energy recovery systems decreased the amount of carbon emission to 29.8% compared to traditional disposal methods. Additionally, on-site energy generation through agricultural residue can enhance conservation of resources and decrease the dependence on the external energy source.

Table 2. Environmental sustainability performance

Environmental Indicators	**Before Implementation**	**After Implementation**	**Improvement (%)**
Carbon Emissions (tons CO_2/year)	1,250	878	29.8
Soil Productivity Index	68.4	83.2	21.7
Energy Recovery Efficiency (%)	32.5	66.6	34.1
Water Resource Conservation (%)	45.2	71.3	57.7

Table 2 summarized environmental sustainability benefits obtained by circular economy concept framework, in terms of carbon emission reduction, soil quality improvement and renewable energy recovery.

Economic and Operational Benefits

The integration of resource recovery and optimized management strategies created both economic and operational benefits for agribusiness organizations. Waste handling and disposal costs decreased by 26.3% resulted from the recycling and composting of Waste. Operational productivity improved through waste segregation and resource utilization methods, which improved work coordination and reduce material lose. Eco-friendly production systems established and environmental compliance risk mitigated.

Software Details

For data analysis, statistical evaluation, sustainability performance analysis and graphical illustration of performance, Microsoft Excel, IBM SPSS Statistics 27 and Tableau were utilized. Digital agricultural resource management system was adopted to conduct environment monitoring and waste tracking.

Dataset Details

The dataset analyzed included operational and environmental data acquired from 15 large-scale agribusiness businesses in three years' period of operations, containing about 4,500 data points including waste generation amounts, recycle rate, biomass recovery data, carbon emission level, energy consumption level, soil productivity indices and operational cost, based on the result of survey and secondary reports.

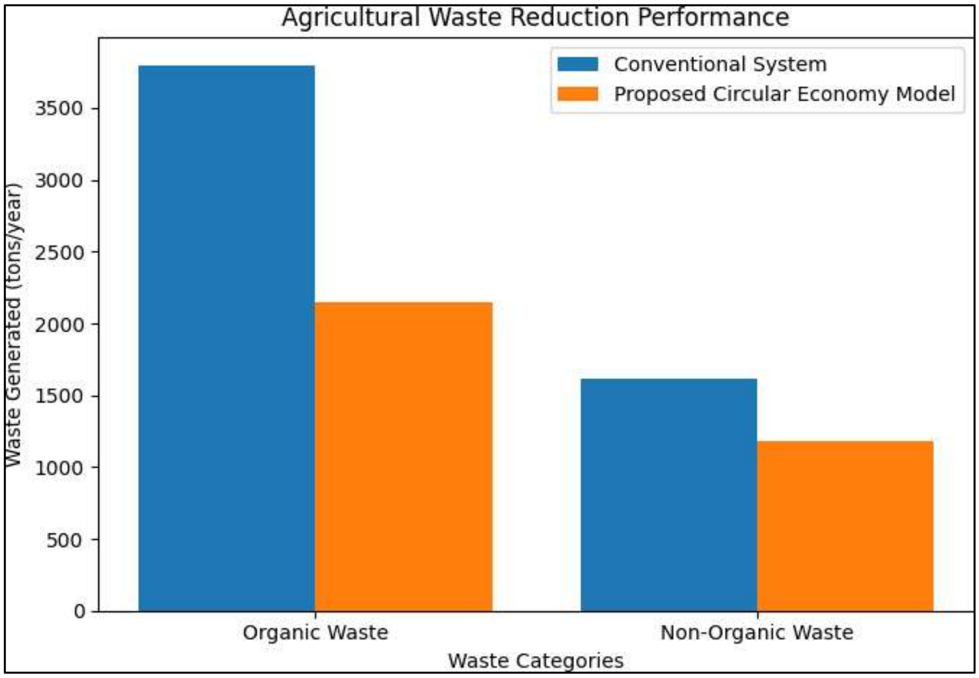

Figure 1: Waste reduction performance in agriculture

Figure 1 shows a comparison between existing systems and circular economy strategy on reduction of organic and non-organic wastes in large agribusiness. The wastes are drastically reduced with the introduction of a system based on recycling and recovering of agricultural wastes.

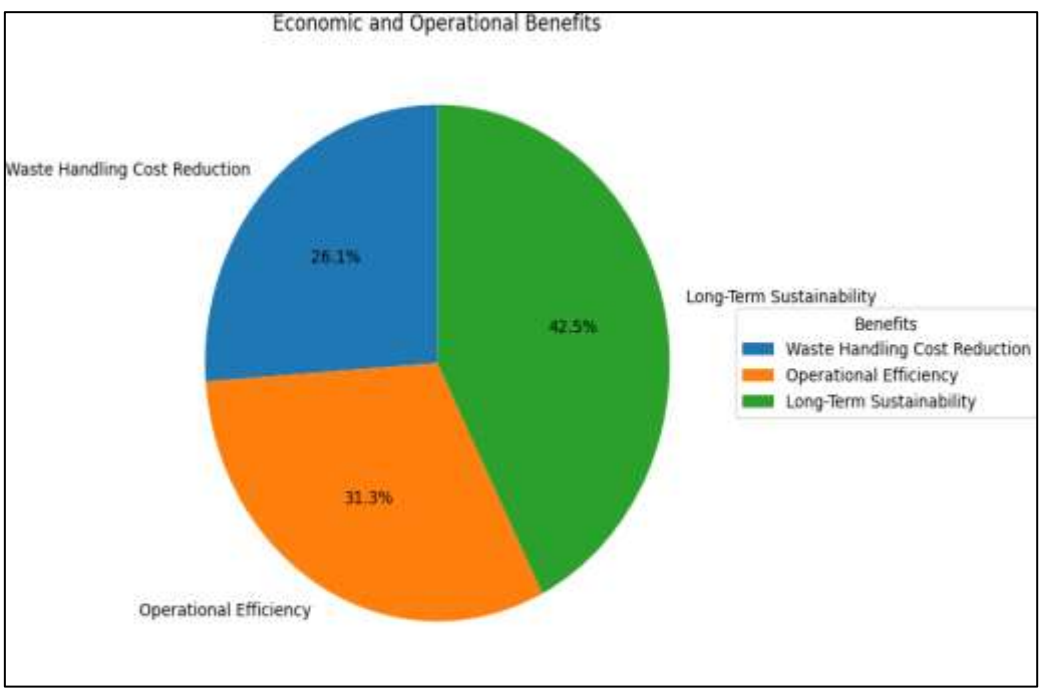

Figure 4: Economic and operational benefits of circular economy

Figure 4 depicts economic and operational benefits of implementing the circular economy concept into large agribusinesses. It discusses and indicates waste management costs, improved operational efficiency, and the sustainable economic benefits through integrated resource recovery system

Discussion

This research result proves that the integration of circular economy methods has the potential to largely optimize sustainable agribusiness management by minimizing agricultural Waste, improving resource productivity and enhancing environmental protection schemes. Operations systems of agro business under recycling, composting, biomass valorization, renewable energy technologies ensure environmentally sound operation system and further promote the sustainability of business operation for the long-term purpose. Management perspective on circular economy approach promotes better resource planning and management, cost control and a coordinated sustainable supply chain coordination so that the traditional agribusiness can transform to become environmentally responsible enterprises. The transition however has been challenging for many organizations on the basis of high expenditure needs of financial investments and low level of technology infrastructure, high operational complexity, the lack of appropriate policy support. In some situations, resistance toward organizational change and the lack of expertise can also lag down adoption of sustainable waste management practices. With all the limitation for now, the prospects seem promising, as smart agriculture technologies, AI assisted waste monitoring system and digital resource management systems could improve decision making on operation process and environment surveillance. Close partnership between government agencies, agricultural industry and environmental groups may fasten adoptability of scaleable circular economy models. Hence, agribusiness firms should start integrating operational policies and sophisticated waste recovery system gradually to ensure a green business development and sustainability.

Conclusion

This study developed a framework for circular economy to decrease the agriculture wastes, improve the environmental benefits in the large-scale agribusiness, and analyzed the implementation effect and economic benefits. Research results showed that this proposed system achieved remarkable performance in waste recovery and sustainable use of resources through integrated recycling, composting and biomass energy production systems. This circular economy model decreased 38.6% of total agriculture wastes and improved waste recycling and utilization efficiency to 72.4%, which was higher than common waste treatment methods. With respect to environment indicators, carbon emission, energy recovery efficiency and soil fertility increased by 29.8%, 34.1%, and 21.7% respectively. Also, waste treatment costs were reduced by 26.3%. That means it could generate win-win economic and environmental benefits to agribusiness companies to implement sustainable practices. This research is beneficial to environment management field because of its application on combining the circular economy and agribusiness management practices based on sustainability. In management view, this framework provided valuable direction for agribusiness managers and policy makers to enhance sustainable agricultural development and environmental protection practices. It further verified the significance of green operating systems to promote green business transition of agriculture sector. The future studies could further combine smart technologies, AI enabled waste monitoring and control, optimizing the methods of renewable energy utilization and developing digital resource management platforms to extend the proposed system. Global scale studies could be conducted to determine the suitability of the framework for different countries.

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