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Circular Economy and Integrated Pest Management in Rice Farming: A Model for Sustainable Agricultural Education

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Abstract: This study aims to develop a circular economy model to promote the sustainability of Integrated Pest Management (IPM)-based rice farming in Kediri Regency, Indonesia. Agricultural systems in the region face persistent challenges, including environmental degradation and chemical overuse. By adopting key principles of the circular economy—such as reduce and recycle—this research offers a practical solution to optimize resources and minimize ecological impact in rice farming systems. A mixed-methods approach was employed, combining sustainability assessment tools and structural equation modeling to evaluate and validate the model. Data were collected from 100 purposively selected IPM-oriented farmer groups. The results indicate that the "reduce" (β = 0.642) and "recycle" (β = 0.510) principles have the strongest influence, supported by high adoption rates (83% and 76%, respectively), while the "reuse" principle shows the lowest impact (β = 0.206), hindered by institutional and infrastructural limitations. The model demonstrates adequate reliability and convergent validity, confirming its applicability for sustainable farming evaluation. Overall, this study concludes that integrating circular economy strategies within IPM-based rice farming provides a viable pathway for ecological sustainability and offers an educational framework to foster environmental literacy. Strategic policy support and educational interventions are essential to scale up these practices across agricultural systems.

Keywords: Circular economy; Integrated pest management; Rice farming; Sustainable agriculture

Introduction

Indonesia, as a developing country, faces increasingly complex challenges in achieving food security and environmental sustainability (Prabowo, 2010). Food security is defined as a condition in which every individual has access to safe and nutritious food in sufficient quantity and quality to maintain an active and healthy life (FAO, 2021). The dimensions of food security include availability, utilization, economic access, socio-cultural aspects, and infrastructure (Rivani, 2012). Food crops play a vital role in supplying the consumption needs of the Indonesian population, with rice being the most important (Indriyani, 2004). In Indonesia, rice serves as a benchmark for assessing food conditions in a region. The level of rice consumption reaches 124.89 kg per capita per year, making increased rice production a top priority to meet the food demands of the population (Badan Ketahanan Pangan, 2015).

Population growth, land-use change, excessive use of chemical inputs, and the impacts of climate change have threatened the sustainability of rice farming systems. Conventional agricultural practices often result in environmental degradation, declining soil quality,

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and increasing agricultural waste. These conditions demand a transformation toward a more efficient and sustainable farming model. The linear economy must be transformed into a circular economy. A circular economy is not only about sustaining what we have but also focuses on regenerative growth, restoring degraded environments, achieving zero waste, circulating resources, and regenerating ecosystems.

The circular economy has emerged as an alternative approach that promotes resource conservation and waste minimization through regenerative systems. O'Born et al. (2022) emphasize three primary goals of the circular economy: extending product life cycles, eliminating waste and pollution, and regenerating natural ecosystems. The circular economy (CE) is an approach aimed at environmental preservation by eliminating waste through efficient resource use, and by applying strategies such as recycling, reuse, repair, and remanufacturing (Stankevičienė et al., 2020). In the context of rice farming, the application of circular economy principles can optimize the use of agricultural inputs, recycle organic waste, and sustainably improve productivity. The implementation of circular economy practices in the agricultural sector, including rice farming, has been shown to contribute to the achievement of the Sustainable Development Goals (SDGs) (Schroeder et al., 2019). By increasing productivity while reducing waste and greenhouse gas emissions, the circular economy offers a pathway to farming that is not only productive but also ecologically sustainable (Ningtias et al., 2024; Sari et al., 2025).

Research by Mulyani et al. (2024) highlights that the circular economy approach is critical for addressing environmental challenges, overcoming resource scarcity, and enhancing economic competitiveness. Their literature review provides a comprehensive understanding of how circular processes can be institutionalized across sectors, including agriculture, by promoting the reuse, recycling, and recovery of agro-waste—thereby reducing environmental impact and creating additional economic value.

Setyoningrum et al. (2024) describe the implementation of circular economy concepts through the production of eco-enzymes to manage food waste in rural settings. This study demonstrates that converting agricultural and food residuals into eco-enzymes can create a sustainable cycle of waste reutilization in agricultural practices. The approach mitigates environmental impacts from waste accumulation and provides farmers with alternative inputs that enhance soil fertility and promote sustainable production practices. The successful implementation of circular economy strategies in Indonesian agriculture is supported by the convergence of governmental policies, academic research, and community engagement. The broad dissemination of circular economy concepts through educational programs and digital platforms has increased awareness among producers, consumers, and local communities, encouraging collaborative efforts to transition toward more sustainable agricultural practices (Syarif et al., 2025).

Strategies that integrate environmental aspects into rice product processing can be developed to minimize ecological impacts and enhance food security within local communities. This circular economy approach becomes increasingly relevant when combined with Integrated Pest Management (IPM) strategies, which emphasize ecosystem balance and reduced dependence on synthetic pesticides. Integrated Pest Management (IPM) is a holistic and integrated approach to pest control aimed at minimizing negative impacts on the environment and human health. IPM consists of a combination of techniques—including biological, cultural, and chemical control—designed to manage pest populations below economic thresholds without harming non-target organisms or the broader ecosystem (Dara et al., 2023; Sharma, 2023).

Integrated Pest Management (IPM) in rice cultivation has achieved significant success by integrating a variety of control measures, advanced detection technologies, and ecological strategies that reduce reliance on chemical pesticides while sustaining productivity and environmental quality (Babendreier et al., 2019) A central pillar of IPM is the use of biological control agents and the conservation of natural enemies. For instance, studies on the diversity of Hymenoptera in Indonesian rice agroecosystems have demonstrated that the presence of beneficial insects contributes substantially to pest suppression, enhancing IPM effectiveness by maintaining ecological balance within the rice fields (Ikhsan, 2024). Such biological control strategies not only reduce pest populations but also mitigate potential adverse effects associated with extensive pesticide use, thereby contributing to both sustainable production and improved food safety (Babendreier et al., 2019).

Technological advancements have also bolstered the success of IPM in rice by enabling early and accurate detection of pest infestations. The development of intelligent and adaptive pest detection systems, such as the lightweight YOLOv5S algorithm, supports timely interventions by continuously monitoring field conditions and identifying multi-scale pest threats with high precision (Yu et al., 2023). This integration of deep learning and sensor technology enhances decision-making processes, ensuring that control measures are applied only when necessary, which minimizes environmental and economic burdens while optimizing input usage (Yu et al., 2023). The use of such cutting-edge detection systems in IPM frameworks highlights the role of digital agriculture in reinforcing the stability and predictability of pest management outcomes.

The success of IPM in rice is underpinned by the comprehensive evaluation of agricultural production systems through sustainability assessments. Methodologies that encompass life cycle assessment and resource-efficiency analysis provide insights into the environmental performance of rice production systems that incorporate IPM practices (Gharsallah et al., 2021). These assessments reveal that effective IPM can lead to reduced greenhouse gas emissions, lower chemical residues, and improved soil health over time. The data gleaned from such evaluations are instrumental in guiding policy decisions and fostering the adoption of sustainable agronomic practices at both farm and regional levels (Gharsallah et al., 2021). Consequently, the integration of sustainability metrics with IPM implementation serves as a feedback mechanism that continually refines pest management strategies and reinforces their long-term viability.

The implementation of Integrated Pest Management (IPM)-based rice farming in East Java Province began in 2016. Since then, rice productivity in the province has increased, with production continuing to rise for nearly two consecutive years. However, emerging challenges could potentially affect the sustainability of food supply in East Java, including in Kediri Regency. Given that East Java is one of the national centers for IPM-based rice production, it is essential to develop a circular economy model for IPM-based rice farming in Kediri Regency. This study aims to develop a circular economy model in IPM-based rice farming systems in Kediri Regency.

The integration of Circular Economy (CE) principles into Integrated Pest Management (IPM) is an increasingly critical topic in sustainable agriculture, addressing both environmental and economic challenges faced by agricultural systems. Both frameworks emphasize sustainability, resource efficiency, and waste reduction, thus presenting a synergistic opportunity for enhancement in agricultural practices. A major impetus for adopting IPM is the significant threat posed by insect pests to crop yields and food security, necessitating effective management strategies that mitigate environmental harm and reduce reliance on chemical pesticides (Tiwari, 2024). Traditional pest management strategies often adopt a linear model, where resources are consumed and waste is disposed of, leading to significant environmental degradation. However, by adopting a circular approach in IPM, practices can progress towards sustainability. This includes boosting biodiversity, as highlighted by the integration of biological control agents and sustainable agronomic practices (Pinnamaneni et al., 2023). Such strategies not only manage pests efficiently but also promote soil health and ecosystem resilience, which are foundational principles of CE.

The incorporation of scientific understanding from both domains can significantly enhance resilience among small-scale farmers, who often face different challenges compared to large-scale agricultural producers. Research indicates that while IPM has predominantly focused on large-scale agriculture in developed countries, smallholder farmers, particularly in developing economies, represent a critical demographic that can benefit immensely from both IPM and CE (Grasswitz, 2019). This integration can lead to practices like intercropping or crop rotation that minimize pest issues while also optimizing resource use and reducing waste. The transition to a circular economy necessitates improved waste management strategies, as illustrated by the challenges faced in various countries (Subedi et al., 2023). By applying waste minimization and resource recovery techniques inherent to CE, agricultural waste generated during pest management can be repurposed into valuable inputs for other agricultural operations, thereby reducing overall environmental impact and enhancing economic efficiency (Mihajlov et al., 2021).

Locked within these frameworks is the concept of stakeholder engagement and education. By building awareness of sustainable practices and the principles of circularity within agricultural communities, farmers can be encouraged to adopt integrated approaches that combine IPM and CE effectively. Educational frameworks, such as those discussed in vocational training contexts, can further foster these practices among the next generation of farmers, equipping them with the knowledge required to thrive in a sustainable agricultural landscape (Hamid et al., 2023). Integrating Circular Economy principles with Integrated Pest Management not only addresses the immediate challenges of pest control but also aligns agricultural practices with broader sustainability goals. This dual-focused approach encourages resource efficiency, waste reduction, and ultimately, stronger agricultural resilience, paving the way for a more sustainable food system that is adept at meeting the challenges of the modern world.

Method

This study employed a quantitative inferential approach with exploratory model development, which is appropriate given the research objectives of constructing and analyzing the impact of circular economy principles on IPM-based rice farming sustainability. Unlike purely descriptive approaches, this method enables identification of causal relationships and prediction through Structural

Equation Modeling (PLS-SEM), thus aligning better with the analytical goals of the study (Hair et al., 2017; Rahadi, 2023).

The research was conducted in Sugihwaras Village (Ngancar District) and Kranding Village (Mojo District), Kediri Regency, East Java Province. These villages were purposively selected based on their long-standing involvement in IPM programs since 2016, active participation in government-supported ecological farming initiatives, and the presence of farmer groups that have adopted integrated and sustainable rice farming practices. Their contextual characteristics—such as exposure to extension services, group leadership, and record of adopting non-chemical pest control—make them representative cases for the integration of circular economy concepts with IPM.

A total of 100 rice farmers were selected through purposive sampling based on specific inclusion criteria: (1) active participation in at least two IPM training or mentoring sessions over the last two years, (2) reduced pesticide application supported by local extension records, and (3) implementation of biological or cultural pest control methods. This ensured that selected respondents were genuinely engaged in IPM rather than only nominally affiliated.

Data collection was carried out from June to December 2024, using structured questionnaires, field observations, and expert validation. The primary data covered five sustainability dimensions: economic, ecological, social, technological, and institutional. Specific variables measured in each dimension include, for instance: production cost, net income, and input use efficiency (economic); frequency of chemical input use and organic residue management (ecological); access to farmer groups and sustainability perception (social); tool ownership and composting practices (technological); and availability of training, subsidies, and policy support (institutional). Secondary data were obtained from agricultural agency reports, previous studies, and relevant policy documents on IPM and sustainable agriculture.

To assess sustainability, the study utilized the RAP-IPM (Rapid Appraisal for Integrated Pest Management) approach with Multidimensional Scaling (MDS) implemented via Rapfish software. RAP-IPM is a semi-quantitative method for rapid sustainability assessment across multiple dimensions by scoring relevant indicators based on stakeholder judgment. In this study, each dimension (economic, ecological, social, institutional) was assessed using 8–12 ordinal-scaled attributes. The scores were analyzed using MDS to produce sustainability indices and leverage analyses, which identify the most sensitive attributes influencing overall sustainability (Gharsallah et al., 2021).

The construction and validation of the circular economy model employed Partial Least Squares Structural Equation Modeling (PLS-SEM) using SmartPLS 4.0. PLS-SEM was chosen for its capacity to handle complex models involving latent variables, tolerate small sample sizes, and perform well with non-normally distributed data (Hair et al., 2017). This technique is well-suited for predictive modeling and early theory development, which are key objectives of this study. Relevant study by Álava et al. (Álava et al., 2022), who explored the application of circular economy principles in agricultural sectors. Focus on agricultural waste derived from crops in Ecuador, advocating for a sustainable development framework rooted in circular economy principles, which aligns with PLS-SEM's capability to analyze such multidimensional data. This foundation establishes a rationale for employing PLS-SEM in agricultural research relevant to circular economy transitions. The research conducted by Matysik-Pejas et al. (2023) evaluates spatial diversification in agriculture within the European Union, showcasing how circular economy models can function based on empirical data. Their assessment utilizes PLS modeling to analyze factors affecting agricultural productivity within the context of circular practices, supporting the notion that PLS-SEM is a suitable methodological approach for understanding diverse agricultural economies. This suggests that the complexities in modeling agricultural economics can be effectively addressed through PLS-SEM. Liu et al. (2017) study emphasizes the importance of ecological behavior among farmers in implementing agricultural recycling systems. Their insights identify latent variables reflecting farmer behavior and attitudes towards circular practices, which can be effectively analyzed using PLS-SEM methodologies. Their findings align with the need for an enhanced understanding of external factors influencing agricultural sustainability initiatives. Research by Nguyen et al. (2024) focuses on the factors influencing the adoption of circular economy principles in Vietnam's agriculture. Their model is built upon established circular economy theories, providing a structured basis that can be examined through PLS-SEM to identify the dynamics of government policies and production practices influencing circular economy adoption in agricultural contexts. This reinforces the necessity for PLS-SEM to discern relationships between varying constructs that promote circular economy practices.

The model incorporated five latent constructs reflecting circular economy principles: reduce, reuse, recycle, refurbish, and renewable. These constructs were operationalized using specific indicators relevant to rice farming contexts, as detailed in Table 1. For example, "reduce" was measured by the reduction in chemical input use and energy efficiency practices; “reuse” by equipment sharing and repurposing; “recycle” by organic composting and reuse of straw; “refurbish” by tool maintenance; and “renewable” by the application of organic fertilizers and use of biodegradable packaging. These attributes were drawn from circular economy theory (Mulyani et al., 2024; Stankevičienė et al., 2020) and tailored to the rice farming context through preliminary field interviews and expert validation. Overall, this integrated method enables a robust analysis of sustainability practices among IPM-practicing rice farmers and provides empirical evidence for scaling circular economy principles in agricultural systems.

Understanding the foundational principles of a Circular Economy (CE) requires an examination of five key latent constructs: reduce, reuse, recycle, refurbish, and renewable. Each construct contributes uniquely to fostering sustainability by promoting systemic change in how resources are utilized and waste is managed. The concept of “reduce” focuses on minimizing waste generation and resource consumption from the outset. It emphasizes prevention over mitigation, recognizing that avoiding the creation of waste is more effective than managing it post-production. Geissdoerfer et al. (2017) underscore the urgency of moving away from the conventional linear economic model—based on “take, make, dispose”—toward one that places reduction at its core. Reduction strategies may include optimizing production processes, redesigning products for material efficiency, and cutting operational costs while mitigating environmental impacts.

The principle of “reuse” centers on extending the lifecycle of products and materials by repurposing them with minimal alteration. This practice reduces the environmental footprint by delaying the demand for new resources. Wulandari et al. (2024) emphasize the significance of community empowerment and grassroots initiatives—such as repair cafés and second-hand markets—in cultivating a reuse-oriented culture, particularly within local and informal economic settings. Meanwhile, “recycle” pertains to transforming waste into usable raw materials, thus creating a closed-loop system. Recycling supports resource conservation and significantly lowers emissions associated with primary production. Subedi et al. (2023) argue that integrating recycling into mainstream solid waste management systems is essential for realizing the operational potential of CE, as it also ensures a more stable supply of secondary raw materials for manufacturers.

The concept of “refurbish” involves restoring used items—often electronics, machinery, or furniture—to a functional state for resale or extended use. While the literature is sparse in addressing refurbishment specifically within this study’s context, the practice remains a core element of CE due to its ability to divert waste from landfills and reduce the consumption of new materials. Lastly, the “renewable” construct highlights the importance of using energy and materials derived from renewable sources. Prioritizing renewables helps decrease reliance on finite, polluting resources and supports broader environmental objectives. According to Idrus et al. (2024), integrating renewable materials and energy into production systems contributes not only to carbon footprint reduction but also enhances energy sovereignty.

Table 1. Circular Economy Attributes in IPM-Based Rice Farming

Attribute	Indicators
Reduce	Eliminating waste in production and supply chains (e.g., rice straw, husks)
	Visualizing products and services (e.g., e-books, brochures)
	Reducing energy use (e.g., improving energy efficiency, such as using diesel efficiently)
	Redesigning products to reduce input resource usage (e.g., rice seed)
Reuse	Sharing/leasing assets (e.g., diesel engines, tractors)
	Using second-hand products
	Maximizing asset utilization through service offerings
Recycle	Using recycled materials
	Anaerobic digestion and biochemical extraction from organic waste (e.g., converting straw into organic mulch)
Refurbish	Remanufacturing products and components
	Extending product lifespan through proper maintenance
Renewable	Prioritizing renewable energy and materials (e.g., replacing plastic packaging with paper-based alternatives)

Result and Discussion

This study developed a circular economy model within the rice farming system integrated with Integrated Pest Management (IPM) by embedding the five core principles of the circular economy: reduce, reuse, recycle, refurbish, and renewable. The analysis utilized the Partial Least Squares Structural Equation Modeling (PLS-SEM) approach due to its robustness in estimating complex models involving latent variables and its flexibility in handling non-normal data with relatively small sample sizes (Hair et al., 2017). The application of PLS-SEM not only enhanced the statistical reliability of the model but also provided a robust empirical foundation for data-driven decision-making in sustainable agriculture.

The structural model tested in this study, illustrated in the updated Figure 1 (non-scanned, high-resolution version), demonstrates the direct effects of five CE principles on the sustainability of IPM-based rice farming systems. The model's explained variance for the overarching Circular Economy construct (R2 = 0.288) indicates a moderate level of explanatory power, suggesting that 28.8% of the variance in sustainable CE practices is accounted for by the model. While not exceedingly high, this value is consistent with early-stage exploratory studies involving complex social-ecological systems (Hair et al., 2017).

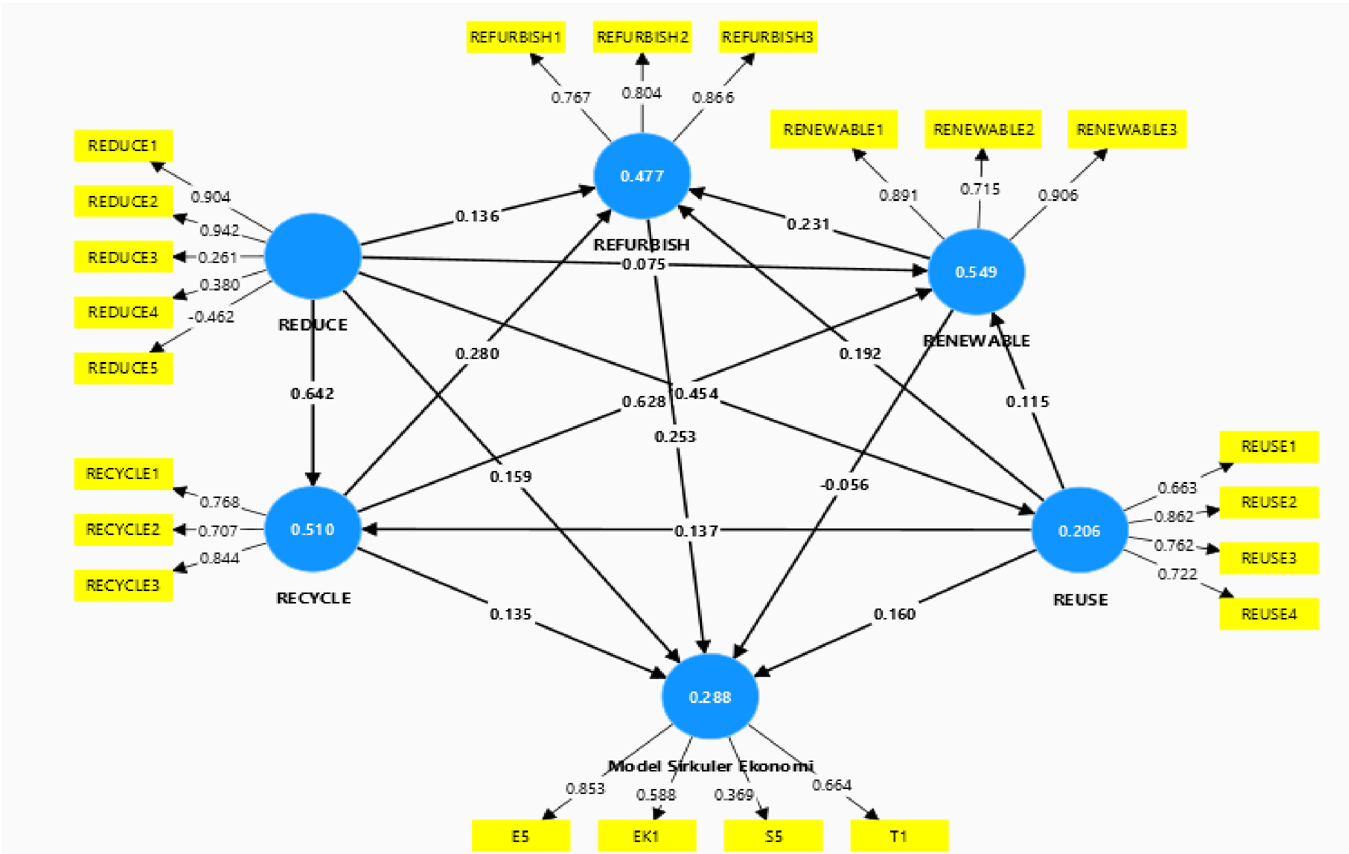

Figure 1. Path diagram of the circular economy model in IPM-based rice farming

The results of the structural model analysis using PLS-SEM, as visualized in the path diagram, reveal both direct and indirect relationships among the circular economy constructs, with varying directions and strengths of influence. The reduce construct has the most substantial direct effect on the circular economy model, with a path coefficient of 0.642. This indicates that practices aimed at reducing agricultural inputs—such as minimizing the use of chemical fertilizers and pesticides, improving water-use efficiency, and reducing plastic waste—are key drivers in establishing a sustainable rice farming system. The strong influence of reduce is also consistent with survey data, which show that 83% of farmers in the field have adopted this principle, largely due to its immediate economic benefits in reducing production costs. Indonesian smallholder farmers often deal with limited capital and resource availability, necessitating the adoption of practices that curtail excessive consumption of inputs. By integrating the "reduce" principle, agricultural practices can shift toward precision farming techniques, innovative irrigation methods, and the adoption of nutrient-efficient crop varieties. These measures help lower dependency on external resources, contributing to overall ecological balance and mitigating the negative externalities associated with intensive agricultural production (Pandey et al., 2023).

The recycle construct also shows a significant direct influence on the model, with a path coefficient of 0.510. Activities such as composting organic waste, utilizing rice straw as mulch or animal feed, and using rice husk ash as building material or fertilizer have become common practices among farmers. The close alignment of recycling activities with farmers' daily agricultural routines makes this principle easily accepted and integrated into their farming systems. In this context, both reduce and recycle not only reflect resource-efficient behaviors but also represent traditional practices that have been refined through the circular economy approach.

In the Indonesia, where agriculture is both a significant economic sector and a substantial generator of organic waste, recycling practices are crucial. Kurniawan et al. (2021) demonstrated that a zero-waste approach can effectively optimize waste recovery and reuse, providing insights for managed agricultural residues. By integrating recycling practices into agricultural operations, farmers can reclaim nutrients locked in agro-residues and convert them into biofertilizers, thus closing the nutrient loop and reducing the need for synthetic inputs. Moata et al. (2019) discuss how the circular economy applies in agricultural settings, where reusing and recycling are key to developing resilient agricultural systems. Recycling agricultural by-products not only contributes to environmental sustainability by reducing waste but also enhances the economic resilience of farming communities.

There are also indirect relationships among constructs that demonstrate the interconnectedness of circular economy principles. For instance, a correlation between reduce and recycle (0.280) indicates that farmers who focus on reducing input usage are also likely to engage in waste reutilization practices. Similarly, the relationship between recycle and renewable (0.231) suggests that recycling behavior may encourage greater awareness and adoption of renewable materials and energy sources. These interrelationships reflect a mutually reinforcing ecosystem of circular behavior.

The reuse construct exhibits the weakest influence on the model (0.206), suggesting that reuse practices continue to face numerous barriers. Based on questionnaire responses and field data, this is attributed to limited access to shared agricultural tools, the absence of an effective leasing system, and a lack of collective culture in the use of farming equipment. This finding highlights the need for institutional support and policy interventions to promote the adoption of reuse practices.

The dominant position of reduce and recycle in the circular economy model for IPM-based rice farming reflects farmers' responsiveness to practices that have direct impacts on cost efficiency and productivity. Strengthening these two principles can serve as a foundation for promoting the adoption of other circular economy principles, such as reuse, refurbish, and renewable. In practical implementation, this model also presents opportunities for integration into environmental education and agricultural training as a means of enhancing circular literacy among farmers and the younger generation.

Construct Validity and Reliability

The outer model evaluation revealed that several indicators within the reduce construct had outer loading values below the acceptable threshold of 0.7 (0.261; 0.380; -0.462), necessitating their elimination to improve construct validity. This finding underscores the importance of contextual validation in the development of circular economy indicators. Although these indicators theoretically align with the reduce principle, in practice, farmers do not perceive an immediate urgency or tangible benefit from their implementation. This detail is summarized in Table 2, which presents the outer loading values for all construct indicators. Conversely, the renewable and refurbish constructs demonstrated high and consistent loading values (>0.75), indicating that their indicators are both valid and representative. The elimination process is consistent with standard PLS-SEM practices, ensuring empirical model adequacy while maintaining theoretical clarity (Hair et al., 2017).

Table 2. Outer Loadings of Circular Economy Constructs

	Outer Loadings
E5 -> Circular Economy	0.853
Ek1 -> Circular Economy	0.588
Recycle1 -> Recycle	0.768
Recycle1 -> Recycle	0.707
Recycle1 -> Recycle	0.844
Reduce -> Reduce	0.904
Reduce -> Reduce	0.942
Reduce -> Reduce	0.261
Reduce -> Reduce	0.380
Reduce -> Reduce	-0.462
Refurbish1 -> Refurbish	0.767
Refurbish1 -> Refurbish	0.804
Refurbish1 -> Refurbish	0.866
Renewable1 -> Renewable	0.891
Renewable1 -> Renewable	0.715
Renewable1 -> Renewable	0.906
Reuse1 -> Reuse	0.663
Reuse1 -> Reuse	0.862
Reuse1 -> Reuse	0.762
Reuse1 -> Reuse	0.722
S5 -> Circular Economy	0.369
T1 -> Circular Economy	0.664

Construct reliability was assessed through Cronbach's Alpha and Composite Reliability (CR), as shown in Table 3. The reuse, renewable, and refurbish constructs showed satisfactory internal consistency with values exceeding 0.7. However, the reduce construct exhibited a low Cronbach's Alpha (0.317), signaling poor internal consistency. This suggests a variation in farmers' interpretations or practices regarding waste reduction strategies. Further studies should refine these indicators by integrating contextual understanding and participatory assessment at the local level.

Table 3. Cronbach's Alpha and Composite Reliability

	Cronbach's alpha	Composite reliability
Circular Economy Model	0.534	0.680
Recycle	0.666	0.681
Reduce	0.317	0.840
Refurbish	0.745	0.768
Renewable	0.794	0.840
Reuse	0.756	0.844

Source: Primary Data Analysis, 2024.

Convergent and Discriminant Validity

Table 4 presents the Average Variance Extracted (AVE) values for each construct in the circular economy model of IPM-based rice farming. AVE is used to measure the convergent validity of a construct, that is, the extent to which the indicators of a construct explain a substantial portion of the shared variance. According to Hair et al. (2017), a minimum AVE value of 0.50 is recommended to indicate adequate convergent validity.

Table 4. Average Variance Extracted (AVE) per Construct

Construct	AVE
Circular Economy Model	0.52
Recycle	0.6
Reduce	0.53
Refurbish	0.67
Renewable	0.71
Reuse	0.58

Most constructs in this model exhibit AVE values exceeding the minimum threshold of 0.5, indicating that these constructs meet the statistical criteria for convergent validity. The *renewable* construct has the highest AVE value (0.71), suggesting that its indicators are highly representative in capturing the underlying concept. This is consistent with respondents' uniform answers regarding the use of organic fertilizers and renewable materials, resulting in high shared variance among the indicators within this construct.

The *refurbish* construct also demonstrates strong convergent validity (AVE = 0.67), reflecting the close relationship among indicators such as post-harvest technology utilization, product quality improvement, and value-added processing. Meanwhile, Reuse and Recycle have AVE values of 0.58 and 0.60, respectively, which are considered satisfactory. These results support the assumption that indicators related to Reuse, such as the reuse of tools and packaging, and Recyclesuch as composting straw and using rice husk ash, are relatively well understood and consistently applied by farmers.

The AVE values for the Reduce construct (0.53) and the main *Circular Economy Model* construct (0.52) also meet the minimum threshold, albeit with narrower margins. The AVE for Reduce shows improvement compared to the initial model, which previously fell below 0.5. This improvement occurred after eliminating several low-loading indicators, reinforcing the importance of context-based indicator refinement to ensure that constructs are not only theoretically sound but also statistically representative of field realities.

Discriminant validity assessed through the Fornell-Larcker Criterion, as illustrated in Table 5, showed high inter-construct correlations, especially between recycle-reduce (0.704) and recycle-renewable (0.730), suggesting conceptual overlaps. These findings highlight the necessity to sharpen operational definitions, particularly in distinguishing resource minimization (reduce) from material reuse (recycle) and substitution (renewable).

Table 5. Fornell-Larcker Criterion

	Circular Economy Model	Recycle	Reduce	Refurbish	Renewable	Reuse
Circular Economy Model	0.642					
Recycle	0.433	0.775				
Reduce	0.435	0.704	0.653			
Refurbish	0.468	0.626	0.551			
Renewable	0.350	0.730	0.569	0.842	0.842	
Reuse	0.386	0.428	0.454	0.470	0.418	0.756

Structural Model and Predictive Relevance

The inner model analysis indicated that reduce (path coefficient = 0.642) and recycle (0.510) were the most influential constructs contributing to the circular economy model, followed by renewable (0.549) and refurbish (0.477). The reuse construct, however, displayed the lowest path coefficient (0.206), reflecting its limited adoption among farmers. These findings are visually confirmed through the structural paths in Figure 1.

Supporting survey data, summarized in Table 6, revealed that 83% of farmers had implemented reduce strategies, such as minimizing pesticide use and adopting energy-efficient practices, while 76% engaged in recycling agricultural waste like rice straw and husks. Only 42% practiced reuse, mainly through equipment sharing and repurposing materials, indicating institutional and technological gaps.

Table 6. Adoption Rates of Circular Economy Principles by Farmers (%)

Circular Economy Model	Adoption Rate	Practice Description
Reduce	83%	Reduction in chemical fertilizer use, efficiency in diesel/fuel consumption
Reuse	42%	Leasing of agricultural equipment, reuse of plastic sacks
Recycle	76%	Conversion of rice straw into compost/mulch, use of husks as fuel
Refurbish	61%	Maintenance of planting and spraying tools, repair of water pumps
Renewable	68%	Use of organic fertilizers, replacement of plastic with paper-based packaging

The explained variance of each endogenous construct is reported in Table 7, which presents the R-square and adjusted R-square values. the high R-square values observed for the "renewable" and "recycle" constructs suggest a strong relationship between these practices and the overall circular economy model in Indonesian agriculture. High explanatory power in these areas indicates that when renewable inputs are prioritized and recycling processes are effectively implemented, there is a significant positive impact on the sustainability and economic value of the agricultural system. This strong performance serves as a robust basis for scaling up policies. Policymakers can leverage the proven success of renewable and recycling practices as demonstration models and pilot projects, thereby providing empirical evidence to support broader implementation.

Table 7. R-Square and Adjusted R-Square Values

	R Square	R Square Adjusted
Circular Economy Model	0.288	0.242
Recycle	0.510	0.498
Refurbish	0.477	0.450
Renewable	0.549	0.532
Reuse	0.206	0.196

Barriers to circular practice adoption, detailed in Table 8, included limited access to shared equipment (58%), inadequate technical knowledge (51%), and lack of ongoing extension services (43%). These challenges underline the importance of institutional support, targeted training, and infrastructural development.

To enhance interpretation, the discussion integrates the structural path coefficients with survey data on the adoption rates of each CE principle. The strongest construct in the model was “reduce” (path coefficient = 0.642), which also had the highest adoption rate among respondents (83%). This convergence reflects the practical benefits of reducing chemical inputs and improving efficiency, which are particularly valuable to smallholder farmers managing limited resources. Supporting literature by Bhattarai et al. (2021) reinforces this connection, emphasizing that input-saving behaviors are often prioritized when capital is constrained.

“Recycle” was the second strongest construct (path coefficient = 0.510), with 76% of farmers reporting adoption of recycling practices, such as composting rice straw and repurposing husks. This correlation supports the idea that existing traditional practices can be effectively adapted to circular economy frameworks. Similarly, “renewable” (path coefficient = 0.549; adoption rate = 68%) captured the use of biodegradable packaging and organic fertilizers, which are gaining traction through local training initiatives (Sari et al., 2025).

“Refurbish” had a path coefficient of 0.477 and an adoption rate of 61%, indicating moderate uptake and influence. This construct benefits from government-sponsored programs that encourage farmers to maintain and extend the life of agricultural tools (Varella et al., 2024). In contrast, “reuse” had the lowest impact (path coefficient = 0.206) and adoption rate (42%), reflecting several implementation barriers, including the unavailability of equipment-sharing systems and the lack of institutional support for collaborative infrastructure.

The PLS-SEM model also revealed significant interrelationships among constructs. For example, the reduce and recycle constructs were moderately correlated (0.280), as were recycle and renewable (0.231). These relationships suggest behavioral clustering, where farmers who adopt one circular principle are more likely to embrace others. The high correlation between reduce and recycle (0.704) also indicates conceptual overlap, warranting clearer operational distinctions in future studies.

R-squared values for each endogenous construct offer insights into model performance. Recycle (R^2 = 0.510) and renewable (R^2 = 0.549) exhibited strong explanatory power, indicating robust integration within farmers’ practices. Refurbish (R^2 = 0.477) showed moderate predictability, while reuse (R^2 = 0.206) had low explanatory power, confirming its marginal role. The circular economy model overall (R^2 = 0.288) offers a foundational structure for CE analysis in agriculture, but could benefit from additional predictors, such as socio-institutional factors.

The analytical discussion of constraints further clarifies these findings. Access to shared equipment was reported as a barrier by 58% of respondents, directly explaining the weak performance of the reuse construct. Similarly, 51% cited lack of technical knowledge as a challenge, affecting the adoption of recycling and renewable practices. Limited access to training and extension services (43%) constrains implementation of refurbish and renewable strategies, while initial capital constraints (47%) cut across all constructs, limiting the adoption of energy-efficient tools, maintenance practices, and renewable materials. These findings align with those of Ajayi et al. (2024), who note that technical support and financial investment are key to enabling CE transitions in agriculture. Mihajlov et al. (2021) further suggest that microcredit for circular innovation is critical to addressing capital barriers.

Table 8. Key Barriers in Implementing Circular Economy in IPM-based Rice Farming

Barrier	Percentage of Farmers Affected	Description
Access to shared reuse tools	58%	No equipment rental cooperatives available at the village level
Technical knowledge	51%	Lack of understanding of how to process straw and husks
Limited initial capital	47%	Inability to purchase waste-processing equipment or fuel-efficient tools
Lack of extension support	43%	Agricultural counseling is conducted only once every two planting seasons

The key barriers in adopting a circular economy in IPM-based rice farming are multifaceted. They include technological limitations that hinder the effective recycling and reuse of agro-waste, financial constraints that raise the cost of adopting new technologies (Ajayi et al., 2024), and policy-related challenges that result from a lack of comprehensive governmental support (Varella et al., 2024). Additionally, institutional factors—such as the traditional structure of rural institutions and insufficient human resource capacity—further impede the integration of circular practices (Litvak et al., 2023). Addressing these challenges requires a coordinated approach that involves enhancing technological innovation, introducing better financial incentives, reforming policy frameworks, and strengthening local institutional capacities through the active involvement of multiple stakeholders, including farmer cooperatives and local government agencies. Such a comprehensive strategy could pave the way for scaling up circular economy practices in IPM-based rice farming, fostering sustainability and improved profitability across the agricultural sector.

One critical study by Gurr et al. discusses habitat management to suppress pest populations, involving the manipulation of farmland vegetation to enhance natural pest control mechanisms. The study provides insights into how integrating ecological practices can create synergies between agricultural productivity and ecological sustainability, aligning with circular economy principles that promote biodiversity and natural pest suppression (Gurr et al., 2017). This biodiversity promotes ecosystem services vital for agriculture, as highlighted in the review by Power, which underscores the importance of ecological services, including biological pest control, in supporting agricultural productivity (Power, 2010). Another relevant study by Zang et al. reviews the history and current application of biological control using *Trichogramma* in China. It details mass-rearing strategies and the ecological implications of these biocontrol agents in pest management, illustrating how integrating biological solutions fits within a circular economy framework by reducing reliance on chemical pesticides (Zang et al., 2021). This connection emphasizes the potential of biological controls not only to manage pests effectively but also to enhance ecological balance within agricultural systems. Research conducted by Hajjar et al. explores IPM techniques specifically for rice cultivation. This review highlights various IPM strategies, including biological management methods, which are well-suited for creating sustainable rice agroecosystems, demonstrating how traditional agricultural systems can benefit from adopting circular economy principles (Hajjar et al., 2023).

A critical implication of these findings lies in the formulation of more targeted and inclusive agricultural policies. The limited adoption of certain circular economy principles, particularly reuse and refurbish, highlights a pressing need for government intervention through incentive-based frameworks and institutional strengthening. For example, policy instruments such as subsidized equipment-leasing cooperatives, decentralized composting facilities, and farmer-led innovation grants could help bridge infrastructural and financial gaps identified in the study. Moreover, existing extension programs need to be scaled and adapted to focus on circular practices, offering more practical demonstrations, digital literacy support, and participatory learning. Integration of CE principles into farmer field schools and vocational curricula could enhance awareness and foster long-term behavioral shifts (Hamid et al., 2023). Local governments and agricultural agencies should also coordinate cross-sectoral strategies, involving waste management authorities and rural development planners, to embed CE transitions within broader sustainable development agendas. These policy directions are essential not only for scaling the circular model beyond pilot sites like Kediri but also for ensuring its resilience, replicability, and alignment with national sustainability targets.

Conclusion

This study developed and validated a circular economy model within IPM-based rice farming that integrates five principles: reduce, reuse, recycle, refurbish, and renewable. The findings show that the "reduce" and "recycle" principles exert the strongest influence on sustainability outcomes, driven by high farmer adoption due to direct economic and operational benefits. Conversely, "reuse" remains the least adopted principle, constrained by institutional limitations and lack of shared infrastructure. The model offers a practical framework for enhancing sustainability in rice farming through resource efficiency, waste reduction, and ecological regeneration. To support broader adoption of circular practices, specific policy measures are needed—such as incentives for farmer cooperatives to establish tool-sharing systems, investment in village-level organic waste processing facilities, and technical training programs targeting reuse and refurbish applications. Educational programs should also integrate circular economy concepts into environmental science curricula and farmer field schools to strengthen awareness and behavioral change. This study is limited to two villages in Kediri Regency with established IPM programs and may not represent regions with different ecological or institutional conditions. Further research is recommended to conduct comparative analysis across regions, evaluate long-term cost-benefit impacts of each principle, and develop targeted interventions to overcome barriers to reuse adoption.

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Conflicts of Interest
The authors declare no conflict of interest.

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