



Development of a Green Palm Oil Agroindustry Model Based on Resource Efficiency and Circular Economy in Medan, Indonesia

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ABSTRACT: Palm oil processing created substantial economic value while intensifying demands for materials, energy, water, and responsible residual management. This study developed and empirically tested a company-level green palm oil agroindustry model that integrated resource efficiency and circular economy practices at PT Musim Mas in Medan City. Explanatory quantitative research was conducted with 50 internal respondents representing management, production and operations, engineering and maintenance, environment and sustainability, quality control, and workers. Data were collected through a five-point Likert-scale questionnaire, observations, interviews, and documentation and were analyzed using descriptive statistics and structural equation modeling–partial least squares (SEM-PLS). The questionnaire results represented internal perceptions of practice implementation and did not constitute direct audited measurements of water consumption, energy use, waste generation, or emissions. The mean scores for resource efficiency, circular economy, and green agroindustry were 3.98 (good), 4.14 (good), and 4.03 (good), respectively. Resource efficiency was positively associated with green agroindustry ($\beta = 0.382$; $t = 4.216$; $p < 0.001$), circular economy was positively associated with green agroindustry ($\beta = 0.447$; $t = 5.031$; $p < 0.001$), and resource efficiency was positively associated with circular economy ($\beta = 0.516$; $t = 6.284$; $p < 0.001$). Together, resource efficiency and circular economy explained 71.4% of the variance in green agroindustry ($R^2 = 0.714$). Within the investigated model and sample, circular economy exhibited a stronger standardized direct association with green agroindustry than resource efficiency. The findings were also consistent with a pathway in which efficient resource use facilitated higher-value resource recovery and waste-to-value practices. Water efficiency, emission control, renewable energy utilization, and green technology innovation were identified as priority areas for further improvement. Overall, the findings provided company-level, cross-sectional evidence supporting the integration of resource efficiency and circular economy practices into green palm oil agroindustry development; however, broader replication and longitudinal assessment were required to establish their generalizability and long-term effects.

KEYWORDS: Green agroindustry; palm oil; resource efficiency; circular economy; SEM-PLS; sustainable production

1. Introduction

Palm oil is central to Indonesia's agroindustrial economy because of its high land productivity, diverse downstream applications, contribution to exports, and capacity to support employment and regional development. Indonesia and Malaysia remain the dominant global producers, while palm oil continues to account for a substantial share of global vegetable oil demand [1]. However, its productivity advantage does not eliminate the environmental burdens associated with plantation expansion, energy-intensive processing, water consumption, effluent generation, solid biomass residues, and greenhouse gas emissions. Recent sustainability research has therefore shifted the focus from whether palm oil should be produced to how its value chain can be transformed through cleaner production, traceability, resource conservation, and credible environmental governance [1–4].

At the mill and refinery levels, environmental performance depends on how raw materials, energy, water, and residual streams are managed. Poor material control reduces extraction efficiency and creates avoidable losses, while inefficient boilers, steam systems, pumps, and motors increase energy demand. Water is required for sterilization, clarification, cleaning, cooling, and utility systems; inadequate metering and limited reuse can increase both freshwater withdrawal and wastewater generation. Palm oil mill effluent (POME) and lignocellulosic residues, including empty fruit bunches, shells, fibers, fronds, and trunks, may become sources of pollution when inadequately managed. However, these residual streams also contain recoverable energy, nutrients, carbon, cellulose, and water [5–9].

Resource efficiency provides an operational foundation for addressing these pressures. It aims to generate greater value with fewer inputs and lower losses throughout the production system. At the company level, practical measures include material-balance control, preventive maintenance, process optimization, real-time metering, heat integration, efficient motors, condensate return, water cascading, and performance accountability. Such measures can simultaneously reduce production costs and environmental intensity; however, efficiency alone may leave residual streams outside productive use. The circular economy extends this approach by retaining resource value through reduction, reuse, recycling, recovery, and waste-to-value strategies [10–13].

The palm oil agroindustry is particularly suitable for circular transformation. Fibers and shells can supply process energy; POME can support biogas and biomethane production; empty fruit bunches and decanter cake can be composted or processed into soil amendments; and biomass can be converted into fuels, chemicals, biochar, activated carbon, silica, and other value-added products [5–9, 14–19]. These pathways replace the conventional linear sequence of extraction–production–disposal with more circular resource flows. They also integrate waste management with resource recovery and by-product utilization, thereby creating environmental and economic value rather than treating residual materials solely as compliance costs.

Green agroindustry integrates these operational and circular principles into a production system that minimizes environmental impacts while maintaining productivity, competitiveness, and innovation. In this study, green agroindustry is reflected in environmentally friendly production, waste control, emission control, renewable energy utilization, production-process efficiency, and green technology innovation. Circular economy

practices can strengthen these outcomes because waste prevention and resource recovery directly reduce disposal requirements, emissions, and demand for virgin inputs. Resource efficiency may also facilitate circularity because accurate measurement, stable processes, controlled losses, and segregated material streams make reuse and recovery more technically and economically feasible [20–24].

Previous studies have examined sustainable palm oil certification, life-cycle impacts, biomass valorization, POME treatment, bioenergy technologies, and circular bioeconomy options [1–9, 14–19, 25–28]. Other studies have developed circular economy indicators and supply-chain frameworks for agriculture and manufacturing [10–13, 20–24, 29–34]. However, much of the existing literature has been technology-specific, supply-chain-oriented, or conceptual. Limited empirical research has simultaneously examined resource efficiency as a factor directly associated with green agroindustry, circular economy as another directly associated factor, and resource efficiency as an antecedent of circular economy at the company level within the Indonesian palm oil sector. This study therefore provides context-specific empirical evidence that complements these broader frameworks while remaining cautious about generalization beyond the company investigated.

The novelty of this study lies in developing and empirically testing an integrated company-level green palm oil agroindustry model that simultaneously examines three structural relationships: the relationship between resource efficiency and green agroindustry, the relationship between circular economy and green agroindustry, and the relationship between resource efficiency and circular economy. Rather than examining these dimensions independently, the proposed model operationalizes resource efficiency and circular economy as organizational practice constructs and evaluates their standardized structural relationships with green agroindustry within an operating Indonesian palm oil company. This approach differs from previous studies that have focused primarily on (i) conceptual or indicator-based circular economy and circular bioeconomy frameworks at the sectoral or supply-chain level, (ii) sustainable palm oil frameworks emphasizing certification, governance, or life-cycle impact assessment, and (iii) palm oil waste valorization studies evaluating individual technologies, such as POME biogas production or biomass conversion, without simultaneously examining organization-wide relationships among resource efficiency, circularity, and green agroindustry practices. Thus, this study addresses an important research gap by providing company-level empirical evidence of how efficiency-oriented operational practices and circular value-retention practices are interconnected and associated with green agroindustry implementation within a single integrated model. Accordingly, this study aimed to assess the performance of the three constructs and test their structural relationships at PT Musim Mas in Medan City. Three hypotheses were proposed: H1, resource efficiency has a positive relationship with green agroindustry; H2, circular economy has a positive relationship with green agroindustry; and H3, resource efficiency has a positive relationship with circular economy.

2. Materials and Method

2.1. Research Design and Location.

This study employed an explanatory quantitative design to examine the hypothesized structural relationships among resource efficiency, circular economy, and green agroindustry. The

research was conducted at PT Musim Mas in Medan City, Indonesia. The company-level setting was selected to capture internal perceptions of operational practices and sustainability implementation within a palm oil agroindustry organization using cross-sectional data.

2.2. Population and Respondents.

The study involved 50 internal respondents selected from functions directly related to production, maintenance, environmental management, quality assurance, decision-making, and shop-floor implementation. The respondents comprised management personnel (8), production and operational personnel (12), engineering and maintenance personnel (6), environment and sustainability personnel (5), quality control personnel (5), and workers (14). This cross-functional representation enabled the model to incorporate managerial, technical, and operational perspectives.

Respondents were purposively selected based on the relevance of their functions to the investigated constructs, including production and operations, maintenance and engineering, environment and sustainability, quality control, and management. This approach was used to ensure informed assessments of operational and circular practices. Eligible respondents were internal employees whose roles involved exposure to production processes, resource-use control, residual management, or related decision-making. External parties, personnel without sufficient exposure to the relevant operational practices, and respondents who did not complete the questionnaire were excluded.

Regarding sample size, the structural model was relatively parsimonious, consisting of three latent constructs and three structural paths, with a maximum of two predictors for green agroindustry and one predictor for circular economy. In this context, PLS-SEM was considered appropriate for predictive and explanatory modelling with a moderate sample size. Heuristic minimum-sample criteria based on model complexity indicated that a sample of 50 respondents could be considered acceptable. However, a formal a priori power analysis was not performed based on the retained study materials. Therefore, the relatively small sample size remained a limitation, and replication using larger, multi-site samples was considered necessary to strengthen the generalizability of the findings.

2.3. Research Variables and Indicators.

Resource efficiency was measured through raw material efficiency, energy efficiency, water efficiency, by-product utilization, and material loss control. Circular economy was measured through reduction, reuse, recycling, recovery, and waste-to-value utilization. Green agroindustry was measured through environmentally friendly production, waste control, emission control, renewable energy utilization, production-process efficiency, and green technology innovation. These indicators reflected recent resource-efficiency and circular-production literature emphasizing input optimization, value retention, industrial symbiosis, digital monitoring, and waste valorization [10–13, 20–24, 29–34]. The indicator dimensions captured the perceived implementation of practices as reported by internal respondents. The retained study materials summarized the indicator dimensions but did not include the complete wording of individual questionnaire items. Therefore, item-level replication and detailed measurement-model diagnostics were limited by the available data.

2.4. Data Collection.

Primary and supporting data were collected through questionnaires, observations, interviews, and documentation. Questionnaire items were assessed using a five-point Likert scale ranging from 1 (very poor/strongly disagree) to 5 (very good/strongly agree), consistent with the source data. Observations and interviews were used to contextualize operational practices, particularly those related to resource monitoring, by-product utilization, and water reuse. Documentation was used to support the interpretation of company processes and sustainability activities. Consequently, the quantitative scores represented perceived and reported implementation of practices rather than direct, audited environmental performance outcomes, such as measured reductions in water consumption, energy use, waste generation, or emissions. Observations, interviews, and documentation provided contextual support for the reported practices; however, the study did not retain a complete audited dataset of objective environmental performance indicators.

2.5. Data Analysis.

Descriptive analysis was used to summarize respondent characteristics and mean indicator scores. Structural equation modeling using partial least squares (SEM-PLS) was employed to test the hypothesized relationships. The analytical procedure involved conceptual assessment of the measurement model followed by evaluation of the structural model. Measurement-model assessment typically examined indicator reliability and construct validity, whereas structural-model assessment evaluated path direction, coefficient magnitude, statistical significance, and explained variance. Because the source data did not provide outer loadings, average variance extracted, composite reliability, Cronbach's alpha, predictive relevance, effect sizes, or variance inflation factors, values for these statistics were neither inferred nor fabricated. The reported analysis was therefore limited to the available path coefficients, t-statistics, p-values, and coefficients of determination. In addition, statistical diagnostics for common-method bias, indirect-effect bootstrapping, and structural model quality were not retained in the available outputs. Consequently, these statistics were not reported and should be incorporated into future studies for which complete SEM-PLS outputs are available.

3. Results and Discussion

3.1. Respondent Characteristics

The characteristics of the respondents are presented in Table 1. Workers constituted the largest group (28%), followed by production and operational personnel (24%) and management personnel (16%). Engineering and maintenance personnel accounted for 12%, while environment and sustainability personnel and quality control personnel each accounted for 10%. This distribution reflects the actual organizational structure of palm oil mills, where general workers and production staff form the bulk of the workforce, while managerial and specialized technical roles are comparatively fewer in number. The relatively high proportion of workers and production/operational personnel (52% combined) indicates that the sample was weighted towards individuals with direct, hands-on involvement in daily mill operations, including feedstock handling, processing, and waste generation activities. This is particularly

relevant to the present study, as these respondents are most likely to have first-hand exposure to inefficiencies, waste streams, and resource losses occurring at the operational level.

At the same time, the inclusion of management personnel (16%) ensured that the perspectives of those responsible for strategic planning, policy formulation, and decision-making regarding circular economy and sustainability initiatives were also captured. Engineering and maintenance personnel (12%) contributed insight into the technical feasibility of adopting new technologies, equipment upgrades, and process modifications necessary for improving resource efficiency. Meanwhile, environment and sustainability personnel and quality control personnel (10% each) provided specialized knowledge regarding regulatory compliance, environmental monitoring, and product/process quality standards, both of which are integral to the successful implementation of green agroindustry practices.

Table 1. Respondent Characteristics.

No.	Function	Frequency	Percentage
1	Management	8	16%
2	Production and Operational	12	24%
3	Engineering and Maintenance	6	12%
4	Environment and Sustainability	5	10%
5	Quality Control	5	10%
6	Workers	14	28%
	Total	50	100%

3.2. Resource Efficiency Performance.

The resource efficiency performance results are presented in Table 2. The overall mean score for perceived resource efficiency was 3.98, which was categorized as good. By-product utilization received the highest score (4.21; very good), followed by raw material use efficiency (4.18; good). These results indicated that respondents perceived relatively strong implementation of operational loss control and by-product utilization practices. However, these scores represented reported implementation of practices rather than objective evidence of quantified reductions in resource consumption. The findings were consistent with recent oil palm biomass research demonstrating that residual materials can support energy generation, carbon-based products, biorefinery pathways, and other value-added applications [5–9, 14–19]. As further shown in Table 2, energy use efficiency (4.02) and material loss control (3.88) were categorized as good, indicating established but potentially improvable operational practices.

Water use efficiency received the lowest score (3.61), although it remained within the good category (Table 2). This finding is important because water consumption and effluent generation are closely interconnected. Reducing freshwater intake, cascading suitable water between processes, and recovering treated water can potentially reduce both operating costs and wastewater discharge loads. Interviews indicated that water consumption monitoring was available, although water reuse had not yet been fully integrated across all processes. PT Musim Mas could therefore strengthen process-level sub-metering, establish water-intensity baselines, identify abnormal consumption, expand condensate and treated-water reuse where technically appropriate, and integrate water-performance indicators into preventive maintenance programs. Membrane-based water recovery and integrated POME treatment represent potential technical approaches, although technology selection should be supported by site-specific assessments of water quality, energy requirements, operational feasibility, and

economic performance [6, 8, 15, 16]. Importantly, the water efficiency score did not demonstrate actual water savings; rather, it indicated the perceived implementation status and provided a basis for prioritizing future monitoring and improvement.

Table 2. Resource Efficiency Performance.

Indicator	Mean	Category
Raw material use efficiency	4.18	Good
Energy use efficiency	4.02	Good
Water use efficiency	3.61	Good
By-product utilization	4.21	Very Good
Material loss control	3.88	Good
Average	3.98	Good

3.3. Circular Economy Performance.

The circular economy performance results are summarized in Table 3. The overall mean score was 4.14, which was categorized as good and reflected respondents' perceptions of the implementation of circular economy practices. Waste-to-value utilization received the highest score (4.28; very good), closely followed by reuse (4.24; very good). Recycling (4.17), recovery (4.06), and reduction (3.94) were also categorized as good. As shown in Table 3, this pattern suggested that respondents perceived a transition from conventional waste disposal toward greater resource recovery and value retention. However, these Likert-scale results should not be interpreted as direct measurements of material recovery rates, resource savings, or avoided emissions. Objective circularity and environmental performance indicators would be required to verify the realized outcomes [10–13, 20–24].

Table 3. Circular Economy Performance.

Indicator	Mean	Category
Reduce	3.94	Good
Reuse	4.24	Very Good
Recycle	4.17	Good
Recovery	4.06	Good
Waste-to-value utilization	4.28	Very Good
Average	4.14	Good

The higher scores for reuse and waste-to-value utilization compared with reduction (Table 3) suggested that the company may have been more advanced in managing residual materials after their generation than in preventing waste at the source. A mature circular system should integrate both prevention and recovery. Waste prevention could be strengthened through material-balance accounting, yield-loss analysis, procurement specifications, and process-control improvements. Resource recovery could subsequently be organized through a portfolio of strategies, including internal reuse where quality and safety requirements permit, energy recovery from suitable biomass and POME, nutrient recovery, composting, and external industrial symbiosis for materials that cannot be recirculated internally [5–9, 14–19]. The economic value of these approaches should be evaluated together with avoided disposal costs, potential emission reductions, and substitution of purchased energy or raw materials.

3.4. Green Agroindustry Performance.

The green agroindustry performance results are presented in Table 4. The overall mean score was 4.03, indicating a good level of perceived implementation. Waste control received the highest score (4.29; very good), indicating that respondents perceived waste management as a particularly well-established organizational practice. Environmentally friendly production (4.16) and production-process efficiency (4.08) were also categorized as good. As with the other constructs, the results presented in Table 4 reflected respondents' perceptions of implementation rather than direct measurements of changes in waste generation, water withdrawal, energy consumption, or emissions.

Table 4. Green Agroindustry Performance.

Indicator	Mean	Category
Environmentally friendly production	4.16	Good
Waste control	4.29	Very Good
Emission control	3.82	Good
Renewable energy utilization	3.97	Good
Production-process efficiency	4.08	Good
Green technology innovation	3.86	Good
Average	4.03	Good

As shown in Table 4, renewable energy utilization recorded a mean score of 3.97, followed by green technology innovation (3.86) and emission control (3.82). Although all three indicators were categorized as good, their comparatively lower scores identified potential priority areas for further improvement. Strong waste-control practices could be integrated more closely with decarbonization initiatives through methane capture, optimization of biomass-based energy, energy-efficiency improvements, electrification where technically feasible, and systematic monitoring of direct and indirect emissions. Previous studies have demonstrated that POME-to-biogas systems, integrated bioenergy systems, and biomass valorization can reduce environmental burdens while generating energy and economic value. However, successful implementation depends on feedstock consistency, process control, capital requirements, operational capacity, and viable markets for recovered products [7–9, 15–19, 25–28].

The comparatively lower score for green technology innovation in Table 4 also indicated an opportunity to strengthen systematic innovation management. Green innovation could be advanced through a structured process involving the identification of environmental challenges, pilot-scale testing of potential solutions, quantification of operational and life-cycle benefits, scaling of technically and economically viable technologies, and systematic documentation of implementation outcomes. Such an approach could strengthen the transition from established waste-control practices toward a more integrated green agroindustry model that combines resource efficiency, circularity, emission reduction, renewable energy, and technological innovation.

3.5. Structural Model and Hypothesis Testing.

All three hypothesized relationships were positive and statistically significant, as shown in Table 5. Resource efficiency was positively associated with green agroindustry ($\beta = 0.382$; $t = 4.216$; $p < 0.001$), supporting H1. Within the proposed model, this coefficient indicates that

stronger perceived operational discipline in input control, loss reduction, and by-product utilization was associated with stronger perceived implementation of green agroindustry practices. However, this relationship should not be interpreted as definitive evidence of causality because the study employed a cross-sectional, perception-based design.

Table 5. SEM-PLS Hypothesis Testing Results.

Hypothesis	Relationship	Path coefficient (β)	t-statistic	p-value	Decision
H1	Resource Efficiency and Green Agroindustry	0.382	4.216	<0.001	Supported
H2	Circular Economy and Green Agroindustry	0.447	5.031	<0.001	Supported
H3	Resource Efficiency and Circular Economy	0.516	6.284	<0.001	Supported

Circular economy showed a stronger standardized direct association with green agroindustry ($\beta = 0.447$; $t = 5.031$; $p < 0.001$), supporting H2. Beyond its statistical significance, this relationship is theoretically plausible because circular practices can translate residual resource management into observable green agroindustry outcomes. Waste valorization, reuse and recovery systems, and secondary resource substitution can contribute directly to waste reduction, renewable energy utilization, and green technology initiatives. In the palm oil industry, circular practices may include the conversion of palm oil mill effluent (POME) into biogas, energy generation from fibres and shells, composting and nutrient recovery from empty fruit bunches, and other forms of residue valorization. These activities represent tangible environmental practices that employees can observe in daily operations. In contrast, resource-efficiency initiatives, including metering, preventive maintenance, and process optimization, often function as enabling capabilities that reduce resource losses and stabilize production processes but may be less directly visible as green outcomes unless they are integrated with recovery, substitution, and innovation initiatives. Nevertheless, the difference between $\beta = 0.447$ and $\beta = 0.382$ represents an empirical finding specific to the present sample and model and should not be generalized as evidence that circular economy practices are universally more important than resource efficiency.

Resource efficiency was also positively associated with circular economy ($\beta = 0.516$; $t = 6.284$; $p < 0.001$), supporting H3. This relationship had the largest path coefficient in the structural model, indicating a strong alignment between circular practices and upstream operational control. Resource recovery depends on predictable quantities and quality of residual materials, reuse requires appropriate segregation of resource streams, recycling depends on adequate knowledge of material characteristics, and waste valorization requires reliable measurement and stable production processes. Resource efficiency therefore appears to function as an enabling capability that supports the implementation of circular resource flows.

The coefficient of determination for green agroindustry was $R^2 = 0.714$, indicating that resource efficiency and circular economy jointly explained 71.4% of the variance in perceived green agroindustry implementation. The remaining 28.6% of the variance may be associated with factors outside the specified model, including governance, market pressures, technological readiness, and supplier or customer pressures. However, these additional variables were not examined in the present study.

The statistically significant relationships between resource efficiency and circular economy, circular economy and green agroindustry, and resource efficiency and green agroindustry indicate a theoretically plausible indirect pathway in which resource efficiency may influence green agroindustry implementation through circular economy practices. This

potential relationship is illustrated in Figure 1. However, the retained PLS-SEM outputs did not include bootstrapped estimates of indirect effects or their confidence intervals. Therefore, mediation cannot be formally established from the present analysis. Future studies should estimate indirect effects using bootstrapping and report the corresponding confidence intervals to determine whether circular economy practices mediate the relationship between resource efficiency and green agroindustry implementation.

Quantitative comparisons with previous PLS-SEM studies should be interpreted cautiously because of differences in constructs, operationalization, samples, and industrial contexts. Sahoo (2023), for instance, reported a positive relationship between circular economy practices and environmental performance in the manufacturing sector, with $\beta = 0.188$ ($t = 2.845$; $p = 0.004$) and an R^2 value of 0.531 for environmental performance. In comparison, the present study found a larger standardized association between circular economy and green agroindustry ($\beta = 0.447$) and greater explained variance ($R^2 = 0.714$). The larger coefficient observed in the present study may be associated with the broader organizational scope of the green agroindustry construct, the operational visibility of residue valorization in palm oil processing, and the use of internal organizational respondents. Nevertheless, differences in sampling, construct definitions, and measurement approaches limit direct comparison of the coefficients.

3.6. Proposed Green Palm Oil Agroindustry Model.

Figure 1 synthesizes the empirical relationships and their managerial implications within the proposed green palm oil agroindustry model. Resource efficiency represents the stabilization and optimization of material, energy, and water flows, whereas circular economy practices emphasize value retention through reduction, reuse, recycling, recovery, and waste valorization. Green agroindustry implementation is reflected in cleaner production, waste and emission control, renewable energy utilization, efficient production processes, and green technology innovation. From a cross-sectional perspective, the model is consistent with a potential pathway in which improvements in operational efficiency support the implementation of circular practices, which are subsequently associated with stronger green agroindustry implementation.

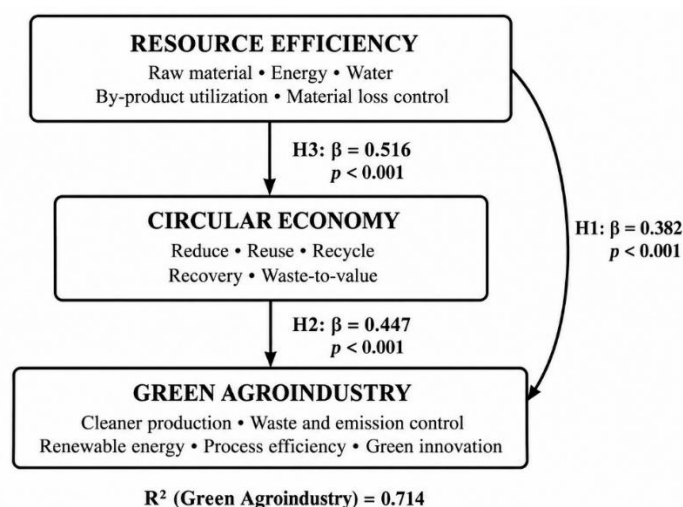


Figure 1. Proposed Green Palm Oil Agroindustry Development Model Based on Resource Efficiency and Circular Economy Notes: β indicates standardized path coefficients; all reported paths are significant at $p < 0.001$; R^2 is reported for Green Agroindustry.

Based on the relationships presented in Figure 1, the proposed model suggests a phased implementation strategy for the palm oil agroindustry. The first phase should strengthen the measurement foundation by integrating material, energy, water, waste, and emission monitoring into a coordinated performance system. The second phase should prioritize water reuse because this dimension showed comparatively weaker performance among the resource-efficiency indicators. The third phase should build on existing strengths in by-product utilization and waste management by developing higher-value recovery portfolios, including internal energy generation, methane capture, nutrient recovery, and carefully evaluated biomaterial applications. The fourth phase should integrate environmental and economic criteria into capital budgeting so that investments in green technologies are assessed according to lifecycle value rather than initial cost alone. Finally, cross-functional governance should be institutionalized by involving production, engineering, sustainability, quality control, and operational personnel in the implementation and monitoring of green agroindustry initiatives. Digital technologies may further improve resource traceability, performance monitoring, and decision-making efficiency; however, effective organizational routines and sustained employee participation remain essential for successful implementation [21–24, 31–34, 37–40].

4. Conclusions

This study demonstrated that resource efficiency and circular economy practices were significantly associated with green agroindustry implementation in the palm oil industry. Resource efficiency showed a significant positive association with green agroindustry ($\beta = 0.382$), while circular economy showed a stronger direct association ($\beta = 0.447$). Resource efficiency was also strongly associated with circular economy practices ($\beta = 0.516$), indicating that effective control of raw materials, energy, water, by-products, and material losses underpins circular resource flows. Together, these constructs explained 71.4% of the variance in green agroindustry implementation ($R^2 = 0.714$), highlighting their complementary roles in supporting sustainable palm oil production. By-product utilization and waste control emerged as established strengths, while water efficiency, emission control, and green technology innovation were priority areas for improvement. The proposed model therefore emphasizes an integrated strategy combining resource optimization with waste reduction, reuse, recycling, recovery, renewable energy utilization, and waste valorization. Implementation should be supported by measurable indicators, including water consumption and reuse rates, energy intensity, renewable energy contribution, greenhouse gas emission intensity, methane recovery from palm oil mill effluent, waste recovery and biomass valorization rates, and adoption of validated green technologies. Audited baseline data and continuous monitoring would help translate the model into measurable operational improvements. Overall, the study offers an empirical framework for integrating resource efficiency and circular economy principles into green palm oil agroindustry development. However, the findings reflect cross-sectional perceptions from 50 internal respondents within a single company and should not be interpreted as direct evidence of reduced resource consumption, waste, or emissions. Future studies should validate the model across multiple mills and companies using larger samples, comprehensive PLS-SEM assessment, and objective environmental data, and examine longitudinally whether these practices yield measurable environmental and economic benefits over time.

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Author Contribution

Kimberly Febrina Kodrat: Conceptualization, methodology, data collection, data analysis, writing – original draft. Hasan Sitorus: Supervision, methodology, validation, writing – review and editing.

Competing Interest

The authors declare that they have no competing interests.

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