



# Circularity Assessment of Coffee Waste-Based Products with Supervised Learning Classification

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## ABSTRACT

The rapid growth of the global coffee industry has led to increased coffee production and consumption, which consequently generates significant amounts of agro-industrial waste such as cascara. If not properly managed, these residues may contribute to environmental pollution and inefficient resource utilization. Converting coffee waste into value-added materials represents a promising strategy to support circular economy implementation. This study aims to evaluate the circularity performance of coffee waste-based composite products produced by Regoods by integrating circular economy indicators with supervised learning classification. A quantitative approach was applied using the Linear Flow Index (LFI) and Material Circularity Indicator (MCI), followed by logistic regression to analyze the influence of electricity consumption, cascara utilization, and polymer matrix composition. The dataset consists of six observations from three product categories: plates, cups, and boards. The results show high LFI values (0.8786-0.9204) and low MCI values (0.0796-0.1214), indicating a predominantly linear system due to the dominant use of virgin polymer materials. Among the products, cups exhibit the highest circularity performance. Polymer matrix usage significantly reduces circularity, while cascara utilization improves it. These findings highlight the importance of increasing secondary material utilization to enhance product circularity.

**Keywords:** circular economy; coffee waste; cascara; circularity indicator; logistic regression

## INTRODUCTION

The global coffee industry has experienced rapid growth over the past decade due to increasing consumer demand worldwide. Coffee is one of the most widely traded agricultural commodities and plays a significant role in global economic activities and consumption patterns. Global coffee consumption has increased by approximately 10 million tons since 2018, reflecting the expanding coffee market and changing lifestyle trends (Pongsiriyakul et al., 2024). Indonesia is one of the major contributors to global coffee production, ranking as the fourth largest coffee producer in the world with approximately 10.7 million bags produced during the 2024/2025 harvest season (International Coffee Organization, 2025) Despite its economic benefits, the rapid growth of the coffee industry also generates a considerable amount of waste across the supply chain, including during cultivation, processing, and consumption stages. Coffee processing produces several by-products such as cascara, silverskin, and spent coffee grounds, which represent significant waste streams within the coffee industry (Pongsiriyakul et al., 2024). If not properly managed, these residues may lead to environmental problems such as greenhouse gas emissions, soil degradation, and ecosystem pollution. Inefficient coffee waste management can also negatively affect environmental sustainability and the economic stability of coffee-producing communities

(Tsigkou et al., 2025). Similarly, uncontrolled disposal of agro-industrial waste can contribute to environmental degradation in surrounding areas (Putri & Bandiyono, 2025). These concerns highlight the need for more sustainable and resource-efficient production systems.

In response to these challenges, researchers have increasingly explored the potential of converting coffee waste into value-added materials and eco-products. Coffee residues contain bioactive compounds such as polysaccharides and phenolic substances that make them promising raw materials for developing sustainable materials including biopolymers and composite products (Pongsiriyakul et al., 2024). The valorization of agro-industrial waste is closely aligned with circular economy principles, which emphasize the efficient use of resources and the reintegration of waste into production systems. In the Indonesian business context, circular economy practices have also been discussed as part of broader sustainable business strategies, particularly through waste reduction, recycling systems, and operational sustainability initiatives (Wibowo & Wicaksono, 2025). This indicates that circular economy implementation is not only relevant for large-scale industries but also for smaller eco-product developers that aim to transform waste materials into value-added products. Previous studies have demonstrated that agricultural waste can be transformed into renewable materials through material engineering approaches that support sustainability goals (Gumulya et al., 2024). Transforming food waste into bio-based products has also been identified as an important strategy for advancing circular economy practices (Dhiman et al., 2025; Papaioannou et al., 2022). In this context, coffee waste can serve not only as a waste reduction strategy but also as a valuable resource for developing environmentally friendly products. The development of eco-products from biomass waste is also closely related to the concept of ecodesign, which integrates environmental considerations into the product design process to improve resource efficiency and reduce environmental impacts throughout the product life cycle (Sampaio et al., 2023). Bio-based materials derived from agricultural waste have been reported to provide environmental advantages such as lower carbon footprints, improved biodegradability, and enhanced functional properties (Rosenboom et al., 2022).

Several studies have demonstrated practical applications of coffee waste utilization for sustainable product development. For example, Gumulya et al. (2024) investigated the use of spent coffee grounds as an additive material in ceramic production to develop self-watering planters. The study reported that incorporating approximately 5% of fine coffee grounds into clay mixtures improved the porosity and water absorption capacity of the ceramic material without compromising its structural integrity. The resulting composite material was developed into functional ceramic planters designed to support plant growth through natural water absorption mechanisms. In addition, user evaluation results indicated positive responses toward the developed eco-products, with the sustainable design concept receiving an average acceptance score of 4.2 out of 5. These findings demonstrate that coffee processing residues can be successfully transformed into functional eco-products with both environmental and economic value. By converting waste into useful materials, such approaches contribute to reducing environmental burdens while extending the lifecycle of resources within production systems. Therefore, coffee waste utilization represents a promising strategy for implementing circular economy principles in the agro-industrial sector.

In addition to material innovation, recent studies have explored the use of artificial intelligence (AI) and machine learning (ML) to support circular economy implementation. AI technologies are capable of processing large datasets and identifying patterns that can improve

waste management efficiency and resource circulation within production systems. Machine learning algorithms can analyze material flows, predict recycling performance, and optimize waste management processes in circular production systems (Yarlagadda, 2023). For example, deep learning models based on convolutional neural networks have been developed to automatically classify waste materials and support recycling processes. Du et al. (2022) reported that a convolutional neural network model can classify textile waste into 13 different material categories with an accuracy of 95.4%. Similarly, Toğaçar et al. (2020) developed a waste classification system capable of distinguishing recyclable and non-recyclable waste with an accuracy of 99.5%. These findings indicate that AI-based analytical approaches can significantly enhance waste classification, recycling efficiency, and resource circulation. Consequently, the integration of machine learning techniques into sustainability assessment frameworks has become a promising approach for improving circular economy implementation.

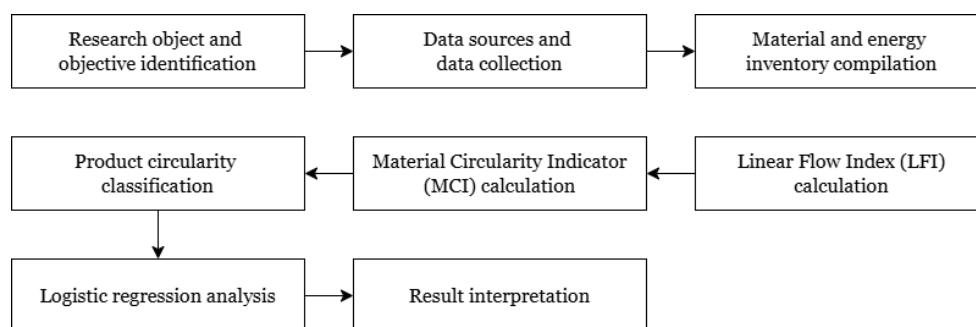
The novelty of this study lies in integrating Linear Flow Index (LFI), Material Circularity Indicator (MCI), and supervised learning classification to evaluate the circularity performance of coffee waste-based products at a small-scale production level, linking product outcomes with production variables including electricity consumption, cascara utilization, and polymer matrix composition. Most previous research primarily focuses on material development or environmental impact assessment without quantitatively evaluating the circularity performance of eco-products derived from coffee waste. Moreover, studies applying machine learning in circular economy contexts often emphasize waste classification or recycling optimization rather than analyzing how production variables influence circularity performance at the product level. However, production parameters such as energy consumption, material composition, and reinforcement materials may significantly affect the efficiency of material flows within production systems. Understanding the relationship between these variables and circularity outcomes is therefore essential for improving the sustainability performance of eco-products. This study aims to evaluate the circularity performance of coffee waste-based products produced by Regoods by integrating circular economy indicators with supervised learning classification. Specifically, the study applies the Linear Flow Index (LFI) and the Material Circularity Indicator (MCI) to measure circularity performance, while supervised learning models are used to analyze how production variables influence the probability of achieving higher circularity outcomes.

## **METHOD**

This study employs a quantitative approach to evaluate the circularity performance of coffee waste based products produced by Regoods. The research design focuses on examining how production-related variables influence product circularity through circular economy indicators and statistical modelling. The approach proposed in this study can be divided into three major components: (1) calculating the Linear Flow Index (LFI) to evaluate material flow efficiency, (2) measuring product circularity performance using the Material Circularity Indicator (MCI), and (3) applying logistic regression analysis to examine the influence of production variables on the probability of achieving higher circularity performance.

The overall research procedure consists of several stages, including research object identification, data collection, material and energy inventory compilation, circularity indicator

calculation, product circularity classification, and statistical analysis. These steps describe the analytical process used to evaluate the circularity performance of coffee waste based products. The key steps of the research methodology are illustrated in the flowchart shown in Figure 1.



**Figure 1. Flowchart of the research methodology**

The circularity performance of the products is evaluated using two main indicators, namely the Linear Flow Index (LFI) and the Material Circularity Indicator (MCI). The LFI is used to assess the extent to which material flows within the production system follow a linear pathway, particularly in relation to the use of virgin materials and the generation of unrecovered waste. The MCI represents the overall circularity level of the product and is derived from the LFI value to indicate the balance between linear material flows and circular resource utilization (Ellen MacArthur Foundation, 2019).

The experimental data used in this study were derived from production parameters associated with Regoods products. Several production variables were considered to influence circularity performance, including electricity consumption (kWh/kg), cascara material usage (kg), and polymer matrix with reinforcement (kg). Logistic regression analysis was applied to examine the relationship between these variables and the circularity category of the product. The dependent variable represents the circularity category determined based on the MCI value, where products with  $MCI \geq 0.5$  are classified as high circularity (1) and products with  $MCI < 0.5$  are classified as low circularity (0) (Rocchi et al., 2021).

### Linear Flow Index (LFI) Calculation

The circularity assessment of coffee waste based products began with the calculation of the Linear Flow Index (LFI). The LFI is used to evaluate the extent to which material flows within a product system follow a linear pathway (Brändström & Eriksson, 2022). This indicator reflects the proportion of material inputs and outputs that remain in a linear economy, such as the use of virgin resources and the generation of unrecovered waste.

The value of the Linear Flow Index ranges between 0 and 1. A value of  $LFI = 0$  indicates a fully circular material flow, where no virgin resources are consumed and no unrecovered waste is generated. Conversely, a value of  $LFI = 1$  represents a completely linear system dominated by the use of virgin materials and the generation of waste that is not recovered back into the production cycle. The Linear Flow Index was calculated using the equation shown in Equation (1):

$$LFI = \frac{V + W}{M} \quad (1)$$

where  $V$  represents the mass of virgin raw materials used in the product,  $W$  represents the mass of unrecovered waste generated during production, and  $M$  represents the total mass of

materials used in the product. The calculated LFI value indicates the degree to which a product relies on virgin material inputs and produces unrecovered waste during the production process. Lower LFI values indicate better circularity performance, while higher values suggest a stronger dependence on linear material flows.

#### Material Circularity Indicator (MCI) Calculation

After calculating the Linear Flow Index (LFI), the Material Circularity Indicator (MCI) was determined to evaluate the overall circularity performance of coffee waste based products. The MCI measures the extent to which materials are circulated within a product system by considering the balance between linear material flows and circular resource utilization (Linder et al., 2017). The MCI value is derived directly from the Linear Flow Index and represents the complement of the linear material flow within the system. The Material Circularity Indicator was calculated using the equation presented in Equation (2):

$$MCI = 1 - LFI \quad (2)$$

The resulting MCI value ranges between 0 and 1. A value of MCI = 0 indicates a fully linear system characterized by minimal circular material flow, whereas a value of MCI = 1 represents a fully circular system in which materials are effectively reused and recovered within the production cycle (Zhang et al., 2024). Higher MCI values therefore indicate better circularity performance. In this study, the MCI values were calculated for each coffee waste based product to evaluate their level of material circularity within the production system.

#### Logistic Regression Model

The outcome observed in this study is not a continuous numerical value but a categorical variable representing the circularity performance of the product. To accommodate this type of data structure, binary logistic regression was employed to investigate the relationship between production variables and the probability of achieving higher circularity performance. Logistic regression is a probability-based statistical model commonly used when the dependent variable has two categories (Lin & Januardi, 2023). The response variable represents the circularity category of the product, where products with Material Circularity Indicator (MCI)  $\geq 0.5$  are classified as high circularity (1) and products with MCI  $< 0.5$  are classified as low circularity (0). The logistic regression model estimates the logit function of the probability that a product belongs to the high circularity category. The model is expressed in Equation (3).

where MCI represents the probability that a product achieves high circularity performance.  $X_1$ ,  $X_2$ , and  $X_3$  denote the independent variables, namely electricity consumption (kWh/kg), cascara material usage (kg), and polymer matrix with reinforcement (kg), respectively. The parameter  $\beta_0$  represents the intercept of the model, while  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$  represent the regression coefficients that measure the influence of each production variable on circularity performance. The regression analysis was conducted using Microsoft Excel to estimate the coefficients of the logistic regression model and evaluate the influence of production variables on the probability of achieving high circularity performance. Logistic regression has also been applied in a previous study (Made et al., 2023) to examine the influence of several independent variables on a binary outcome variable, indicating its suitability for studies that classify observations into categorical outcomes.

## RESULT

### Description of Coffee Waste Based Product Dataset

This study evaluates the circularity performance of coffee waste based composite products produced by Regoods. The dataset used in this research consists of three product categories, namely plates, cups, and boards. Each product type was produced in two production runs, resulting in a total of six observations used for the circularity assessment and regression analysis. The production process of these composite products involves the combination of virgin materials and secondary materials.

The virgin materials consist of polymer matrix with reinforcement and binder, which function as the primary structural components of the composite material. Meanwhile, cascara, a by-product of coffee processing, is utilized as the secondary material incorporated into the composite formulation. The inclusion of cascara in the product formulation aims to utilize coffee processing waste as an alternative raw material and to support circular resource utilization within the production system. Table 1 presents the material composition of the coffee waste based products used in this study. The table summarizes the total mass of virgin materials, the amount of cascara used as secondary material, and the final product mass for each product type.

**Table 1. Material Composition of Coffee Waste-Based Products**

Product	Virgin Material (g)	Cascara (g)	Final Product Mass (g)
Plate 1	157.4	13.5	170.9
Plate 2	157.2	13.7	170.9
Cup 1	125.2	17.4	142.6
Cup 2	125.2	17.2	142.4
Board 1	276.2	25.3	301.5
Board 2	276.5	25.2	301.7

Source: Primary data from Regoods

The results show that the proportion of cascara incorporated into the products varies across product categories. Boards contain the highest amount of cascara, reaching approximately 25 g per unit, followed by cups with approximately 17 g, and plates with around 13 g. These differences in material composition may influence the circularity performance of the products, particularly in terms of the proportion of secondary material used in the composite formulation.

### Circularity Assessment Results

The circularity performance of coffee waste based products was evaluated using two circular economy indicators: the Linear Flow Index (LFI) and the Material Circularity Indicator (MCI). The LFI measures the proportion of material flows that remain linear within a production system, while the MCI measures the extent to which materials circulate within the product system by considering the balance between virgin material inputs and recovered resources. The calculation of these indicators was performed for each product sample, and the results were then averaged for each product category to provide a representative circularity performance value.

### Linear Flow Index Results

The Linear Flow Index was calculated to evaluate the degree to which material flows within the production system follow a linear pathway. Higher LFI values indicate greater dependence on virgin materials and unrecovered waste, while lower values reflect better circular material flows. Table 2 presents the LFI results obtained for the coffee waste based products.

**Table 2. Linear Flow Index (LFI) Results**

Product	LFI-1	LFI-2	Mean LFI
Plate	0.92101	0.91984	0.92042
Cup	0.87798	0.87921	0.8786
Board	0.91609	0.91647	0.91628

Source: Author's calculation based on primary data

The results indicate that all products exhibit relatively high LFI values, ranging from 0.8786 to 0.9204. These values suggest that the material flows in the production system remain largely linear due to the substantial use of virgin materials in the composite formulation.

Among the evaluated products, cups demonstrate the lowest mean LFI value (0.8786), indicating a relatively lower dependence on linear material flows compared to the other products. In contrast, plates show the highest LFI value (0.9204), suggesting a higher proportion of linear material inputs within the production system.

### Material Circularity Indicator Results

Following the calculation of the LFI values, the Material Circularity Indicator was determined to assess the overall circularity performance of the coffee waste based products. The MCI represents the complement of the LFI and indicates the degree to which materials are maintained within circular material flows. Table 3 summarizes the calculated MCI values for each product category.

**Table 3. Material Circularity Indicator (MCI) Results**

Product	MCI-1	MCI-2	Mean MCI
Plate	0.07899	0.08016	0.07958
Cup	0.12202	0.12079	0.1214
Board	0.08391	0.08353	0.08372

Source: Author's calculation based on primary data

The results show that the circularity performance of the products varies across product types. Cups exhibit the highest circularity performance with a mean MCI value of 0.1214, while plates show the lowest value at 0.0796. Boards demonstrate an intermediate circularity level with an average MCI value of 0.0837.

These results indicate that products with relatively higher cascara content tend to demonstrate improved circularity performance compared to those with lower amounts of secondary material (Sazdovski et al., 2024). However, the overall MCI values remain relatively low due to the dominant use of virgin polymer materials in the composite structure.

### Statistical Analysis of Production Variables

To further investigate the factors influencing circularity performance, statistical analysis was conducted using production-related variables associated with the manufacturing process. The variables considered in this analysis include electricity consumption, cascara material usage,

and the amount of polymer matrix with reinforcement. Table 4 presents the dataset used in the regression analysis.

**Table 4. Production Variables Used in Regression Analysis**

<b>Electricity (kWh/kg)</b>	<b>Cascara (kg)</b>	<b>Polymer Matrix + Reinforcement (kg)</b>	<b>MCI</b>
0.00111	0.0135	0.1558	0.07899
0.001094	0.0137	0.1555	0.08016
0.000862	0.0174	0.1237	0.12202
0.000872	0.0172	0.1237	0.12079
0.000592	0.0253	0.2732	0.08391
0.000595	0.0252	0.2738	0.08353

Source: Author's calculation based on primary data

The dataset indicates that electricity consumption varies across the product types, ranging from approximately 0.00059 to 0.00111 kWh/kg. The amount of cascara incorporated into the composite products also varies, with higher values observed in board products compared to plates and cups.

### Logistic Regression Results

Binary logistic regression was applied to examine how production variables influence the probability of achieving higher circularity performance. The regression model estimates the logit function of the probability that a product belongs to the higher circularity category. The estimated regression model is expressed as follows:

$$\ln\left(\frac{MCI}{1-MCI}\right) = -1.3836 - 602.7891X_1 + 37.6671X_2 - 5.8584X_3$$

In this model,  $p$  represents the probability that a coffee waste based product achieves higher circularity performance. The independent variables included in the model consist of electricity consumption  $X_1$ , cascara material usage  $X_2$ , and the amount of polymer matrix with reinforcement  $X_3$ . Electricity consumption represents the energy required in the production process and is measured in kWh per kilogram of product. Cascara material usage refers to the amount of coffee processing residue incorporated into the composite material, while the polymer matrix with reinforcement represents the quantity of virgin polymer materials used as the primary structural component of the composite product. Table 5 presents the estimated coefficients and the corresponding significance levels obtained from the logistic regression analysis.

**Table 5. Production Variables Used in Regression Analysis**

<b>Variable</b>	<b>Coefficient</b>	<b>p-value</b>	<b>Chi square p-value</b>
Intercept	-1.3836	0.2928	
Electricity (kWh/kg)	-602.7891	0.4098	0.55818
Cascara (kg)	37.6671	0.3577	
Polymer Matrix + Reinforcement (kg)	-5.8584	0.0112	

Source: Author's calculation based on primary data

The regression results indicate that cascara material usage has a positive coefficient, suggesting that increasing the amount of cascara in the product tends to increase the probability of achieving higher circularity performance. This finding reflects the role of secondary materials derived from coffee processing waste in improving the circularity of

material flows within the production system. However, the associated p-value for this variable is greater than the 0.05 significance level, indicating that the effect is not statistically significant. This means that although the coefficient suggests a positive relationship, the available data do not provide sufficient statistical evidence to confirm that cascara usage significantly influences circularity performance within the observed dataset.

In contrast, electricity consumption shows a negative coefficient, indicating that higher energy consumption during the production process may reduce the probability of achieving higher circularity performance. Similar to cascara usage, the p-value associated with this variable also exceeds the 5% significance threshold, suggesting that its effect is not statistically significant. Therefore, the relationship between electricity consumption and circularity performance cannot be statistically confirmed in this study.

Similarly, the amount of polymer matrix with reinforcement shows a negative coefficient, indicating that increasing the use of virgin polymer materials reduces the probability of achieving higher circularity performance. Unlike the other variables, the p-value associated with this variable is below the 0.05 significance level, indicating that the effect is statistically significant. This result suggests that the proportion of virgin materials plays a significant role in determining the circularity performance of coffee waste based composite products. In other words, higher dependence on polymer matrix materials tends to reduce the circularity level of the product system.

Overall, the regression analysis indicates that increasing the use of cascara as a secondary material while reducing reliance on virgin polymer inputs may contribute to improving the circularity performance of coffee waste based products, although only the effect of polymer matrix usage is statistically supported by the regression results. In addition to evaluating the statistical significance of individual regression coefficients, the overall validity of the logistic regression model can also be assessed using the Chi-square test based on the likelihood ratio statistic (Sur et al., 2019). This test compares the fitted regression model with a null model that includes only the intercept. The Chi-square p-value obtained from this test is 0.55818, which is greater than the significance level of 0.05. This result indicates that the logistic regression model as a whole is not statistically significant, meaning that the independent variables included in the model do not collectively provide strong explanatory power in predicting the circularity category of the products. The relatively small number of observations used in this study may limit the statistical power of the model, which can affect the significance of the overall regression results.

## **DISCUSSION**

The results of this study demonstrate that the circularity performance of coffee waste based composite products remains relatively limited, as reflected by the low Material Circularity Indicator (MCI) values obtained for all evaluated products. Although cascara was incorporated as a secondary material derived from coffee processing waste, the production system still relies heavily on virgin polymer materials, resulting in high Linear Flow Index (LFI) values across all product categories. According to the theoretical framework of circular economy indicators, the Linear Flow Index reflects the proportion of material flows that remain linear within a production system, while the Material Circularity Indicator (MCI) represents the extent to

which materials are retained within circular loops. Therefore, high LFI values and low MCI values observed in this study indicate that the material flow within the production system is still predominantly linear.

Among the evaluated products, cups exhibited the highest circularity performance, followed by boards and plates. The relatively higher MCI values observed in cup products may be associated with their higher proportion of cascara material compared to plates. This finding suggests that increasing the utilization of agricultural waste materials such as cascara can contribute to improving the circularity of composite products. This observation aligns with the principles of the circular economy, which emphasize the importance of integrating secondary materials and reducing dependence on virgin resources in production systems. Previous studies have also highlighted that agro-industrial waste materials can serve as promising alternative inputs for sustainable material development and contribute to reducing environmental burdens associated with conventional raw materials.

However, despite the incorporation of cascara, the overall circularity level of the evaluated products remains relatively low. This condition may be attributed to the structural requirements of composite materials, where a certain proportion of polymer matrix is necessary to maintain the mechanical strength and durability of the products. Similar observations have been reported in studies on bio-based composite materials, where natural fibres or biomass residues are often combined with polymer matrices to achieve the desired mechanical properties. While such formulations can partially reduce the use of virgin materials, the presence of synthetic polymers may still limit the overall circularity of the product system.

The regression analysis further provides insights into how production variables influence circularity performance. The positive coefficient associated with cascara material usage indicates that increasing the proportion of cascara in the composite formulation tends to increase the probability of achieving higher circularity performance. This result reinforces the role of secondary materials derived from waste streams in improving circular material flows. From the perspective of circular economy indicators, increasing the proportion of secondary materials directly reduces the linear material input, thereby contributing to a lower Linear Flow Index and a higher Material Circularity Indicator. By replacing a portion of virgin raw materials with cascara, the production system can reduce its dependence on primary resource extraction and support more sustainable material utilization.

These results are consistent with previous studies that evaluated circularity indicators in other food and biomass systems (Sazdovski et al., 2024; Rocchi et al., 2021). The circularity performance improves when secondary materials replace a greater share of virgin inputs, demonstrating the sensitivity of circularity indicators to the balance between reusable and linear materials. The modified Material Circularity Indicator can quantify agricultural system circularity, supporting the validity of LFI and MCI metrics applied in this study.

Conversely, the amount of polymer matrix with reinforcement shows a negative and statistically significant coefficient, suggesting that increasing the use of virgin polymer materials significantly reduces circularity performance. This finding is consistent with the theoretical basis of the Material Circularity Indicator, where higher proportions of virgin materials increase linear material flows and consequently reduce the circularity level of the

product system. Therefore, reducing the proportion of polymer matrix materials or substituting them with more sustainable alternatives could potentially improve the circularity of coffee waste based products.

Electricity consumption also exhibits a negative coefficient, indicating that higher energy consumption during production may reduce circularity performance. However, the statistical significance of this variable is relatively weak, suggesting that energy consumption may not be the primary factor influencing circularity performance in this particular case. Instead, material composition appears to play a more dominant role in determining the circularity level of the products. However, the overall logistic regression model was not statistically significant, which may be influenced by the relatively small dataset used in this study. This limitation may reduce the statistical power of the model in explaining circularity outcomes and suggests that further studies with larger datasets are needed to obtain more robust statistical results.

These findings are consistent with previous research emphasizing the importance of material selection in improving product sustainability. Studies on ecodesign and circular economy practices have shown that integrating waste-derived materials into product development can significantly enhance resource efficiency and reduce environmental impacts. The results of this study therefore contribute to the growing body of literature on circular material utilization by providing empirical evidence on how agricultural waste such as cascara can be integrated into composite products and how production variables influence circularity performance at the product level.

In addition to supporting existing literature, this study also provides new insights into the application of circular economy indicators in evaluating eco-products developed by small and medium-sized enterprises (SMEs). These findings are also relevant to circular economy implementation in Indonesian business practices (Wibowo & Wicaksono, 2025). Sustainability initiatives in Indonesian companies commonly include waste reduction, recycling improvement, and transition toward more sustainable operational systems. While their study focused on corporate-level sustainability practices, the present study contributes at the product level by showing how circularity performance can be quantitatively measured using LFI and MCI. This distinction is important because small-scale eco-product developers may not yet have comprehensive sustainability reporting systems, but they can still use product-level circularity indicators to identify material inefficiencies and improve product formulation. Furthermore, the integration of circular economy indicators with statistical modelling provides a quantitative framework for identifying production factors that influence circularity performance. This approach may assist product developers and SMEs in optimizing material compositions and production processes to improve the sustainability of eco-products derived from agricultural waste.

## **CONCLUSION & RECOMMENDATION**

This study evaluates the circularity performance of coffee waste based composite products produced by Regoods by applying circular economy indicators and statistical analysis. The results indicate that the evaluated products exhibit relatively low circularity levels, reflecting the continued dominance of linear material flows within the production system despite the incorporation of cascara as a secondary material derived from coffee processing waste.

Among the evaluated products, cups demonstrate relatively higher circularity performance compared to boards and plates. Products containing higher proportions of cascara tend to exhibit improved circularity performance, indicating the important role of agricultural waste utilization in supporting more circular material systems. The regression analysis further highlights that increasing the use of secondary materials such as cascara can contribute positively to circularity performance, while greater reliance on virgin polymer inputs tends to reduce the circularity level of the products.

The findings of this study contribute to the growing research on circular economy practices by providing empirical evidence on the application of circularity indicators for evaluating biomass-based eco-products. The integration of circular economy metrics with statistical modeling also offers a practical analytical framework for understanding how production variables influence circularity outcomes. Such an approach may support SMEs and eco-product developers in designing more sustainable materials, optimizing production systems, and improving the circularity performance of biomass-based products.

Despite its contributions, this study has several limitations. The dataset used in the analysis consists of a relatively small number of product samples, which may limit the generalizability of the regression results. In addition, the circularity evaluation focuses primarily on material flow indicators and does not incorporate broader environmental impact assessments such as life cycle assessment. Therefore, future research may expand the dataset and integrate additional sustainability evaluation methods to provide a more comprehensive assessment of eco-product performance.

Future studies may also explore alternative material formulations that increase the proportion of biomass-based components or replace conventional polymer matrices with biodegradable or bio-based polymers. Such approaches could potentially improve the circularity performance of coffee waste based products while maintaining their functional properties. Furthermore, integrating circular economy indicators with ecodesign strategies and life cycle assessment methods could provide a more holistic framework for evaluating and improving the sustainability of agro-industrial waste-based products.

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## **DECLARATION**

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