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Environmental Impact Assessment of Tuni Coffee Production Using Life Cycle Assessment in West Seram Regency

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ABSTRACT

Environmental sustainability in smallholder coffee production remains a critical concern, particularly in regions where resource management practices and ecological pressures are insufficiently documented. This study examines the associations between resource consumption, energy utilization, waste management, and perceived environmental impacts in Tuni coffee production in West Seram Regency, Indonesia. A quantitative cross-sectional survey involving 85 respondents was conducted using a life-cycle-informed environmental assessment framework. Data were collected through a structured questionnaire and analyzed using multiple linear regression with SPSS version 25. The findings reveal significant negative associations between perceived environmental impacts and resource consumption management, energy utilization management, and waste management. Resource consumption demonstrated the strongest association, while the model explained 22.5% of the variation in perceived environmental impacts. These findings suggest that more efficient resource use, responsible energy management, and improved waste practices are associated with lower perceived environmental pressures. The study contributes to smallholder agricultural sustainability research by extending life-cycle thinking to a locally distinctive coffee production system through a perception-based assessment. The findings provide practical insights for identifying environmental management priorities while emphasizing the need for inventory-based assessments to quantify actual environmental impacts.

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1. INTRODUCTION

Coffee production plays a significant role in agricultural development and rural livelihoods, yet its environmental sustainability remains a growing concern. Cultivation and processing activities involve agricultural inputs, water consumption, energy utilization, and waste generation that may contribute to ecological degradation. These environmental pressures extend across the production cycle, highlighting the need for integrated assessment rather than evaluations limited to individual activities. [1] emphasized the importance of examining

environmental burdens throughout the coffee supply chain, while [2] demonstrated that fertilizer management significantly influences environmental performance. Similarly, [3] identified variations in global warming potential across coffee processing methods, indicating that production practices and technological choices are critical to environmental sustainability.

Environmental challenges are particularly relevant to smallholder coffee production, where limited resources, traditional cultivation practices, and technological constraints may affect environmental management [4]. Inefficient fertilizer application, excessive resource consumption, and inadequate waste treatment can generate environmental pressures, while improved production efficiency and organic waste utilization offer opportunities for more sustainable practices [2], [3]. These challenges are especially important in geographically diverse agricultural systems such as Indonesia, where environmental conditions and production methods vary across regions. Tuni coffee, a locally distinctive commodity cultivated in West Seram Regency, Maluku Province, represents an underexplored context for environmental sustainability research. Although [5] documented the morphological diversity and distinguishing characteristics of Tuni coffee, its environmental management practices and production-related ecological concerns remain insufficiently examined.

Life Cycle Assessment (LCA) provides a systematic framework for evaluating environmental implications across interconnected production stages [6]. According to ISO 14040:2006, LCA comprises goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [7]. Previous studies have applied this framework to examine environmental burdens associated with coffee supply chains, fertilizer management, and processing technologies. However, conventional LCA generally requires quantitative inventory data on material inputs, energy consumption, emissions, and waste flows. Where such measurements are unavailable, a life-cycle-informed assessment of producers' reported practices and environmental perceptions can provide complementary evidence for identifying environmental management priorities, although it cannot substitute for a conventional environmental footprint assessment.

Despite growing research on coffee production sustainability, limited empirical attention has been directed toward environmental management practices and perceived ecological pressures associated with locally distinctive coffee commodities. Existing studies primarily emphasize measurable environmental impacts, fertilizer alternatives, and processing technologies, while research on Tuni coffee has largely focused on its morphological characteristics [5]. Consequently, the relationships between resource consumption management, energy utilization, waste management, and perceived environmental impacts in Tuni coffee production remain inadequately understood. Addressing this gap requires a context-specific, perception-based assessment that incorporates life-cycle thinking while distinguishing reported environmental conditions from objectively measured ecological impacts.

This study examines the associations between resource consumption management, energy utilization, waste management, and perceived environmental impacts in Tuni coffee production in West Seram Regency. Using a quantitative cross-sectional survey involving 85 respondents, the research adopts a life-cycle-informed framework to evaluate environmental management practices across relevant production stages. The study contributes to the literature by extending life-cycle thinking to a locally distinctive smallholder coffee production system and providing empirical evidence on the relationships between reported environmental practices and perceived ecological pressures. Its methodological contribution lies in applying a structured, perception-based assessment where

comprehensive life cycle inventory data are unavailable, without claiming to quantify actual environmental footprints. Practically, the findings are intended to inform locally appropriate strategies for improving resource efficiency, energy management, and waste utilization in support of sustainable coffee production.

2. LITERATURE REVIEW

2.1 Environmental Impact Assessment in Agricultural Production

Environmental impact assessment provides a systematic approach to understanding ecological pressures associated with agricultural production, including resource consumption, energy use, and waste generation. In coffee production, these pressures arise across cultivation, processing, drying, and waste management, highlighting the importance of a life-cycle perspective. [1] emphasized the need to evaluate environmental burdens across interconnected production stages, while [2] demonstrated that fertilizer management influences environmental performance, energy requirements, and economic sustainability. Beyond physical environmental indicators, producers' perceptions offer complementary insights into resource management practices and environmental concerns, particularly in smallholder farming systems. Although perception-based assessments cannot quantify actual emissions or ecological damage, integrating them with life-cycle thinking provides a useful exploratory framework for identifying environmental management priorities when comprehensive inventory data are unavailable.

2.2 Life Cycle Analysis as an Environmental Assessment Framework

Life Cycle Assessment (LCA) provides a systematic framework for evaluating environmental impacts across interconnected production stages. According to the International Organization for Standardization [7], LCA comprises four phases: goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation. In coffee production, environmental pressures arise from cultivation, harvesting, processing, drying, and transportation, involving resource consumption, energy use, and waste generation [8]. [3] demonstrated that processing methods influence environmental performance, while [2] highlighted the environmental implications of fertilizer management. Although conventional LCA relies on quantitative inventory data, life-cycle thinking can also guide questionnaire-based assessments of environmental practices and perceptions. Such assessments do not quantify actual environmental burdens but provide preliminary insights into environmental management priorities. For Tuni coffee production, this approach enables the examination of perceived environmental impacts across production stages while distinguishing reported practices from measurable ecological outcomes.

2.3 *Environmental Impacts of Coffee Production*

Coffee production generates environmental pressures through agricultural inputs, resource consumption, energy use, and organic waste, with impacts varying according to cultivation practices, processing technologies, and environmental management. [2] demonstrated that fertilizer management influences environmental performance, while [3] highlighted the environmental implications of different coffee processing methods. Inadequate management of coffee residues, including pulp, husks, and wastewater, may contribute to environmental contamination, whereas composting and resource recovery offer opportunities to improve sustainability [9]. However, environmental improvements may involve trade-offs between resource efficiency and energy requirements. Therefore, assessing the environmental impacts of Tuni coffee production requires a multidimensional perspective encompassing resource consumption, energy utilization, and waste management across production stages.

2.4 *Resource Consumption and Environmental Sustainability*

Resource consumption is a critical dimension of environmental sustainability, as agricultural production depends on efficient land, water, energy, and material utilization. In coffee production, effective fertilizer application, water management, and processing efficiency can reduce resource wastage and environmental pressures [10]. [2] demonstrated that fertilizer management and energy requirements influence sustainability outcomes, while [3] highlighted the environmental implications of different processing practices. Water-intensive operations and inefficient technologies may increase resource consumption and waste generation, particularly during post-harvest processing. Among smallholder producers, resource efficiency is further influenced by technological accessibility, financial capacity, and environmental awareness. Accordingly, assessing reported resource management practices and perceptions provides insights into operational efficiency and potential sustainability improvements in Tuni coffee production.

2.5 *Energy Utilization and Environmental Impacts*

Energy utilization is an important determinant of environmental sustainability in coffee production, particularly during processing, drying, and transportation [11]. Energy consumption and its environmental implications depend on production technologies, operational efficiency, and energy sources, with fossil fuel dependence potentially increasing environmental burdens. [2] emphasized the relationship between energy requirements and environmental performance, while [3] demonstrated that different coffee processing methods generate varying environmental impacts. Efficient equipment operation, reduced fuel consumption, and

appropriate drying techniques may improve energy management, particularly among smallholder producers. Accordingly, assessing reported energy management practices and producers' perceptions provides insights into potential environmental pressures and opportunities for improving energy efficiency in Tuni coffee production without equating perceived improvements with measured reductions in energy consumption or emissions.

2.6 *Waste Management in Coffee Production*

Waste management is essential to environmental sustainability in coffee production, as processing activities generate organic residues and wastewater that may contribute to environmental degradation when improperly handled. Coffee by-products, including pulp, husks, parchment, and mucilage, can cause pollution through uncontrolled decomposition and inadequate disposal [12]. However, waste separation, composting, and resource recovery offer opportunities to reduce environmental pressures and support circular economy practices [13]. The effectiveness of these approaches depends on processing technologies, infrastructure, technical knowledge, and local production conditions. In smallholder coffee systems, evaluating reported waste management practices and perceived environmental impacts can help identify opportunities for improving residue utilization, reducing waste generation, and strengthening environmental sustainability. For Tuni coffee production, this assessment provides a basis for understanding existing waste management practices and identifying locally appropriate sustainability improvements.

2.7 *Environmental Sustainability in Smallholder Coffee Production*

Environmental sustainability in smallholder coffee production requires balancing agricultural productivity, resource conservation, and economic viability under local technological and financial constraints [14]. Sustainable practices, including efficient input utilization, responsible land management, and waste reduction, can support environmental performance, although their effectiveness depends on production conditions and implementation. [2] emphasized the importance of integrating environmental, energy, and economic considerations into coffee sustainability assessments. In West Seram Regency, Tuni coffee represents a distinctive agricultural commodity whose morphological diversity has been documented by [5]. However, its environmental management practices remain insufficiently explored. Therefore, examining producers' reported practices and environmental perceptions can provide preliminary insights into resource efficiency and sustainability priorities, while recognizing that perceived improvements do not necessarily reflect measurable ecological outcomes.

3. METHODS

This study employed a quantitative cross-sectional survey design to examine environmental management practices and perceived environmental impacts associated with Tuni coffee production in West Seram Regency, Maluku Province, Indonesia. The research adopted a life-cycle-informed assessment framework based on ISO 14040:2006, covering five production stages: cultivation, harvesting, post-harvest processing, drying, and waste management. The study involved 85 respondents engaged in Tuni coffee production, with purposive sampling specified to target individuals possessing direct knowledge of cultivation, processing, and resource management. The unit of analysis was the individual respondent. Unlike conventional Life Cycle Assessment (LCA), which quantifies material flows, emissions, and environmental footprints, this study applied life-cycle thinking to assess reported production practices and perceived environmental pressures through questionnaire-based data.

Primary data were obtained using a structured questionnaire comprising respondent characteristics and 16 measurement indicators across four constructs: Resource Consumption (X1), Energy Utilization (X2), Waste Management (X3), and Perceived Environmental Impact (Y). Each construct was measured using four indicators on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Resource Consumption assessed water-use efficiency, fertilizer management, material conservation, and resource wastage; Energy Utilization examined equipment efficiency, fuel consumption, energy-saving practices, and energy management during processing; and Waste Management measured waste separation, organic residue utilization, disposal practices, and waste reduction. Perceived Environmental Impact captured respondents' concerns regarding soil degradation, water contamination, air pollution, and ecological disturbance. Higher scores on the independent variables indicated more environmentally responsible practices, whereas higher scores on the dependent variable reflected greater perceived environmental pressures.

Data were analyzed using SPSS version 25 through descriptive statistics, instrument assessment, regression diagnostics, and multiple linear regression. Descriptive analysis included frequencies, means, and standard deviations, while item consistency was assessed using corrected item–total correlations (≥0.30) and internal reliability using Cronbach's alpha (≥0.70). Regression assumptions were evaluated through residual normality, multicollinearity, heteroscedasticity, and linearity diagnostics. Multiple linear regression examined the associations between Resource Consumption, Energy Utilization, Waste Management, and Perceived Environmental Impact, with individual coefficients assessed using t-tests and overall model significance evaluated using the F-test at a 5% significance level. Model explanatory power was assessed using R^2 and adjusted R^2. Given the cross-sectional design, self-reported measurements, and non-probability sampling approach, findings were interpreted as statistical associations rather than causal effects or objectively measured environmental impacts.

4. RESULTS AND DISCUSSION

4.1 Descriptive Statistical Analysis

Descriptive statistical analysis was used to summarize the central tendencies and variability of the four research constructs.

Table 1. Descriptive Statistics of Research Variables

Variable	N	Mean	Std. Deviation	Minimum	Maximum
Resource Consumption (X1)	85	3.379	0.661	1.75	4.75
Energy Utilization (X2)	85	3.091	0.665	1.50	4.50
Waste Management (X3)	85	2.903	0.628	1.50	4.25
Perceived Environmental Impact (Y)	85	3.576	0.837	1.75	5.00

Table 1 presents the descriptive statistics for the four research variables based on 85 respondents. Perceived Environmental Impact recorded the highest mean (3.576, SD = 0.837), indicating relatively high perceived environmental pressures associated with Tuni coffee production. Resource Consumption showed a moderate mean (3.379, SD = 0.661), followed by Energy Utilization (3.091, SD = 0.665), suggesting moderate levels of reported resource and energy management practices. Waste Management exhibited the lowest mean (2.903, SD = 0.628), highlighting potential limitations in waste handling and reduction practices. The relatively higher variability in Perceived Environmental Impact suggests greater differences in respondents' environmental concerns.

4.2 Descriptive Analysis of Measurement Indicators

The indicator-level analysis provides a more detailed representation of the environmental management dimensions examined in the study.

Table 2. Descriptive Statistics of Measurement Indicators

Code	Measurement Indicator	Mean
X1.1	Water-use efficiency	3.46
X1.2	Fertilizer-use efficiency	3.38
X1.3	Material conservation	3.36
X1.4	Reduction of resource wastage	3.32
X2.1	Efficient equipment operation	3.21
X2.2	Fuel-use efficiency	3.05
X2.3	Energy-saving practices	3.11
X2.4	Energy management during processing	3.00
X3.1	Waste separation	2.93
X3.2	Organic waste utilization	2.95
X3.3	Appropriate waste disposal	2.86
X3.4	Waste reduction practices	2.87
Y1	Perceived soil degradation	3.54
Y2	Water contamination concerns	3.53
Y3	Air pollution concerns	3.69
Y4	Production-related ecological disturbance	3.54

Table 2 presents the descriptive statistics of measurement indicators across the four research variables. Resource Consumption showed relatively favorable responses, particularly for water-use efficiency (3.46), while resource wastage reduction recorded the lowest mean within this construct (3.32). Energy Utilization indicators ranged from 3.00 to 3.21, with efficient equipment operation receiving the highest score and energy management during processing the lowest. Waste Management exhibited consistently lower means, particularly for appropriate waste disposal (2.86) and waste reduction practices (2.87), suggesting areas requiring greater attention. Among the Perceived Environmental Impact indicators, air pollution concerns recorded the highest mean (3.69), followed by perceived soil degradation and ecological disturbance (3.54 each), and water contamination concerns (3.53).

4.3 Instrument Reliability and Item Analysis

Instrument reliability and item consistency were assessed using Cronbach's alpha and corrected item–total correlations, respectively.

Table 3. Reliability and Item Consistency Results

Variable	Number of Items	Cronbach's Alpha	Corrected Item–Total Correlation Range	Assessment
Resource Consumption	4	0.772	0.528–0.599	Acceptable
Energy Utilization	4	0.727	0.437–0.597	Acceptable
Waste Management	4	0.747	0.468–0.617	Acceptable
Perceived Environmental Impact	4	0.901	0.738–0.828	High internal consistency

Table 3 presents the reliability and item consistency results for the four research constructs. Cronbach's alpha values ranged from 0.727 to 0.901, exceeding the recommended threshold of 0.70 and indicating acceptable to high internal consistency. Perceived Environmental Impact demonstrated the highest reliability (α = 0.901), followed by Resource Consumption (0.772), Waste Management (0.747), and Energy Utilization (0.727). Corrected item–total correlations ranged from 0.437 to 0.828, with all indicators exceeding the minimum criterion of 0.30. These findings suggest that the measurement scales exhibit satisfactory internal consistency and item coherence, supporting their use in subsequent statistical analyses.

4.4 Classical Assumption Testing

Regression diagnostic tests procedures were intended to assess whether the estimated regression model satisfied relevant statistical assumptions.

Table 4. Regression Diagnostic Results

Diagnostic Test	Indicator	Result	Interpretation
Residual normality	Shapiro–Wilk p-value	0.086	No significant departure detected
Heteroscedasticity	Breusch–Pagan p-value	0.622	No significant heteroscedasticity detected
Multicollinearity (X1)	VIF	1.029	Low multicollinearity
Multicollinearity (X2)	VIF	1.002	Low multicollinearity
Multicollinearity (X3)	VIF	1.031	Low multicollinearity

Table 4 presents the regression diagnostic results, indicating no significant violations of the assessed assumptions. The Shapiro–Wilk test (p = 0.086) showed no significant departure from residual normality, while the Breusch–Pagan test (p = 0.622) indicated no evidence of heteroscedasticity. Furthermore, Variance Inflation Factor (VIF) values ranged from 1.002 to 1.031, suggesting negligible multicollinearity among the independent variables.

4.5 Multiple Linear Regression Analysis

Multiple linear regression examined the associations of resource consumption, energy utilization, and waste management with perceived environmental impact.

Table 5. Multiple Linear Regression Results

Predictor	B	Std. Error	Standardized Beta	t	p-value
Constant	6.649	0.644	—	10.326	<0.001
Resource Consumption (X1)	−0.382	0.126	−0.302	−3.041	0.003
Energy Utilization (X2)	−0.277	0.123	−0.220	−2.248	0.027
Waste Management (X3)	−0.318	0.132	−0.239	−2.406	0.018

Table 5 presents the multiple linear regression results, indicating that all three predictors are significantly and negatively associated with Perceived Environmental Impact. Resource Consumption exhibited the strongest association (β = −0.302, t = −3.041, p

= 0.003), followed by Waste Management (β = −0.239, t = −2.406, p = 0.018) and Energy Utilization (β = −0.220, t = −2.248, p = 0.027). These findings suggest that more efficient resource use, improved waste management, and responsible energy utilization are associated with lower perceived environmental pressures in Tuni coffee production. All relationships were statistically significant at the 5% level, supporting the proposed hypotheses while reflecting associations rather than causal effects.

4.6 Model Fit and Coefficient of Determination

The model summary, indicating a moderate multiple correlation between the predictors and Perceived Environmental Impact (R = 0.475). The R^2 value of 0.225 indicates that Resource Consumption, Energy Utilization, and Waste Management collectively explain 22.5% of the variation in Perceived Environmental Impact, while the remaining 77.5% is attributable to factors not captured by the model and unexplained variation. The adjusted R^2 of 0.197 suggests modest explanatory power after accounting for the number of predictors, while the standard error of estimate (0.750) reflects the residual variability.

4.7 Simultaneous Model Testing

The overall significance of the regression model was assessed using the F-test to determine whether Resource Consumption, Energy Utilization, and Waste Management collectively explained variation in Perceived Environmental Impact.

Table 6. ANOVA Results

Source	Sum of Squares	df	Mean Square	F	p-value
Regression	13.260	3	4.420	7.849	<0.001
Residual	45.617	81	0.563	—	—
Total	58.878	84	—	—	—

Table 6 presents the ANOVA results, indicating that the overall regression model is statistically significant ($F(3, 81) = 7.849$, $p < 0.001$). The regression sum of squares (13.260) and residual sum of squares (45.617) indicate that the model explains a significant proportion of the variation in Perceived Environmental Impact, although substantial unexplained variation remains. These findings demonstrate that Resource Consumption, Energy Utilization, and Waste Management collectively have a statistically significant association with Perceived Environmental Impact in Tuni coffee production, supporting the overall model's statistical significance.

Discussion

The findings demonstrate that Resource Consumption, Energy Utilization, and Waste Management are significantly and negatively associated with Perceived Environmental Impact in Tuni coffee production. Resource Consumption exhibited the strongest association, suggesting that more efficient management of water, fertilizers, and production materials corresponds to lower perceived environmental pressures. This finding aligns with [2], who demonstrated that fertilizer management influences the environmental performance of Indonesian coffee production. Similarly, the significant associations observed for Energy Utilization and Waste Management reinforce the importance of production efficiency and responsible residue handling. [3] highlighted variations in environmental impacts across coffee processing methods, while [1] emphasized the interconnected environmental burdens arising throughout the coffee supply chain. Collectively, these findings suggest that environmental sustainability in Tuni coffee production is associated with multiple management dimensions rather than isolated agricultural practices. However, these

relationships reflect respondents' reported experiences and perceptions rather than directly measured reductions in environmental impacts.

From a theoretical perspective, the findings extend the application of life-cycle thinking to smallholder coffee production by highlighting the relationships between environmental management practices and perceived ecological pressures across interconnected production stages. Consistent with the Life Cycle Assessment framework established by the International Organization for Standardization (ISO, 2006), environmental concerns should be examined throughout production activities rather than attributed to individual processes. Previous research has primarily examined measurable environmental burdens associated with fertilizer management and processing technologies [2], [3], whereas the present study provides complementary evidence based on producers' environmental perceptions. Moreover, [5] documented the morphological characteristics of Tuni coffee without examining its environmental management dimensions. By addressing this contextual gap, the study broadens understanding of Tuni coffee sustainability beyond its biological characteristics. Nevertheless, the model's modest explanatory power indicates that environmental perceptions are also associated with factors beyond the management practices investigated, suggesting opportunities for further research incorporating technological, institutional, and socioeconomic considerations.

From a practical perspective, the findings highlight the importance of strengthening resource efficiency, energy management, and waste handling practices among Tuni coffee producers. Although Resource Consumption demonstrated the strongest statistical association, the relatively lower descriptive scores for Waste Management indicate a particular need to improve residue separation, organic waste utilization, and disposal practices. These priorities are consistent with [2], who emphasized integrated environmental and resource management, and [3], who identified processing practices as important determinants of environmental performance. Locally appropriate interventions, including efficient agricultural input utilization, improved drying practices, and organic residue recovery, may therefore support more responsible production (Pongsiriyakul et al., 2024). However, the cross-sectional design, purposive sampling, and self-reported measurements limit causal interpretation and broader generalizability. Furthermore, because the assessment did not quantify physical material flows, emissions, or standardized environmental impact categories, its findings should not be interpreted as a conventional LCA environmental footprint. Future research should integrate producer-level assessments with inventory-based environmental measurements to provide a more comprehensive evaluation of Tuni coffee sustainability.

5. CONCLUSION

This study examined the associations between resource consumption, energy utilization, waste management, and perceived environmental impacts in Tuni coffee production in West Seram Regency, Indonesia. The findings indicate that all three environmental management dimensions are significantly and negatively associated with perceived environmental impacts, with resource consumption demonstrating the strongest relationship. These results highlight the relevance of efficient agricultural input utilization, responsible energy management, and improved waste handling in addressing environmental concerns within smallholder coffee production. The study contributes to agricultural sustainability research by applying life-cycle thinking to a locally distinctive coffee commodity and providing empirical insights into producers' reported environmental practices and perceptions. Practically, the findings suggest prioritizing resource efficiency, energy-saving practices,

and organic waste management to support more environmentally responsible production. Nevertheless, the modest explanatory power, cross-sectional design, and reliance on self-reported data limit causal interpretation and generalizability. As the assessment did not quantify physical environmental flows, future studies should integrate standardized life cycle inventory data with producer-level assessments to establish actual environmental impacts and develop more comprehensive sustainability strategies for Tuni coffee production.

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