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RESEARCH ARTICLE

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Comparative Life Cycle Assessment of Robusta Green Coffee Cultivation Systems and Post-Harvest Processing in Pagar Alam, South Sumatra, Indonesia

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ABSTRACT

Pagar Alam Robusta coffee contributes significantly to the regional economy. Its cultivation and processing systems pose environmental challenges. This study compares the environmental performance of two cultivation methods (conventional-K1 and non-pesticide-K2) and six processing methods (natural origin-A1, broken skin origin-A2, natural aerobic-N1, natural anaerobic-N2, honey aerobic-H1, and honey anaerobic-H2). A cradle-to-gate Life Cycle Assessment (LCA) was conducted using a functional unit of 100 kg of green coffee beans, covering four impact categories: global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), and eutrophication potential (EP). In the cultivation subsystem, K1 produced emissions of 85.70–117.00 kg CO_2-eq (GWP), 3.53×10^{-6}–4.80×10^{-6} kg CFC-11-eq (ODP), 0.37–0.50 kg SO_2-eq (AP), and 0.16–0.22 kg PO_4-eq (EP), while K2 produced much lower emissions: 23.00–31.30 kg CO_2-eq (GWP), 2.22×10^{-7}–3.03×10^{-07} kg CFC-11-eq (ODP), 0.09–0.13 kg SO_2-eq (AP), and 0.03–0.04 kg PO_4-eq (EP). In the processing subsystem, H2 had the highest emissions: 14.77 kg CO_2-eq (GWP), 6.48 kg CFC-11-eq (ODP), 0.04 kg SO_2-eq (AP), and 0.02 kg PO_4-eq (EP), while A1 had the lowest emissions: 5.23 kg CO_2-eq (GWP), 3.87 kg CFC-11-eq (ODP), 0.01 kg SO_2-eq (AP), and 0.001 kg PO_4-eq (EP). Implementing an improvement scenario based on non-pesticide cultivation (K2) could reduce emissions by approximately 65–93% across all impact categories. These findings demonstrate that adopting pesticide-free cultivation combined with simpler processing methods can significantly reduce the environmental footprint of Robusta coffee production in Pagar Alam and support more sustainable coffee management practices.

Introduction

Coffee ranks second after oil as a commodity in world trade [1] and is the most widely consumed beverage globally [2] with an average growth rate of 2.3% during the period 1990–2018 [3]. Indonesia is the 4th largest coffee exporting country with 789,609 tons of coffee in 2023 [4] with Sumatra region as the largest contributor [5]. South Sumatra Province plays a strategic role in national coffee production, particularly for Robusta coffee, covering 228,556 ha with a production of 212,612 tons in 2023, equivalent to approximately 25% of Indonesia's total coffee output [6]. Despite its economic significance, coffee production is increasingly associated with sustainability challenges, including greenhouse gas emissions, soil degradation, water pollution, and biodiversity loss [7]. Addressing these challenges requires integrated approaches that balance productivity, environmental performance, and socio-economic sustainability along the coffee value chain [8].

Pagar Alam City is one of the major Robusta coffee-producing areas in South Sumatra, producing 22,520 tons of coffee from 8,089 ha in 2021 [4]. Pagar Alam Robusta coffee has obtained Geographical Indication certification and is recognized for its distinctive quality and flavor [9]. The increasing coffee production intensity may adversely affect environmental quality due to emissions and waste generated throughout cultivation and processing stages [10]. Coffee production generates solid, liquid wastes [11], and requires substantial energy inputs [12]. All of which contribute to soil, water, and air pollution [13] as well as greenhouse gas emissions [14]. Previous studies reported that conventional coffee cultivation can emit up to 124 kg CO_2-eq per 100 kg of green beans and contribute significantly to eutrophication and acidification

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through fertilizer and pesticide use [15]. These findings highlight the importance of quantifying the environmental impacts of coffee production systems, particularly at the local level.

There are several variations in the processing methods of Pagar Alam Robusta coffee, both raw coffee and red-picked coffee. Although several studies have assessed the environmental impacts of coffee production in different regions, to date, no life cycle assessment (LCA) study has been conducted on Robusta coffee production in Pagar Alam that simultaneously considers variations in cultivation and post-harvest processing. Previous impact values from other areas cannot be directly applied to Pagar Alam due to differences in technology, processing stages, and input types [10]. LCA is particularly relevant in this context because it enables the quantification of emissions and impact hotspots along the cradle-to-gate chain, thus providing evidence-based recommendations for reducing environmental burdens in site-specific systems. This study fills that gap by conducting a comprehensive cradle-to-gate LCA using primary field data collected from local producers, enabling a detailed and site-specific evaluation of environmental performance. The novelty of this research lies in its integration of local-scale cultivation and processing data into a complete LCA framework—an approach that has not been explored in existing literature.

The growing demand for competitive and environmentally friendly mass production in the globalization era necessitates the use of life cycle assessment [16], particularly in the robusta coffee industry of Pagar Alam. LCA is a recognized method for evaluating the environmental impacts of a product throughout its life cycle [17]. It accounts for every stage, from cultivating and harvesting coffee cherries, transporting them to processing units, converting them into green coffee beans, and distributing them to the market. This allows for comprehensive and reliable measurement of impacts based on all input–output flows of materials, products, and energy [18]. As a result, LCA outcomes can help identify impact hotspots and serve as a foundation for process improvements and environmentally sound product development [19]. This study aims to compare the environmental performance of two typical coffee cultivation systems and the environmental performance of six Pagar Alam Robusta coffee production processes through the LCA method. By quantifying environmental burdens and evaluating alternative scenarios, the findings provide actionable strategies for emission reduction and contribute to broader discussions on coffee sustainability.

Materials and Methods

Research Setting

This research was conducted from June to December 2024 in Pagar Alam City, South Sumatra Province, Indonesia, covering three districts: South Dempo, Central Dempo, and North Dempo (Figure 1). These districts represent the primary centers of Robusta coffee cultivation and processing in the region and were purposively selected based on production scale, accessibility, and the presence of active micro, small, and medium-sized enterprises (MSMEs). The inclusion of these locations ensured representation of typical cultivation and post-harvest processing practices within the Pagar Alam's coffee agroindustry.

Four MSMEs participated in the study, each specializing in different post-harvest processing methods. One MSME processed natural origin and broken skin origin coffee, another focused on natural aerobic, a third on honey aerobic, and the fourth combined natural anaerobic and honey anaerobic. Raw coffee cherries were sourced from a total of 63 farmers (53 practicing conventional cultivation (K1) and 10 practicing non-pesticide cultivation (K2)), with individual plantation sizes ranging from 1–2 hectares. Farmers were selected using stratified random sampling based on farm size and cultivation method. Primary data were collected during the main harvest season (July–September 2024) and verified against annual production records (2023–2024) to account for seasonal variability.

Data Collection Procedures

Both primary and secondary data were used in this study. Primary data were obtained through direct field measurements, structured interviews with MSME owners and managers, and on-site observations. Data collection focused on material and energy inputs and outputs across cultivation, harvesting, transportation, and processing stages, including fertilizer and pesticide application, water use, electricity and fuel consumption, and waste generation.

Material inputs were measured using calibrated digital scales. Water consumption was recorded manually based on the volume used in each processing stage. Electricity consumption was estimated based on machine nameplate power ratings and recorded operating hours and validated against MSME electricity bills. All primary data were cross-validated using mass balance calculations, production records, and triangulation between interviews and field observations to ensure data reliability. Secondary data were sourced from the SimaPro 9.6.0.1 software (PRé Sustainability), utilizing internationally recognized Life Cycle Inventory (LCI) databases [20], including Ecoinvent 3, Agri-footprint, and USLCI. Indonesia-specific (ID) datasets were prioritized. When local datasets were unavailable, regional (Asia), Global (GLO), or Rest-of-World (RoW) datasets were applied in a hierarchical manner. Additional supporting data were obtained from peer-reviewed journals, theses, and official government publications related to coffee production systems in Indonesia.

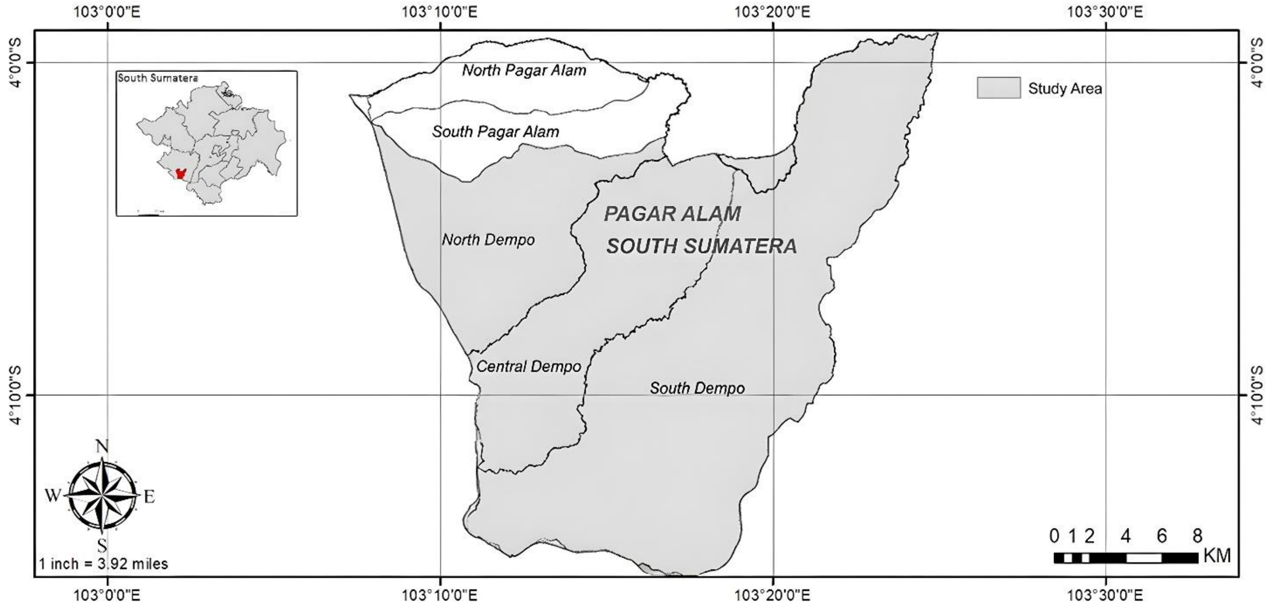

Figure 1. Study area map showing the surveyed districts of South Dempo, Central Dempo, and North Dempo in Pagar Alam City, South Sumatra, Indonesia. These districts represent the main Robusta coffee-producing areas where field data were collected from farmers and coffee-processing MSMEs. The map illustrates the geographical location of the study area used to analyze the environmental impacts of Robusta coffee cultivation and post-harvest processing.

Methodological Framework and Design

The LCA method is based on the LCA framework in SNI ISO 14040:2016, which consists of four stages, namely goal and scope definition, life cycle inventory analysis, life cycle impact assessment and determination of hotspots or areas most affected and and interpretation [21]. These stages are designed to systematically evaluate environmental impacts throughout the product life cycle. The interpretation stage also includes the identification of environmental hotspots and the formulation of improvement recommendations. Each phase applied in this study is described in detail below.

The goal and scope definition stage aimed to evaluate and compare the environmental impacts of two cultivation methods, namely conventional (K1) and non-pesticide (K2), and six coffee processing methods: natural origin (A1), broken skin origin (A2), natural aerobic (N1), natural anaerobic (N2), honey aerobic (H1), and honey anaerobic (H2). The functional unit was defined as the production of 100 kg of green coffee beans. The system boundary followed a cradle-to-gate approach, covering activities from cultivation, harvesting, transportation, and post-harvest processing stages. The environmental impact categories assessed were Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), and Eutrophication Potential (EP).

The life cycle inventory (LCI) stage included the compilation of all relevant material and energy inputs and outputs throughout the production system. These included fertilizers, pesticides, fuel, electricity, water, packaging materials, and waste streams such as solid and liquid residues. A cut-off criterion of 1% based on mass and energy was applied in accordance with ISO 14044. Inputs and outputs below this threshold were excluded from the system boundary, as they were considered environmentally insignificant. For processes generating by-products, allocation procedures followed ISO 14044 guidelines. Coffee husks and other processing residues were not valorized by the MSMEs and were treated as waste. Therefore, no allocation was applied, and the entire environmental burden was conservatively assigned to the main product, namely green coffee beans. This assumption represents a worst-case scenario and prevents underestimation of environmental impacts.

The life cycle impact assessment (LCIA) was conducted using SimaPro 9.6.0.1 software with the CML-IA Baseline (v3.09/World 2000) midpoint method. This approach quantified impact contributions for each selected category per functional unit. Normalization was performed using CML-IA baseline normalization factors (World, 2000) to enable cross-category comparison. The LCA results presented in this study are based on deterministic inventory data generated using SimaPro software. No statistical uncertainty analysis (e.g., Monte Carlo simulation) was performed; therefore, error bars are not shown in the figures.

The interpretation stage involved analyzing the LCIA results to identify environmental hotspots with the highest environmental burdens. Improvement strategies were formulated based on the best-performing scenarios (e.g., non-pesticide cultivation and natural processing), focusing on emission reduction potential, energy efficiency, and material substitution.

Study Limitations

This study used internationally recognized LCI databases for background processes. Indonesia-specific datasets were prioritized. The use of Global (GLO) and Rest-of-World (RoW) datasets may affect the precision of absolute impact values. A relative comparison among scenarios remain valid because all scenarios were modelled consistently using the same data hierarchy. The impact assessment was limited to four categories (GWP, ODP, AP, and EP), and potential burden shifting to other categories (e.g., land use, human toxicity, and ecotoxicity) was not evaluated. Future studies should expand the impact scope to provide a more comprehensive sustainability assessment. Quantitative uncertainty analysis was not conducted due to data and time constraints; instead, uncertainty was addressed qualitatively through mass balance verification, field data triangulation, and cross-validation of production records. The differences in environmental impacts among processing methods should be interpreted as indicative trends rather than statistically significant differences.

Results and Discussion

Result

This study aimed to quantify the environmental impacts of Pagar Alam Robusta green coffee bean production across its cradle-to-gate life cycle, including cultivation, harvesting, transportation, and post-harvest processing. The procedure includes identifying all relevant material and energy inputs as well as main products, by-products, wastes, and emissions generated throughout the system. Inventory data were obtained through field observations, measurements, and interviews, and complemented with background data from the SimaPro database and other secondary sources.

The system boundary included cultivation activities (fertilization, pest and disease control, weed management, grafting, and harvesting) and post-harvest processing leading to green coffee bean production. The functional unit was defined as 100 kg of packaged green coffee beans, following the life cycle assessment reporting guidelines of the Ministry of Environment and Forestry of Indonesia. The selection of this functional unit considers the commonly used product packaging size and aims to provide relevant information on the product's environmental performance to consumers [19]. The assessment was conducted in three major coffee-producing districts in Pagar Alam City (South Dempo, Central Dempo, and North Dempo) based on data collected from four MSMEs. The system boundary and process flow are presented in Figure 2.

The cultivation subsystem inventory was evaluated under two scenarios: conventional cultivation (K1) and non-pesticide cultivation (K2). The K1 scenario relied on chemical fertilizers and pesticides, whereas the K2 scenario excluded pesticide application and applied mechanical weed control. The inventory data for both scenarios are summarized in Table 1. Differences in gasoline consumption between K1 and K2 reflect actual differences in weed control practices. In the conventional system (K1), weed control was performed using chemical herbicides and did not require mechanical equipment, resulting in no gasoline consumption. In contrast, the non-pesticide system (K2) relied on mechanical grass cutting using brush cutters, which required gasoline for operation.

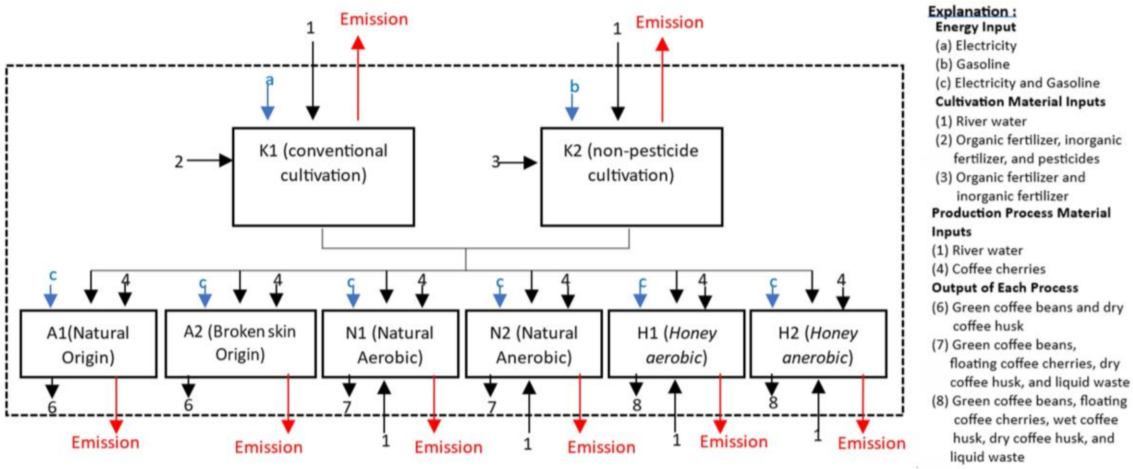

Figure 2. System boundary of Pagar Alam Robusta coffee production, covering two cultivation methods and six coffee processing methods. The cultivation stage includes fertilization, pest and disease control, and harvesting. The processing stage includes transportation, coffee processing and packaging. Foreground data were collected from MSMEs in Pagar Alam, while background data (e.g., fertilizer production, electricity generation, transportation) were sourced from SimaPro databases.

Table 1. Life Cycle Inventory (LCI) data for conventional (K1) and non-pesticide (K2) cultivation systems of Pagar Alam Robusta coffee, expressed per functional unit of 100 kg green coffee beans. The table presents the material and energy inputs used during the cultivation stage of Robusta coffee production in Pagar Alam, Indonesia. The values represent the quantities of inputs required to produce 100 kg of green coffee beans and highlight differences in input use between the two cultivation practices.

Data Inventory	Unit	Cultivation methods	
		K1	K2
Input			
Water	L	335.26	-
Coffee Husk	kg	232.55	253.75
Goat Manure	kg	46.51	-
NPK Fertilizer	kg	17.44	21.14
Urea Fertilizer	kg	6.78	-
KCL Fertilizer	kg	2.91	-
SP36 Fertilizer	kg	3.88	-
Herbicide	kg	2.45	-
Insectiside	kg	1.30	-
Electricity	kWh	0.37	-
Gasoline	L	-	0.85
Output			
Coffee Cherry	kg	647.26	647.26

*Values represent life cycle inventory data per functional unit of 100 kg green coffee beans for the cultivation stage only. K1 refers to a conventional cultivation system using synthetic fertilizers and herbicides, while K2 refers to a non-pesticide cultivation system with mechanical weed control. A dash (–) indicates that the input was not applied in the respective cultivation system. Differences in gasoline consumption reflect different weed control practices. Data are based on primary field surveys. kWh refers to kilowatt-hour.

The cultivation stage produced 647.26 kg of fresh coffee cherries, which after post-harvest processing yielded 100 kg of dried green coffee beans, corresponding to a conversion ratio of 6.47:1. All environmental impacts were normalized and reported based on the functional unit of 100 kg of green coffee beans. The next stage is the processing subsystem of Pagar Alam robusta coffee beans, which is classified into six methods: natural origin (A1), broken skin origin (A2), natural aerobic (N1), natural anaerobic (N2), honey aerobic (H1), and honey anaerobic (H2). Each method has distinct processing characteristics. The types of inventory and the quantities of inputs and outputs used in each processing method are presented in Table 2, while the differences among the six methods are detailed in Table 3.

For processes generating multiple outputs (green coffee beans, husk waste, floating cherries, and liquid waste), although some coffee husks were occasionally reused by farmers as soil amendments in their own fields, these by-products were not commercially valorized and no substitution credits were applied. Therefore, following a conservative approach, the entire environmental burden was assigned to the main product (green coffee beans). This assumption represents a worst-case scenario and avoids underestimation of environmental impacts.

Table 2. Life Cycle Inventory (LCI) data for six coffee cherry processing methods in Pagar Alam, expressed per functional unit of 100 kg packaged green coffee beans. The table presents the material and energy inputs as well as the outputs generated during the coffee cherry processing stage for six different processing methods (A1, A2, N1, N2, H1, and H2). The values represent the quantities required to produce 100 kg of packaged green coffee beans and highlight differences in input use and output generation among the processing methods

Data Inventory	Unit	Processing Methods					
		A1	A2	N1	N2	H1	H2
Input							
Transportation	Person.km	10.00	10.00	14.00	14.00	14.00	14.00
Water	L	-	-	1,286.30	1,294.28	1,293.28	
Unhulled Coffee Cherries	kg	455.55	465.35	-	-	-	-
Red Ripe Coffee Cherries	kg	-	-	643.15	647.14	646.64	647.26
Plastic Sacks	kg	0.01	0.01	0.40	0.40	0.40	0.40
LDPE Plastic	kg	-	-	0.40	0.40	0.40	0.40
Plastic Twine	kg	0.01	0.01	0.02	0.02	0.02	0.02
Electricity	kWh	0.0017	0.0017	0.002	1.061	0.002	0.80
Gasoline	L	0.50	1.50	0.71	0.77	1.90	1.90
Output							
Packaged Green Coffee Beans	kg	100.00	100.00	100.00	100.00	100.0	100.0
Floating Coffee Cherries	kg	-	-	31.96	31.23	30.71	32.21
Wet Husk Waste	kg	-	-	-	-	135.97	135.79
Dry Husk Waste	kg	52.48	52.08	77.63	77.11	33.61	33.33
Liquid Waste	L	-	-	1,285.18	1,291.18	1,290.80	1,291.94

*Values represent average life cycle inventory data per functional unit of 100 kg packaged green coffee beans. A1 = natural process (intact cherry), A2 = natural process (broken skin), N1 = natural aerobic fermentation, N2 = natural anaerobic fermentation, H1 = honey aerobic fermentation, and H2 = honey anaerobic fermentation. A dash (–) indicates that the input or output is not applicable for the respective processing method. person·km refers to labor transportation, and kWh refers to kilowatt-hour.

Table 3. Key characteristics of six Robusta coffee production methods in Pagar Alam based on raw materials, processing stages, and waste types. The table summarizes the main differences among six coffee processing methods (A1, A2, N1, N2, H1, and H2) applied in Robusta coffee production in Pagar Alam, Indonesia. The comparison includes the types of raw materials used, the sequence of processing stages, and the types of waste generated during processing. This overview highlights how variations in processing techniques influence the production workflow and waste generation.

Production methods	Raw Materials	Processing Stages	Waste type
A1	Coffee cherries harvested non-selectively (mixture of ripe, semi-ripe, and unripe cherries)	Sun drying, hulling, and packaging	Solid waste (dried husk)
A2	Coffee cherries harvested non-selectively (mixture of ripe, semi-ripe, and unripe cherries)	Pulping, sun drying, hulling and packaging	Solid waste (dried husk)
N1	Hand-picked ripe coffee cherries	Coffee flotation, sun drying, resting, hulling, sorting and packaging	Solid and liquid waste
N2	Hand-picked ripe coffee cherries	Coffee flotation, Fermentation, sun drying, resting, hulling, sorting, and packaging	Solid and liquid waste
H1	Hand-picked ripe coffee cherries	Coffee flotation, pulping, sun drying, resting, hulling, sorting, and packaging	Wet husk, solid, and liquid waste
H2	Hand-picked ripe coffee cherries	Coffee flotation, fermentation I, pulping, fermentation II, sun drying, resting, hulling, sorting, and packaging	Wet husk, solid, and liquid waste

*A1 (natural origin), A2 (broken skin origin), N1 (natural aerobic), N2 (natural anaerobic),H1 (honey aerobic), and H2 (honey anaerobic).

The environmental impact analysis of Pagar Alam robusta coffee focuses on the mandatory impact categories as regulated by the Ministry of Environment and Forestry Regulation No. 1 of 2021, namely Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), and Eutrophication Potential (EP). The results of the analysis are presented in Figure 3 and 4. Across all impact categories, products derived from the conventional cultivation system (K1) consistently generated higher emissions than those from the non-pesticide system (K2). Overall, emissions from K1 were approximately three to seven times higher than those from K2, indicating that cultivation practices strongly influence the environmental performance of green coffee bean production.

In the cultivation stage, fertilizer application was identified as the dominant contributor to environmental impacts, particularly for the GWP, AP, and EP categories. Nitrogen-based fertilizers contributed most strongly to GWP and AP through N_2O and NOx emissions, while phosphorus-containing fertilizers were the main drivers of EP. Pesticide use showed a relatively higher contribution to ODP, whereas fuel consumption mainly influenced GWP through direct CO_2 emissions. These results indicate that fertilizer management represents the most critical leverage point for emission reduction. A comparison of the emission impacts between K1 and K2 cultivation systems per 100 kg of robusta green coffee beans is shown in Figure 5.

Environmental impacts were further normalized into Person Equivalent units using CML-IA baseline normalization factors (World, 2000). One Person Equivalent represents the average annual environmental burden generated by one global citizen, allowing the relative magnitude of impacts to be interpreted in relation to global per capita emissions. The K1 scenario produced a total impact of 6.31×10^{-12} Person Equivalent, which was approximately four times higher than the 1.56×10^{-12} Person Equivalent recorded for the K2 scenario. In both systems, GWP contributed the largest share of total impacts, followed by AP and EP, whereas ODP contributed only marginally. These results confirm that the non-pesticide cultivation system substantially reduces the overall environmental burden of Robusta coffee production.

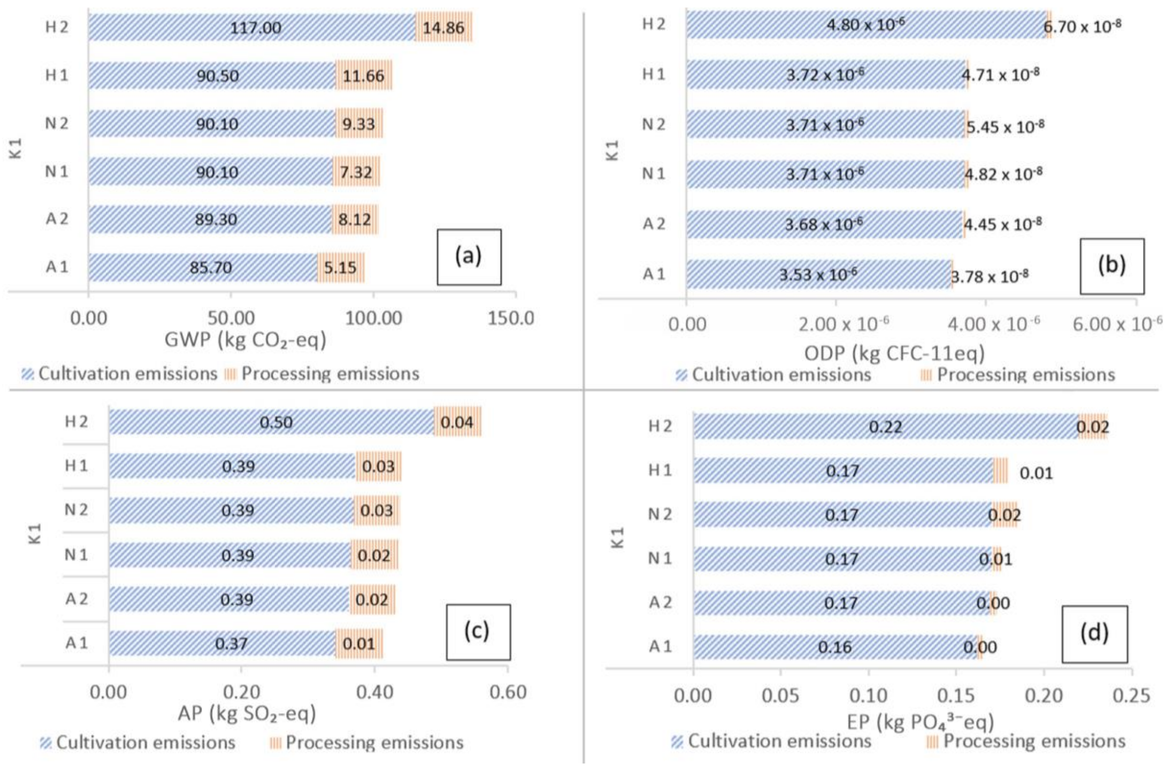

Figure 3. Environmental impact assessment of the K1 (conventional) cultivation system for Robusta coffee production in Pagar Alam. The figure presents a comparative analysis of six coffee processing methods (A1–H2) across four environmental impact categories: (a) Global Warming Potential (GWP, kg CO_2-eq), (b) Ozone Depletion Potential (ODP, kg CFC-11eq), (c) Acidification Potential (AP, kg SO_2-eq), and (d) Eutrophication Potential (EP, kg PO_4^{3-}eq). Emissions are reported per functional unit of 100 kg green coffee beans and separated into contributions from cultivation and processing activities.

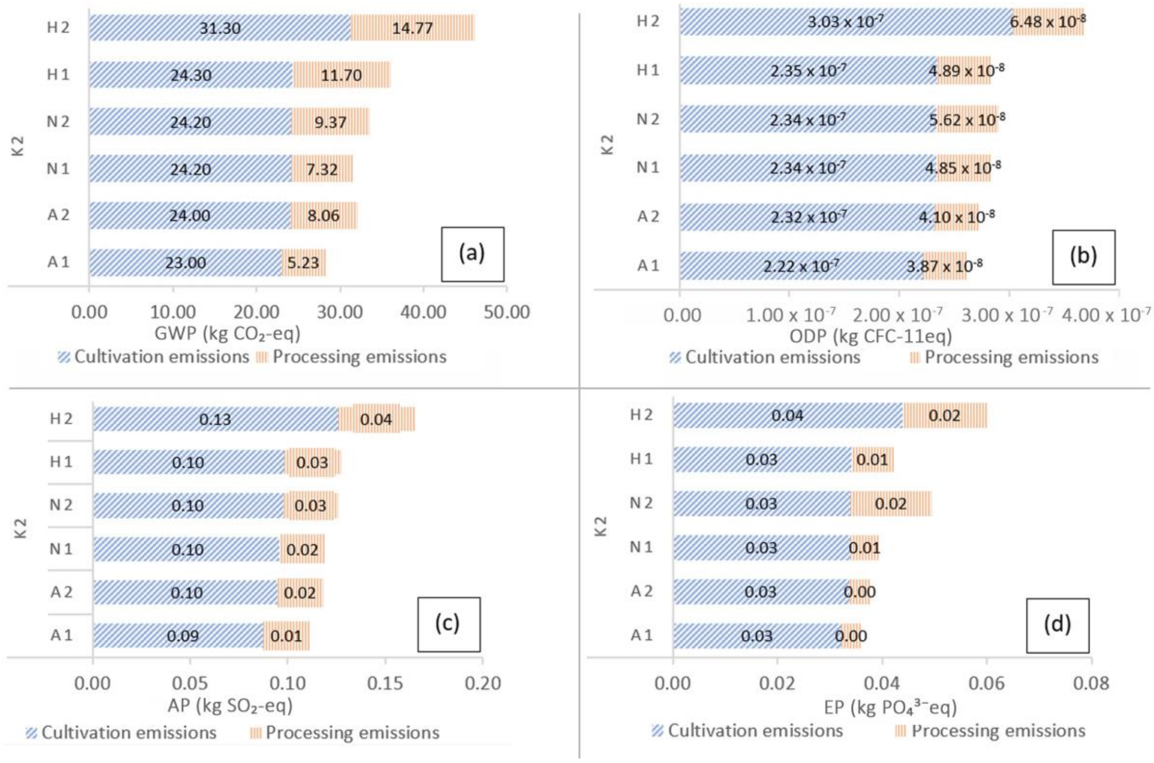

Figure 4. Environmental impact assessment of the K2 (non-pesticide) cultivation system for Robusta coffee production in Pagar Alam. The figure presents a comparative analysis of six coffee processing methods (A1–H2) across four environmental impact categories: (a) Global Warming Potential (GWP, kg CO_2-eq), (b) Ozone Depletion Potential (ODP, kg CFC-11-eq), (c) Acidification Potential (AP, kg SO_2-eq), and (d) Eutrophication Potential (EP, kg PO_4^{3-}eq). Emissions are reported per functional unit of 100 kg green coffee beans and separated into contributions from cultivation and processing activities.

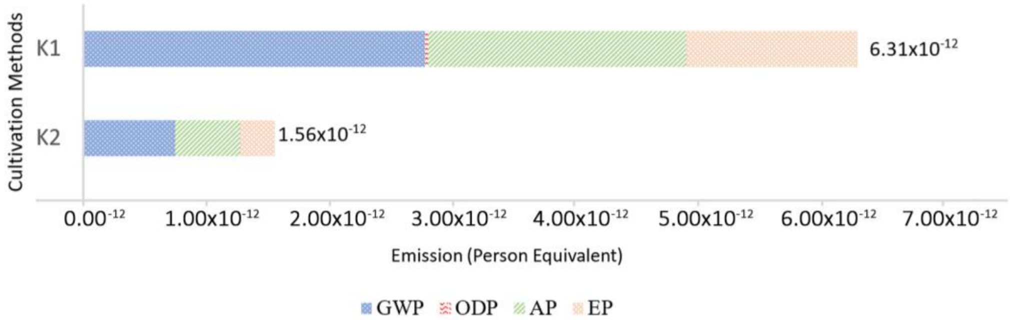

Figure 5. Comparison of the total magnitude and relative contribution of four environmental impact categories between conventional (K1) and non-pesticide (K2) cultivation systems for Robusta coffee production in Pagar Alam. The figure illustrates the contributions of Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), and Eutrophication Potential (EP), expressed in person equivalent units. Results are reported per functional unit of 100 kg green coffee beans

To further identify the drivers of environmental hotspots in the cultivation stage, a contribution analysis was conducted to quantify the relative contribution of major agricultural inputs to each impact category. The results are presented in Table 4. As shown in Table 4, urea fertilizer is the dominant contributor to GWP and AP in the K1 cultivation system, accounting for 27.8% and 33.6% of the total impacts, respectively. In contrast, herbicide application contributes most significantly to ODP (59.5%) and EP (28.5%), indicating that fertilizer management and pesticide reduction represent key leverage points for mitigating environmental impacts at the cultivation stage.

Table 4. Percentage contribution of major agricultural inputs to environmental impact categories in the K1 (conventional) Robusta coffee cultivation system in Pagar Alam, Indonesia. The table presents the relative contribution (%) of major agricultural inputs, including fertilizers, herbicides, insecticides, and electricity, to four environmental impact categories: GWP, ODP, AP, and EP, during the cultivation stage of the K1 system. The values represent the environmental impacts generated throughout the Robusta coffee cultivation process in Pagar Alam. This comparison highlights the variation in contribution levels across input types and impact categories.

Input	GWP (%)	ODP (%)	AP (%)	EP (%)
NPK Fertilizer	20.5	5.2	19.8	16.3
Urea Fertilizer	27.8	9.9	33.6	25.2
KCl Fertilizer	6.4	1.8	6.5	5.2
SP36 Fertilizer	7.6	2.1	11.1	10.4
Herbicide	26.8	59.5	19.9	28.5
Insectiside	10.6	21.5	8.7	13.3
Electricity	0.4	0.0	0.4	1.2

*GWP = Global Warming Potential; ODP = Ozone Depletion Potential; AP = Acidification Potential; EP = Eutrophication Potential. Values represent the relative contribution (%) of each input to the total environmental impact within the cultivation stage of the K1 system.

The processing subsystem was evaluated using inputs from the K2 cultivation scenario. Among the six processing methods, H2 (honey anaerobic) consistently produced the highest emissions across all impact categories, whereas A1 (natural origin) showed the lowest environmental impacts. This pattern indicates that longer and more complex fermentation processes substantially increase energy consumption and associated emissions. Total emissions and relative contributions of four environmental impact categories is shown in Figure 6. Across all processing methods, GWP was the dominant contributor to total emissions, followed by AP and EP, while ODP contributed only marginally. The total environmental burden ranged from 1.35×10^{-12} Person Equivalent for the A1 method to 2.17×10^{-12} Person Equivalent for the H2 method. The higher impact of the H2 method is primarily attributed to its longer processing duration, which leads to increased energy consumption, indicating that processing complexity is a key driver of additional environmental impacts.

Replacing the conventional cultivation system (K1) with the non-pesticide system (K2) resulted in substantial emission reductions across all processing methods (Table 5). Reductions ranged from 65–69% for GWP, 70–72% for AP, 73–78% for EP, and 92–93% for ODP. These results demonstrate that adopting pesticide-free cultivation practices represents an effective mitigation strategy for reducing the environmental footprint of Robusta coffee production in Pagar Alam. Overall, the results indicate that cultivation practices constitute the main hotspot in the production system, while processing methods mainly influence the magnitude of additional emissions. The combination of non-pesticide cultivation (K2) and natural processing (A1) represents the most environmentally favorable production pathway in the studied system.

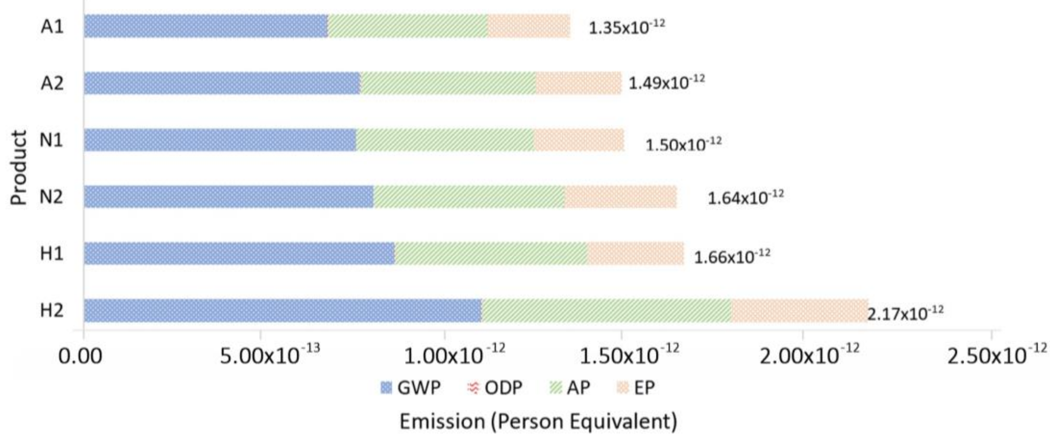

Figure 6. Total emissions and relative contributions of four environmental impact categories resulting from six coffee cherry processing methods in Pagar Alam. The figure presents the contributions of Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), and Eutrophication Potential (EP) associated with six coffee processing methods (A1–H2). Emissions are expressed in person equivalent units and reported per functional unit of 100 kg green coffee beans.

Table 5. Potential reduction in environmental impacts due to the transition from K1 (conventional) to K2 (non-pesticide) cultivation systems across six coffee processing methods. The table presents a comparison of environmental impact values (GWP, ODP, AP, and EP) between K1 and K2 systems for six coffee processing methods (A1, A2, N1, N2, H1, and H2), based on a functional unit of 100 kg of green coffee beans. The values include the calculated impact changes and percentage reductions associated with the transition from K1 to K2. This comparison highlights the differences in environmental performance between the two cultivation systems across processing methods.

Product	Improvement Scenario	Impact Categories / Emission Values			
		GWP	ODP	AP	EP
A1	K1	2.17×10^{-12}	1.57×10^{-14}	1.61×10^{-12}	1.05×10^{-12}
	K2	6.75×10^{-13}	1.15×10^{-15}	4.44×10^{-13}	2.27×10^{-13}
	Impact Change	1.50×10^{-12}	1.46×10^{-14}	1.16×10^{-12}	8.19×10^{-13}
	Percentage	69%	93%	72%	78%
A2	K1	2.33×10^{-12}	1.64×10^{-14}	1.70×10^{-12}	1.09×10^{-12}
	K2	7.66×10^{-13}	1.20×10^{-15}	4.86×10^{-13}	2.39×10^{-13}
	Impact Change	1.56×10^{-12}	1.52×10^{-14}	1.21×10^{-12}	8.55×10^{-13}
	Percentage	67%	93%	71%	78%
N1	K1	2.33×10^{-12}	1.66×10^{-14}	1.72×10^{-12}	1.11×10^{-12}
	K2	7.53×10^{-13}	1.24×10^{-15}	4.93×10^{-13}	2.49×10^{-13}
	Impact Change	1.58×10^{-12}	1.53×10^{-14}	1.22×10^{-12}	8.61×10^{-13}
	Percentage	68%	92%	71%	78%
N2	K1	2.38×10^{-12}	1.66×10^{-14}	1.75×10^{-12}	1.17×10^{-12}
	K2	8.02×10^{-13}	1.28×10^{-15}	5.27×10^{-13}	3.13×10^{-13}
	Impact Change	1.57×10^{-12}	1.53×10^{-14}	1.22×10^{-12}	8.61×10^{-13}
	Percentage	66%	92%	70%	73%
H1	K1	2.44×10^{-12}	1.66×10^{-14}	1.76×10^{-12}	1.13×10^{-12}
	K2	8.60×10^{-13}	1.25×10^{-15}	5.34×10^{-13}	2.68×10^{-13}
	Impact Change	1.58×10^{-12}	1.54×10^{-14}	1.23×10^{-12}	8.65×10^{-13}
	Percentage	65%	92%	70%	76%
H2	K1	3.14×10^{-12}	2.15×10^{-14}	2.27×10^{-12}	1.49×10^{-12}
	K2	1.10×10^{-12}	1.62×10^{-15}	6.91×10^{-13}	3.79×10^{-13}
	Impact Change	2.04×10^{-12}	1.98×10^{-14}	1.58×10^{-12}	1.12×10^{-12}
	Percentage	65%	92%	70%	75%

*A1 = natural origin; A2 = broken skin origin; N1 = natural aerobic fermentation; N2 = natural anaerobic fermentation; H1 = honey aerobic fermentation; H2 = honey anaerobic fermentation. GWP, ODP, AP, and EP are expressed per functional unit of 100 kg green coffee beans. "Impact change" represents the absolute difference between K1 and K2, while "Reduction (%)" indicates the relative decrease in impacts when switching to the K2 system.

Discussion

The analysis results indicate that the pesticide-free cultivation system (K2) provides clear environmental advantages over the conventional system (K1). The substantially higher emissions observed in K1, particularly for Global Warming Potential (GWP) and Acidification Potential (AP), are primarily attributable to the intensive use of chemical fertilizers and synthetic pesticides. Geographical conditions and agricultural practices also play an important role in shaping emission profiles [22]. These findings are consistent with previous studies showing that conventional coffee cultivation generates higher emissions than moderate conventional and organic systems [23]. In general, land use change, fertilizer application, and wet coffee processing have been identified as the main contributors to emissions in coffee production systems [24].

Comparative evidence from other producing regions supports these results. A study in India reported GWP emissions of 124.00 kg CO_2-eq per 100 kg of green beans under conventional cultivation, whereas organic systems produced emissions close to those observed for K2 (27.00 kg CO_2-eq) [15]. Similar trends were reported by Rahmah et al. [15], showing decreasing GWP, AP, and EP values with reduced reliance on chemical inputs. These comparisons confirm that both the type and intensity of agricultural inputs fundamentally determine the environmental performance of coffee cultivation systems.

In the cultivation subsystem, fertilizer application emerged as the dominant driver of environmental impacts [12]. Synthetic nitrogen fertilizers promote emissions of N_2O and Nox [25], thereby increasing GWP and AP [26], while phosphorus-based fertilizers are the main contributors to eutrophication [27]. The use of bromineand chlorine-based pesticides further increases Ozone Depletion Potential (ODP) [28]. These mechanisms explain the consistently higher impacts observed for K1 and indicate that improved nutrient management represents the most effective mitigation option at the farm level [12].

The processing subsystem showed marked differences among the six production methods. Using inputs from the K2 scenario, the honey anaerobic method (H2) generated the highest emissions across all impact categories, whereas the natural origin method (A1) produced the lowest. This pattern indicates that longer and more complex fermentation processes require higher energy inputs and therefore generate greater emissions, consistent with previous findings that natural processing results in lower impacts than anaerobic or lactic fermentation methods [22].

The absolute emission levels obtained in this study are lower than those reported by Irawan et al. [22], particularly for the natural processing method, which was reported at 30.2 kg CO_2-eq per 100 kg of green beans, whereas in this study the A1 method produced only 5.23 kg CO_2-eq per 100 kg of green beans. Another study also reported emissions of 9.3 kg CO_2-eq for specialty processing and 9.1 kg CO_2-eq for the honey method [7]. This difference is likely attributable to shorter drying durations, lower energy requirements, and differences in system configuration and inventory data sources. Irawan et al. [22] reported a sun-drying period of 9–12 days for the Natural process, which may have increased energy use and associated emissions

Overall, the cultivation stage was identified as the main hotspot across all production pathways. This finding reinforces previous studies indicating that agricultural inputs play a dominant role in determining greenhouse gas emissions [29], acidification, eutrophication [8], and ecotoxicity in coffee production systems [24]. Accordingly, mitigation strategies focusing on improved cultivation practices—particularly through the reduction of synthetic inputs and more efficient fertilizer management—represent the most effective approach to lowering the environmental footprint of coffee production [12].

High GWP contributions are partly influenced by increasing atmospheric CO_2 concentrations, which may affect the sustainability of agroforestry systems and the coffee agroindustry [30]. At the processing stage, environmental impacts are mainly associated with greenhouse gas emissions, acidification, and soil and water pollution resulting from fossil fuel consumption and the disposal of solid and liquid wastes [11]. Variations in production methods indicate that the H2 method generates the highest emissions due to longer processing times and higher energy consumption, which directly increase emission levels [31], whereas the natural method produces lower impacts than lactic or anaerobic fermentation methods [22].

The improvement scenario analysis shows that replacing the K1 system with K2 results in substantial emission reductions across all processing methods. This outcome is consistent with previous studies demonstrating that variations in cultivation systems strongly influence environmental performance at the primary production stage [32], and that intensive farming practices using synthetic fertilizers and pesticides increase environmental degradation and carbon footprints [33]. The adoption of pesticide-free cultivation systems is recommended as a feasible mitigation strategy for Robusta coffee production in Pagar Alam.

This study has several limitations. First, the analysis was based on single-season data collected between June and December 2024 and may not capture inter-annual variability. Second, the sample size was limited to four MSMEs and 63 farmers, which may restrict the generalizability of the results. Third, the system boundary followed a cradle-to-gate approach and did not include consumption, disposal, land use change, or water scarcity impacts. Future studies should expand the temporal scope, increase sample size, and incorporate additional impact categories and life cycle stages to provide a more comprehensive sustainability assessment.

Conclusions

This study presents a cradle-to-gate Life Cycle Assessment of Pagar Alam Robusta green coffee bean production by systematically comparing two cultivation systems and six post-harvest processing methods using primary field data. The results consistently show that the non-pesticide cultivation system (K2) performs substantially better than the conventional system (K1), generating approximately three to seven times lower environmental impacts across all assessed categories. Among the processing methods, Natural Origin (A1) exhibited the lowest environmental burden, whereas Honey Anaerobic (H2) resulted in the highest impacts due to increased processing complexity and energy demand. The cultivation practices were identified as the dominant environmental hotspot, while processing methods mainly influenced the magnitude of additional emissions. The combination of non-pesticide cultivation (K2) and natural processing (A1) emerged as the most environmentally favorable production pathway in the studied system.

From a practical and policy perspective, these findings highlight clear adoption pathways for improving the sustainability of Robusta coffee production in Pagar Alam. At the farm level, emission reductions can be effectively achieved through improved nutrient management and the gradual reduction or elimination of synthetic fertilizers and pesticides, supported by technical assistance, farmer training, and incentive schemes. For micro, small, and medium enterprises (MSMEs), the adoption of Natural Origin processing represents a low-cost and low-emission option that can be implemented without major technological investment while maintaining product quality. Incorporating life cycle–based environmental performance indicators into Pagar Alam’s Geographical Indication (GI) framework could strengthen environmental credibility, enhance product differentiation, and improve access to sustainability-oriented markets.

Several limitations should be acknowledged. This study was based on a cradle-to-gate system boundary and single-season data, which may not capture long-term variability. The analysis focused on mandatory environmental impact categories, while economic feasibility and social aspects—such as farmer income, labor requirements, and market acceptance—were not quantitatively assessed. Future research should therefore expand the system boundary to cradle-to-grave, incorporate uncertainty and sensitivity analyses, and integrate Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) to provide a more comprehensive sustainability evaluation of coffee production systems.

Author Contributions

NS: Conceptualization, Methodology, Software, Investigation, Data Curation, Formal Analysis, Writing - Original Draft, Writing - Review & Editing; **MR**: Conceptualization, Methodology, Writing - Original Draft, Supervision; **MY**: Conceptualization, Writing - Original Draft, Writing - Review & Editing, Supervision.

AI Writing Statement

During the preparation of this work, the authors used several tools, including Grammarly for checking English grammar and spelling, Perplexity for identifying relevant scientific literature and summarizing key points, and ChatGPT for improving language clarity and readability of the manuscript. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Conflicts of Interest

There are no conflicts to declare.

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References

1. La Scalia, G.; Saeli, M.; Miglietta, P.P.; Micale, R. Coffee Biowaste Valorization within Circular Economy: An Evaluation Method of Spent Coffee Grounds Potentials for Mortar Production. *Int. J. Life Cycle Assess.* **2021**, *26*, 1805–1815, doi:10.1007/s11367-021-01968-0.
2. FAO (Food and Agriculture Organization). Markets and Trade, Coffee. Available online: https://www.fao.org/markets-and-trade/commodities-overview/beverages/coffee/en (accessed on 20 December 2023).
3. ICO (International Coffee Organization). *Coffee Report and Outlook: December 2023*; ICO: London, UK, 2023;
4. Directorate General of Estates. *Statistics of Estate Crops Volume I 2022-2024*; Directorate General of Estates, Ministry of Agriculture: Jakarta, ID, 2023;

5. Fardinatri, I.D.; Condro, A.A.; Hayati, D.; Anhar, A. Environmental Dynamics in The Sumatran Coffee Landscapes: Opportunities and Challenges Through Spatial Perspectives. *JPSL (J. Nat. Res. Env).* **2024**, *14*, 438–450, doi:10.29244/jpsl.14.3.438.
6. BPS (Badan Pusat Statistik). *Indonesia Coffee Statistics 2023 Volume 8*; BPS: Jakarta, ID, 2024;.
7. Hasan, Y.; Roy, P.; Abbassi, B. Comparative Life Cycle Assessment (LCA) in the Agri-Food Industry, Focusing on Organic and Conventional Coffee. *Sustainability* **2024**, *16*, 1–17, doi:10.3390/su162410819.
8. Gosalvitr, P.; Cuéllar-Franca, R.M.; Smith, R.; Azapagic, A. An Environmental and Economic Sustainability Assessment of Coffee Production in the UK. *Chem. Eng. J.* **2023**, *465*, 1–18.
9. DJKI (Direktorat Jenderal Kekayaan Intelektual). Indikasi Geografis. Available online: https://dgip.go.id/menu-utama/indikasi-geografis/listing (accessed on 20 December 2022).
10. Adiwinata, F.; Suprihatin, S.; Rahayuningsih, M. Analisis Daur Hidup (Life Cycle Assessment) Pengolahan Kopi Bubuk Robusta Secara Basah Di Industri Kecil Menengah (IKM) Beloe Klasik Lampung. *Agrointek J. Teknol. Ind. Pertan.* **2021**, *15*, 1175–1182, doi:10.21107/agrointek.v15i4.11338.
11. Harsono, S.S.; Wibowo, R.K.K.; Supriyanto, E. Energy Balance And Green House Gas Emisson On Smallholder Java Coffee Production At Slopes Ijen Raung Plateau Of Indonesia. *J. Ecol. Eng.* **2021**, *22*, 271–283, doi:10.12911/22998993/138997.
12. Usva, K.; Sinkko, T.; Silvenius, F.; Riipi, I.; Heusala, H. Carbon and Water Footprint of Coffee Consumed in Finland — Life Cycle Assessment. *Int. J. Life Cycle Assess.* **2020**, *25*, 1976–1990, doi:10.1007/s11367-020-01799-5.
13. Diyarma, I.; Bantacut, T.; Suprihatin. Assessment of Environmental Impact of the Gayo Arabica Coffee Production by Wet Process Using Life Cycle Assessment. *Acta Univ. Cibiniensis. Ser. E Food Technol.* **2019**, *23*, 27–34, doi:10.2478/aucft-2019-0004.
14. Ribeiro, P.; Fonseca, F.; Neiva, C.; Bardi, T.; Lourenço, J.M. An Integrated Approach towards Transforming an Industrial Park into an Eco-Industrial Park: The Case of Salaise-Sablons. *J. Environ. Plan. Manag.* **2018**, *61*, 195–213, doi:10.1080/09640568.2017.1300576.
15. Rahmah, D.M.; Putra, A.S.; Ishizaki, R.; Noguchi, R.; Ahamed, T. A Life Cycle Assessment of Organic and Chemical Fertilizers for Coffee Production to Evaluate Sustainability toward the Energy–Environment–Economic Nexus in Indonesia. *Sustainability* **2022**, *14*, 1–28, doi:10.3390/su14073912.
16. Widiyanto, A. *Kontribusi Metode Life Cycle Assessment Biomassa Untuk Agroindustri Berkelanjutan*; Badan Riset dan Inovasi Nasional: Jakarta, ID, 2022; ISBN 9786238052066.
17. Chaerul, M.; Allia, V. Tinjauan Kritis Studi Life Cycle Assessment (LCA) Di Indonesia. *J. Serambi Eng.* **2020**, *5*, 816–823, doi:10.32672/jse.v5i1.1653.
18. Hamdan, H.; Fauzi, A.M.; Rusli, M.S.; Rustiadi, E. A Study of the Smallholder Coffee Agroindustry Sustainability Condition Using the Life Cycle Assessment Approach in Bengkulu Province, Indonesia. *J. Ecol. Eng.* **2019**, *20*, 153–160, doi:10.12911/22998993/108636.
19. Directorate General for Environmental Pollution and Degradation Control. *Pedoman Penyusunan Laporan Penilaian Daur Hidup (LCA)*; Directorate General for Environmental Pollution and Degradation Control, Ministry of Environment and Forestry Republic of Indonesia: Jakarta, ID, 2021;
20. PRé Sustainability. *Simapro Database Manual: Methods Library*; PRé Sustainability: Amersfoort, The Netherlands, 2022;
21. International Organization for Standardization. *ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines*; International Organization for Standardization: Geneva, Switzerland, 2006;
22. Irawan, A.; Rabemanolontsoa, H.; McLellan, B.C. Comprehensive Environmental Impact Analysis of Dry Processing Methods for Specialty Coffee Beans in Bondowoso, Indonesia Using Life Cycle Assessment. *Biomass* **2024**, *4*, 843–864, doi:10.3390/biomass4030047.
23. Trinh, L.T.K.; Hu, A.H.; Lan, Y.C.; Chen, Z.H. Comparative Life Cycle Assessment for Conventional and Organic Coffee Cultivation in Vietnam. *Int. J. Environ. Sci. Technol.* **2020**, *17*, 1307–1324, doi:10.1007/s13762-019-02539-5.

24. Chéron-Bessou, C.; Acosta-Alba, I.; Boissy, J.; Payen, S.; Rigal, C.; Setiawan, A.A.R.; Sevenster, M.; Tran, T.; Azapagic, A. Unravelling Life Cycle Impacts of Coffee: Why Do Results Differ so Much among Studies? *Sustain. Prod. Consum.* **2024**, *47*, 251–266, doi:10.1016/j.spc.2024.04.005.
25. Pratama, R.; Parinduri, L. Penaggulangan Pemanasan Global. *Bul. Utama Tek.* **2019**, *15*, 1410–4520.
26. IPCC (Intergovernmental Panel on Climate Change). *Climate Change 2021: The Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2021;
27. Widowati, L.R.; Hartatik, W.; Setyorini, D.; Trisnawati, Y. *Pupuk Organik Dibuatnya Mudah, Hasil Tanam Melimpah*; Pusat Perpustakaan dan Penyebaran Teknologi Pertanian: Bogor, ID, 2022; ISBN 9789795822035.
28. Faisal, A.; Martini, M.; Hestiningsih, R.; Wuryanto, M.A. Aplikasi Fumigan Gas Fosfin (Hidrogen Fosfida (Ph3)) Untuk Pengendalian Tikus (Rodent). *Vektora J. Vektor dan Reserv. Penyakit* **2019**, *11*, 95–102, doi:10.22435/vk.v11i2.1911.
29. Sakamoto, H.; Bruschi, L.T.; Kulay, L.; Yamakami, A. Using the Life Cycle Approach for Multiobjective Optimization in the Context of the Green Supply Chain: A Case Study of Brazilian Coffee. *Sustainability* **2023**, *15*, 1–18, doi:10.3390/su151813987.
30. Pramulya, R.; Bantacut, T.; Noor, E.; Yani, M.; Zulfajrin, M.; Setiawan, Y.; Pulunggono, H.B.; Sudrajat, S.; Anne, O.; Anwar, S.; et al. Carbon Footprint Calculation of Net CO2 in Agroforestry and Agroindustry of Gayo Arabica Coffee, Indonesia. *Jordan J. Biol. Sci.* **2023**, *16*, 335–343, doi:10.54319/jjbs/160218.
31. Gamatara, M.P.J.; Kusumawardani, D. Pengaruh Deforestasi Terhadap Emisi CO2 Pada Negara Beriklim Tropis Di Benua Asia. *J. Ilm. Manajemen, Ekon. Akunt.* **2024**, *8*, 1239–1256, doi:10.31955/mea.v8i2.4129.
32. Acosta-Alba, I.; Boissy, J.; Chia, E.; Andrieu, N. Integrating Diversity of Smallholder Coffee Cropping Systems in Environmental Analysis. *Int. J. Life Cycle Assess.* **2020**, *25*, 252–266, doi:10.1007/s11367-019-01689-5.
33. United Nations Environment Programme. *Synthesis Report on the Environmental and Health Impacts of Pesticides and Fertilizers and Ways to Minimize Them*; United Nations Environment Programme: Geneva, Switzerland, 2022; ISBN 9789280739299.

