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RESEARCH PAPER

Analysis of potential environmental impacts in the coffee supply chain using the Life Cycle Impact Assessment

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Abstract. Agroindustry refers to industry that process agricultural raw materials into value-added products. Sanrego coffee is a blend of authentic Sanrego coffee and sugar, without the use of chemicals. SMI Sanrego Caffee produces a variety of products, including coffee and chocolate. However, the coffee processing activities at SMI Sanrego Caffee can have potential environmental impacts due to emissions, liquids waste, and solid waste generation. to assess and mitigate these environmental impacts, the Life Cycle Assessment (LCA) method is amployed. LCA evaluates the environmental effects at various stages of a product, process, or service lifecycle. Based on the results from the analysis, using the Simapro software, the potential environmental impacts were compared across several impact categories, abiotic depletion (3.77 kg Sb-eq), global warming (518 kg CO_2-eq), acidification (4.41 kg SO_2-eq). The interpretation stage of the analysis identified several areas improvement: first, optimizing fuel usage; secondly, reducing reliance on aluminum foil; third, minimizing the use of sacks; and lastly, reducing electricity consumption.

Keywords: Life Cycle Assessment; coffee; CML-Baseline; Simapro; Supply chain.

1. Introduction

In the current era of globalization, the rapid expansion of industries has led to widespread environmental pollution, drawing significant attention from various sectors and prompting calls for global cooperation to address environmental issues and protect the planet. One of the largest industrial sectors in Indonesia is agro-industry, which involves utilizing agricultural raw materials to produce value-added products (Chairany et al., 2022). The agro-industrial sector in Indonesia holds great potential because the country's abundant natural resources and favorable climate, particularly in industries such as coffee production (Gelyaman et al., 2020; Putri et al., 2021; Rahman, 2020).

Coffee (*Coffea Sp*) is one of the leading agro-industrial products, widely appreciated by consumers fot its distinctive aroma and taste – characteristics that are rarely found in other beverages. Coffee has become an integral part of daily life, both in Indonesia and globally. The continuous growth in coffee production over the years has cemented its significant role in the industrial sector, particularly within small and medium-sized enterprises (SMEs) (Diyarma et al., 2019).

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Indonesia is one of the world's largest coffee producers, with a total production of 762.38 tons in 2020, which increased to 786.19 tons in 2021 (BPS, 2021). Additionally, Indonesia is a major coffee exporter; in 2022, the country exported 434.19 tons of coffee, marking a 12.92% increase from the previous year (BPS, 2023). With its strong global reputation, Indonesia's coffee industry accounts for approximately 6% of the global coffee production and holds a substantial market share of around 11%.

However, the rapid growth of the coffee industry has also led to environmental concerns. Coffee processing plantations often dispose of waste into rivers, contributing to water pollutes, wildlife loss, and ecosystem disruption. Major environmental issues linked to coffee production include deforestation and soil erosion. As the coffee industry in Indonesia expands, the risk of environmental impacts grows, with supply chain activities – from plantation maintenance and harvesting to processing and packaging – lead to potential negative impacts related to material use, fuel consumption, and electricity usage (Diyarma et al., 2019).

Coffee is one of the flagship products of Sanrego's Small Medium Enterprise (SME). however, the coffee processing activities at SMI Sanrego Caffee have the potential to negatively impact on the environment. For instance, coffee processing plantations often discharge waste into rivers, including chemicals and byproducts from the processing of coffee beans. This practice contributes to water pollution, leading to the contamination of water systems, which not only affects water quality but also poses risks to aquatic life. Wildlife habitats may degrade, and ecosystems can become imbalanced due to pollution (Gosalvitr et al., 2023).

The environmental impact is further exacerbated by emissions from vehicles used during transportation, which contribute to global warming. Liquid waste generated during pulping and cleaning processes can cause toxicity in aquatic ecosystems. Additionally, the use of electricity, fertilizers, pesticides, and other materials in coffee production further increases its environmental footprint.

The environmental impact of coffee has been extensively studied. However, most of these studies have been conducted in developed nations that utilize different technologies (Barreto Peixoto et al., 2023; Gosalvitr et al., 2023; Lingnau et al., 2019) and methodologies compared to those employed in Indonesia. Furthermore, these studies often focus exclusively on the environmental effects of the production phase. It is imperative to acknowledge, however, that the ecological impacts extends beyond production (Gosalvitr et al., 2023; Lingnau et al., 2019) and pervades the entire coffee supply chain. This is particularly relevant in the unique context of Indonesia's coffee production, where supply chain activities present distinct environmental challenges.

This study aims to evaluate the potential environmental impacts across the coffee supply chain at SMI Sanrego Caffee and propose strategies to mitigate these impacts (Nur et al., 2023). One approach to identifying and analyzing environmental impacts is Life Cycle Assessment (LCA). LCA is a "cradle-to-grave" approach to assessing industrial systems. The "cradle-to-grave" approach begins with the extraction of raw materials and continues through the production process, ultimately ending when materials are returned to the earth. LCA allows for the estimation of cumulative environmental impacts across all stages of a product's life cycle, helping to identify which stages contribute the most significant environmental impacts (Cahyana et al., 2023). In the context of coffee production, LCA provides valuable insight into energy use, waste generation, and emissions throughout the production process. These results can be used to assess the environmental impacts of production and explore opportunities for developing more environmentally friendly products (Gelyaman et al., 2020; Goedkoop & Spriensma, 2021).

2. Literature review

Life Cycle Assessment (LCA) is a method used to assess the environmental impact of a specific stage in life cycle of product, process, or service. According to International Organization for Standardization (ISO), LCA is a comprehensive compilation and evaluation of material and energy flows, along with potential environmental impacts, across the life cycle of a product (ISO, 1998). It is versatile approach that can be applied to various products, as it examines each stage of the life cycle – from the analysis of inputs to outputs – to assess the environmental implications of the production process (Awuah-Offei & Adekpedjou, 2011).

LCA method is applicable to wide range of products, as it involves a comprehensive analysis is carried out at every stage of life cycle. It begins by examining the input process and progress to evaluating output to assess the environmental impacts of the production process. Additionally, LCA serves as a valuable tool for determining a product's sustainability (Christie et al., 2011). This method helps identify potential environmental impacts arising from production activities, including the use of fuel and raw materials. Furthermore, LCA can provide insights into opportunities for impact reduction by offering recommendations for environmentally management practices. The methodological framework for conducting an LCA consists of four key components or phases, as defined by ISO-14040 (ISO 14040, 2006), is depicted in Figure 1.

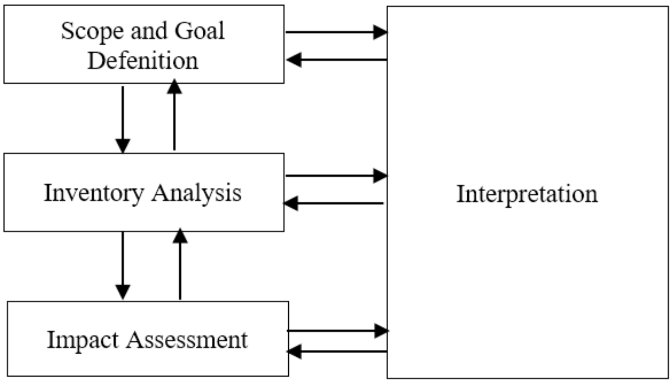

Figure 1. Framework LCA based on ISO 14040

Irawan (2024) used LCA to evaluate the contribution of environmental impacts associated with the use of technology in the coffee production process. Similarly, Astuti et al (2021) also used LCA in combination with the and Analytical Network Process to analyze the environmental impacts of the coffee industry and propose recommendations for improvement. While these studies provided valuable insights and offered tailored recommendations to address the environmental impacts of the coffee production process, they focused exclusively on the production stage. In contrast, this study expands the scope by examining environmental impacts from a supply chain perspective, offering a more comprehensive assessment.

Kelvin (2021) highlighted that SimaPro is a robust software tool designed for conducting environmental impact assessments using the LCA approach. Its key advantage lies in its versatility, as it supports various applications, including sustainability reporting, carbon and water footprint analysis, environmentally conscious friendly product design, manufacturing process, and the identification of key performance indicators (Kelvin, 2021).

3. Research methods

3.1. Data Types and Sources

This research was conducted at SMI Sanrego Coffee in Bintare Village, Ujung Bulu District, Bulukumba Regency, South Sulawesi, over a one-month period. This study used two types of data: primary and secondary. Primary data were collected through direct observations of SME operations, company records, and interviews with the SME owners. Secondary data were obtained from previous research relevant to the study’s topic. Three methods were employed to gather data: literature review, field observation, and interviews. Literature review was conducted to determine the stages of LCA and involved consulting relevant journals, reference books, and credible sources. Field observations were carried out to collect real-time data at the Sanrego

Coffee SME, focusing on identifying inputs and outputs during the production of the two products. Interviews were conducted to gather detailed information required for the study.

The data collected encompassed various aspects of the 5M framework (Man, Money, Method, Machine, and Material) in every stage of production. Specific data points included the types and quantities of fertilizers and pesticides used, their application schedules, the number of harvests per year, tools and materials used, fuel consumption, coffee production volumes, and transportation methods. A summary of collected data is presented in Figure 2.

The data collected spans all stages of the supply chain, including maintenance, harvesting, coffee skin separation, washing, transportation, roasting, grinding, mixing, and packaging. Below is a detailed description of the data collected at each stage.

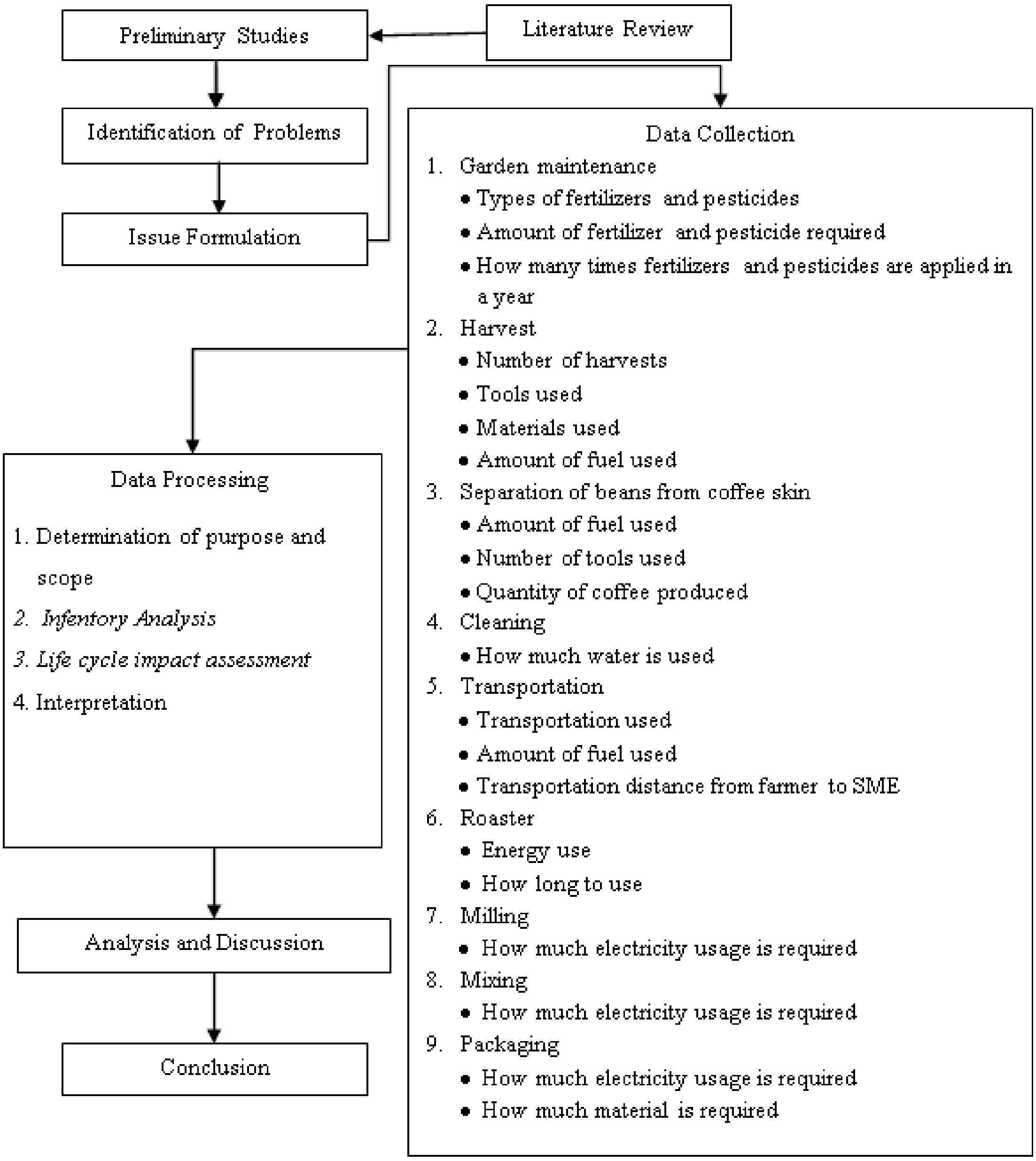

Figure 2. Flowchart research

a. *Maintenance stage*. The maintenance process for coffee plants is essential to achieve optimal quality and yield. This involves plant and land care activities to enhance coffee production quality and protect plantations from pests. Maintenance activities include fertilization using two types of fertilizers – Kaptan fertilizer and organic fertilizer, which includes the application of herbicide pesticides, specifically Gramoxone, mixed with water. Moreover, clearing using a gasoline-fueled clearing machine. Relevant data are shown in Table 1.

Table 1. Inventory Input of Maintenance Stage

Input	Amount	Unit
Kaptan Fertilizers	400	kg
Organic Fertilizers	1,500	kg
Herbisida gramoxone	12	Liter
Tap Water	2,400	Liter
Fuel	10	Liter

b. *Harvesting stage*. Harvesting involves manually picking coffee cherries, focusing on red and yellowish-green cherries. The cherries are collected in sacks transported using motorbike fueled by Pertalite. Table 2 reveals the input data for this stage.

Table 2. Inventory input of harvesting stage

Input	Amount	Unit
Coffee bean	3,000	kg
Fuel	7.5	liter
Motorcycle	3	Unit
Sacks	60	Buah

c. *Coffee skin separations stage*. The separation the coffee skins from coffee beans is carried out using three pulping machines powered by gasoline. Water is used to soften the skin tissue, facilitating the separation process. This stage generates approximately 50% coffee skin waste, which can be repurposed as organic fertilizer. The data used for this stage is presented in Table 3.

Table 3. Inventory input of coffee skin separation stage

Input	Amount	Unit
Coffee bean	3,000	kg
Fuel	27	Liter
Water	6,480	Liter

d. *Washing stage*. This stage removes residual coffee skin and slime from the beans processed during the previous stage. The washing process is performed manually using water, without the aid of machines. Table 4 presents the relevant data.

Table 4. Inventory input of washing stage

Input	Amount	Unit
Coffee bean	1,200	kg
Water	2,600	Liter

e. *Distribution stage*. In the transportation stage, processed raw materials are transported from the farm production site to Sanrego Coffee SME facility. This is done using a pick-up truck fueled by Pertalite. Table 5 provides the input data for this stage.

Table 5. Inventory input of distribution stage

Input	Amount	Unit
Coffee Bean	1,200	kg
Fuel	72	Liter

f. *Roasting stage*. The roasting stage involves transforming raw green coffee beans into roasted beans to develop the coffee's characteristic flavor. This process uses a roasting machine powered by electrical energy and LPG as a heat source. Input data for this stage is detailed in Table 6.

Table 6. Inventory input of roasting stage

Input	Amount	Unit
Coffee Bean	1,200	kg
Gas	7	Unit
Electricity	57,600	Watt

g. *Grinding stage*. The grinding stage crushes roasted coffee beans into fine powder, making the coffee suitable for dissolution. The grinding machine operates using electrical energy. Input data for this stage is provided in Table 7.

Table 7. Inventory input of grinding stage

Input	Amount	Unit
Coffee Bean	1,200	kg
Electricity	105,600	Watt

h. *Mixing stage*. This stage *involves* mixing coffee powder with sugar using a mixer. The energy input is based on the electricity consumed by the by the mixer. Relevant data are shown in Table 8.

Table 8. Inventory input of mixing stage

Input	Amount	Unit
Coffee Powder	1,200	Kg
Electricity	22,000	Watt

i. *Packaging stage*. The finale stage of the production process is packaging. This involves using a packaging machine powered by electricity. Materials required include aluminum foil and duplex paper. Input data for this stage are outlined in Table 9.

Table 9. Inventory input of packaging stage

Input	Amount	Unit
Coffee	1,200	kg
Electricity	300,000	Watt
Aluminium foil	0.2 x 600,000	gram
Duplex paper	0.9 x 120,000	gram

3.2. Stages of research and data analysis

According to International Organization for Standardization, LCA is the compilation and evaluation of material and energy flows, along with the assessment of potential environmental impacts, based on the life cycle of a product. LCA is widely recognized method used to identify the environmental impacts associated with a product's production process. The data processing method for LCA follows the ISO 14040 standard.

This study focusses on determining the scope of each stage within the coffee supply chain. The scope of coffee production is divided into three categories: Scope 1 (agriculture), Scope 2 (transportation), and Scope 3 (SMEs). The LCA methodology is implemented in four key stages, as defined by ISO 14040 (2006):

a. *Definition of purpose and scope*. Clearly defining the purpose and scope is essential for applying LCA methodology effectively. This step includes establishing system boundaries and identifying specific objectives of the research.
b. *Inventory analysis*. Inventory analysis involves the detailed examination of the production process using tools such as Simapro Software. This step identifies and quantities inputs (e.g., raw and supporting materials) and outputs (e.g. energy use and waste) at it stage of the production cycle. The comprehensive data collected allows for a thorough understanding of resources use and environmental emissions.
c. *Impact assessment*. The impact assessment phase evaluates the environmental impacts associated with the production process. This step measures the extent of the impact and identifies areas with the highest environmental burden, providing valuable insights for targeted improvements.
d. *Data interpretation*. The final stage involves interpreting the results of the LCA. This includes analyzing the most significant environmental impacts, formulating strategies to optimize the production process, and proposing improvements. The ultimate goal is to develop more environmentally friendly products and reduce the overall environmental footprint of the production cycle.

4. Result and discussion

4.1. Subpart 1

The life cycle inventory in this study is an essential component that encompasses three primary processes: the cultivation of coffee plantations, the transportation phase, and the production phase. This comprehensive approach enables a detailed evaluation of material inputs, energy consumption, and the outputs generated throughout the coffee production chain.

After identifying the inputs and outputs at each stage, the data will be analyzed using the Simapro Software, providing in-depth insights into the environmental impacts associated with coffee production. The processes and stages within the coffee supply chain are illustrated in Figure 3.

The third stage of LCA is the environmental impact analysis stage, which provides an overview of the environmental impact caused by the coffee supply chain at SMI Sanrego Coffee. This study used the CML-Baseline method, comprising two key stages: characterization and normalization. Characterization involves analyzing the results of the life cycle inventory (LCI) for each impact category. The impact assessment method used for this stage is the CML-Baseline method. The comparative results from the characterization of environmental impacts across the coffee production chain are presented in Table 10.

Normalization is a critical stage in impact assessment, where the overall impacts are compared and simplified using standardized measures. The process ensures consistent comparative values for each impact category, enabling easier and more accurate data interpretation. Normalization ensures that all impact categories are appropriately weighted, allowing for a comprehensive understanding of the overall impact. The comparative results of normalization of environmental impacts for the coffee supply chain are illustrated in Figure 4.

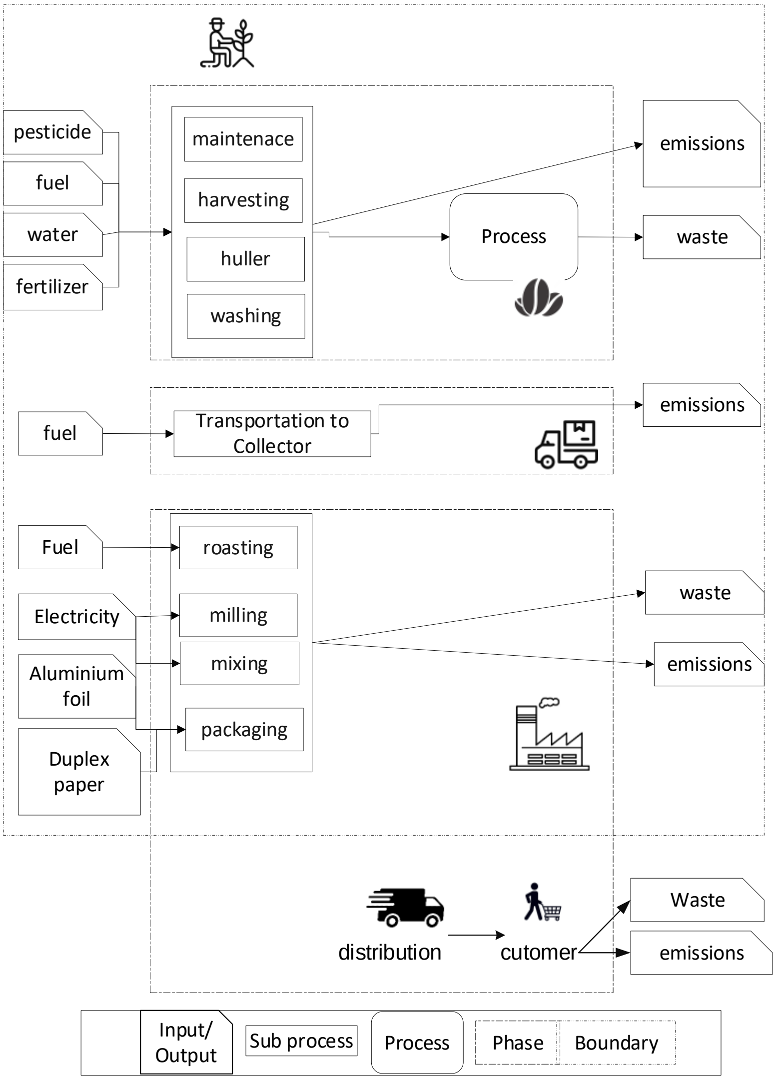

Figure 3. Flowchart of coffee making process at SMI Sanrego Coffee

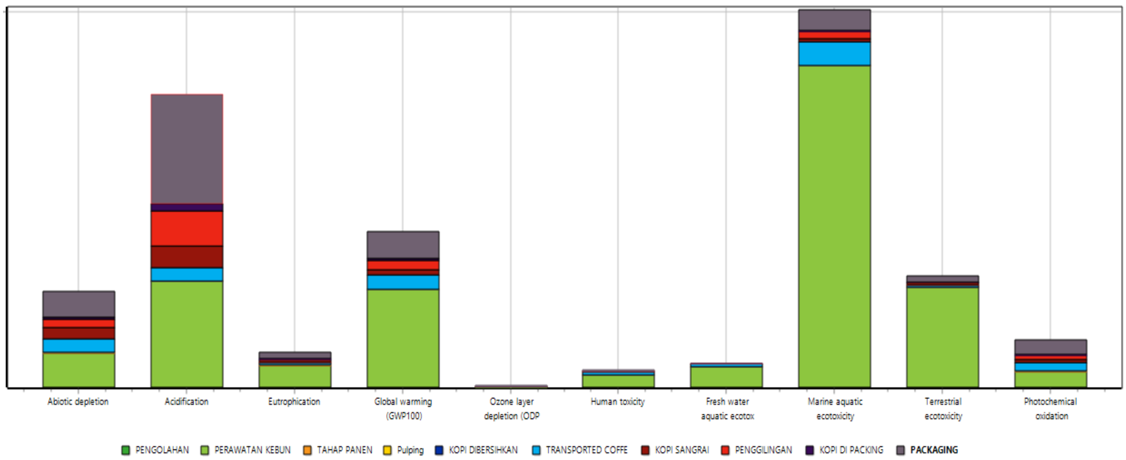

Figure 4. Normalization comparison results on environmental impact

Table 10. Comparative results of environmental impact characterization

Impact Category	Maintenance	Harvest	Pulping	Washing	Transport-ation	Roasting	Grinding	Mixing	Packaging
Abiotic Depletion	2.02	0.073	0.00666	0.00244	0.79	0.71	0.506	0.105	1.58
Acidification	2,49	0.0146	0.00362	0.00144	0.296	0.511	0.827	0.172	2.58
Eutrophication	0.391	0.00159	0.000331	0.000131	0.0411	0.0278	0.0354	0.00737	0.111
Global Warming	866	5.51	1.02	0.404	124	48.3	78.2	16.3	245
Ozone Layer Depletion	2.91×10^{-5}	2.13×10^{-10}	7.57×10^{-8}	3.02×10^{-8}	1.75×10^{-5}	9.7×10^{-7}	1.78×10^{-6}	3.71×10^{-7}	5.58×10^{-6}
Human Toxicity	80.4	0.0531	0.344	0.137	24	1.52	2.63	0.549	8.27
Fresh Water Aquatic Ecotoxicity	5.38	0.00179	0.00997	0.00345	0.762	0.0227	0.0415	0.00865	0.131
Marine Aquatic Ecotoxicity	3.6×10^{4}	4.95	43.7	15.5	2.63×10^{3}	400	733	153	2.29×10^{3}
Terrestrial Ecotoxicity	3.22	0.000113	0.00972	0.00389	0.0608	0.0328	0.0601	0.0125	0.188
Photochemical Oxidation	0.0983	0.00531	0.000425	0.000169	0.0555	0.0174	0.0297	0.00619	0.0928

Table 11. Impact category comparison results

Impact categories	Entire	Unit
Ecotoxicity of marine waters	42.300	kg 1.4-DB eq
Acidification	6.91	kg SO_2-eq
Global warming	1,380	kg CO_2-eq

Based on the graph, the three most significant environmental impacts categories contributing to pollution are acidification, global warming, and marine water toxicity. The contribution of these three categories is detailed in Table 11.

4.2. Subpart 2

An analysis was conducted to identify the most prominent environmental impact categories in the coffee supply chain. Fishbone diagrams were used to identify the factors that significantly affect these impacts. The result revealed that herbicides have the greatest environmental impact on marine water ecotoxicity, while electricity consumption and vehicle emissions during the transportation stage also contribute substantially to the overall impact. Consequently, it is imperative to develop an alternative strategy to mitigate these issues effectively.

Figure 5 illustrated that herbicide use significantly impacts the ecotoxicity of marine waters, alongside electricity consumption and vehicle emissions during the transport stage. Marine aquatic ecotoxicity, as an LCA impact category, refers to pollution affecting seawater ecosystems. Based on data processing using SimaPro software, the primary contributors to marine Aquatic ecotoxicity are electricity usage, emissions generated by transportation, and herbicide applications.

To address this environmental issue, strategies has been proposed, including optimizing the use of electricity-powered equipment, consolidating transportation efforts, and replacing herbicides with more environmentally friendly alternatives. These strategies were identified through a literature review and discussions with verifiers. However, their implementation faces practical limitations. Stakeholders, farmers, and SMEs within the supply chain often face financial constraints. For instance, adopting alternative energy sources, such as renewable power generation or upgrading transportation vehicles would require significant capital investment, which may not be feasible for all participants.

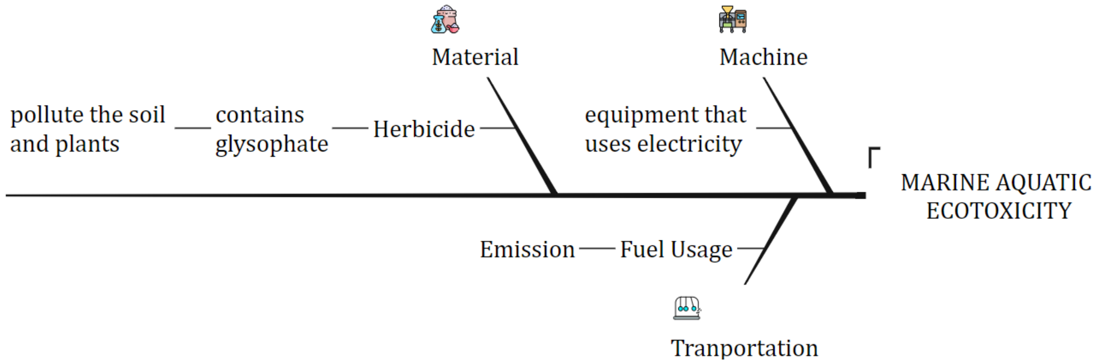

Figure 5. Fishbone diagram of marine waters ecotoxicity category

Figure 6 shows that the environmental impact of acidification is mainly attributed to the use of herbicides, organic fertilizers, electricity, LPG, and vehicle emissions during the transportation stage. Acidification as an LCA impact category, refers to the reduction in the pH levels in the environment – affecting soil, water, or the atmosphere – cause by an increase in acid concentration. this can result from sources such as exhaust emissions, excessive fertilizers use, or the burning of fossil fuels (Dewulf et al., 2014). The study supports the claim that the agriculture stage significantly impacts the acidification category, contributing 91% of the total impact. This finding strengthens the results of the current research.

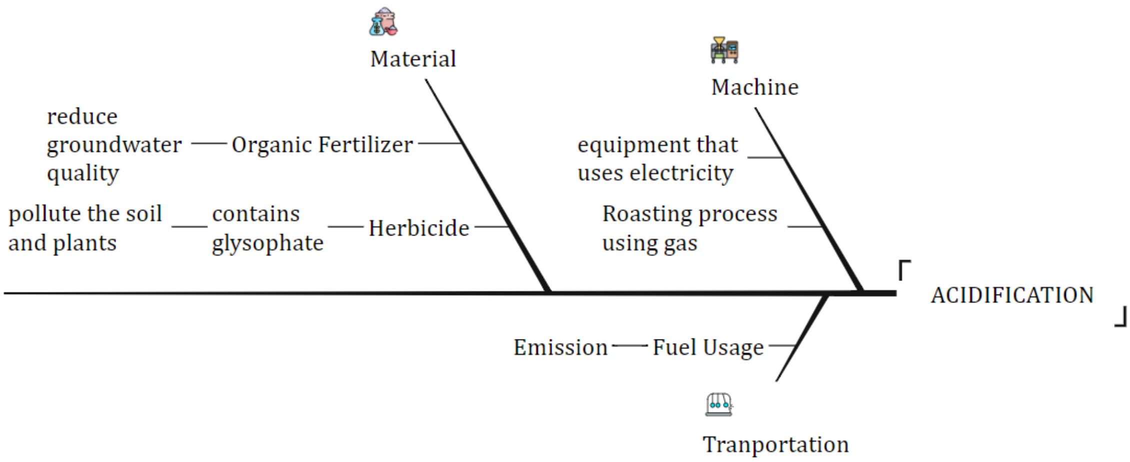

Figure 6. Acidification category acidification of fish bone diagram

To mitigate the environmental issues related to acidification, several strategies have been proposed. This includes optimizing electricity usage in tools, consolidating transportation to improve efficiency and recommending vehicle types upgrades, replacing herbicides with more environmentally friendly alternatives, controlling fertilizer application rates, managing organic fertilizer properly, implementing biochar as an alternative fertilizer, optimizing roasting capacity to reduce LPG consumption, promoting the use of natural gas as a substitute for LPG consumption. These strategies were identified through literature reviews and discussions with verifiers.

However, the implementation of these strategies faces several challenges. Stakeholders - primarily farmers and SMEs within the system - require substantial financial resources and technical knowledge to adopt these measures. For example, transitioning to alternative energy sources or environmentally friendly transportation solutions demand significant capital investment, which may not be feasible for all parties involved.

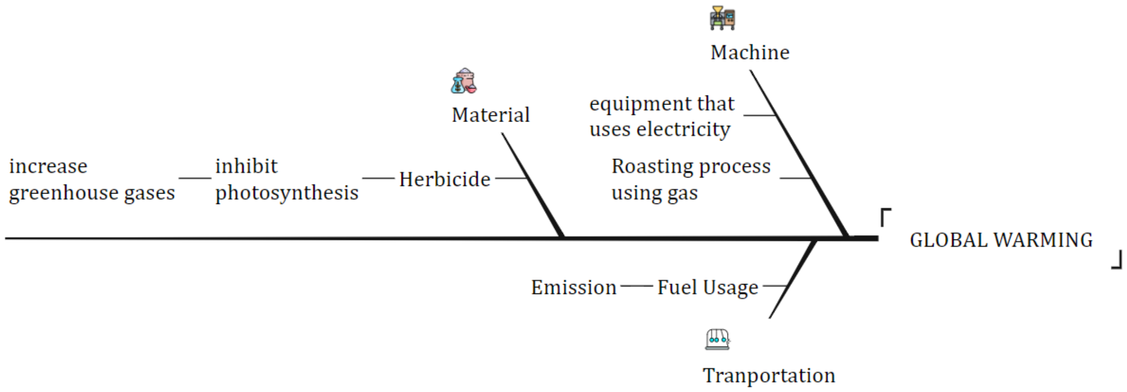

Figure 7. Fishbone diagram from the category of global warming

Figure 7 illustrates that the environmental impact of global warming is mainly attributed to the use of herbicides, organic fertilizers, electricity consumption, and vehicle emissions during the transportation stage. The application of herbicides can disrupt the fundamental process of photosynthesis in plants, hindering their ability to produce oxygen and absorb carbon dioxide. This disruption affects the delicate balance of atmospheric gases, potentially exacerbation global warming, with significant environmental consequences (Ziska et al., 2020).

The use of herbicides in agriculture and plantations has notable environmental impacts, including soil and water contamination, harm to non-target plant and animal species, and contributions to global warming through greenhouse gases emissions. To mitigate these impacts, it is essential to explore and adopt alternative methods and practices that effectively manage weeds and pests while minimizing environmental harm. Techniques such as integrated pest management, organic farming practices, crop rotation, and biological control methods offer sustainable and environmentally friendly approaches to agriculture.

Pesticides and fertilizers used in horticulture, including the coffee industry, are considered among the most significant threat to both human health and environmental stability. This concern arises from the adverse impacts of pesticide usage on both human well-being and ecological balance (Wainwright et al., 2013). Furthermore, inorganic fertilizers, which often contain nitrogen in forms such as ammonium nitrate, urea, or ammonium sulfate can contribute to global warming. When applied to soil, these fertilizers release nitrous oxide, a potent greenhouse gas and a major driver of climate change (Wu et al., 2021).

As an alternative, the use of organic fertilizers presents a promising solution to address these issues. Global warming, as an impact category characterized by an increase in the earth's average surface temperature, underscoring the urgency of adopting sustainable agricultural practices to mi mitigate this pressing environmental challenge.

Table 12, 13, and 14 presents findings from interviews with stakeholders, including plantation managers and SME owners, complemented by insights from a literature review conducted by the author. Stakeholders proposed alternative strategies focused on adopting environmentally friendly resources to promote sustainable practices and mitigate the environmental impacts of their operations.

The strategy to address the challenge of global warming adopts a multi-faceted and collaborative approach. It includes optimizing the use of electricity-dependent tools and appliances, streamlining transportation processes for greater efficiency, transitioning to environmentally friendly herbicides, regulating fertilizer application, adopting sustainable organic fertilizer management practices, and exploring the use of biochar as an alternative fertilizer.

Table 12. Strategies to address potential environmental impacts on marine aquatic ecotoxicity

Issue solved	Strategy selected	Supporting Literature	Validator	Agency/ Organization	Approval
Marine Aquatic Ecotoxicity	1. Electric: 1) Evaluation of energy use 2) Optimize equipment usage 3) Invest in renewable energy types 2. Transportation: 1) Use of environmentally friendly types of transportation 2) Consolidation of shipments 3) Optimize the use of transportation 3. Herbicides: Replace herbicides with more environmentally friendly types, such as organic herbicides	(ESDM, 2012) (Xia et al., 2023) (Chen et al., 2022; Soelistianto et al., 2024) (Gelyaman et al., 2020)	Edi Musah Amirullah	Coffee Plantation Manager SMI Owner	Confirm point 2. 2) and point 3 Confirm point 1. 1) and 2), 2. 2) and 3)

Table 13. Strategies to address potential environmental impacts on global warming

Issue solved	Strategy selected	Supporting Literature	Validator	Agency/ Organization	Approval
Global Warming	1. Electric: 1) Evaluation of energy use 2) Optimize equipment usage 3) Invest in renewable energy types	(ESDM, 2012) (Xia et al., 2023) (Chen et al., 2022; Soelistianto et al., 2024) (Wu et al., 2021) (Gelyaman et al., 2020) (Mesnage, 2022)	Edhi Musah Amirullah	Coffee Plantation Manager SMI Coffee Owner	Confirm points 3 and 4 Confirm point 1. 1) and 2)

Traditional practices, such as using natural materials like salt and olive oil as herbicides alternatives, predates the widespread adoption of synthetic herbicides. Despite their historical usage further research is required to refine the methods for processing and applying these natural materials. Optimizing application techniques, determining effective concentrations, and understanding interactions with various plant species are crucial steps in evaluating their viability as herbicide substitutes (Mesnage, 2022).

This comprehensive strategy was developed through an extensive literature review and consultations with domain experts. Its implementation requires active collaboration among stakeholders, including farmers and SMEs. However, potential limitations must be considered, financial constraints faced by stakeholders when adopting these strategies. For instance, transitioning to alternative energy sources, such as renewable power generation and eco-friendly transportation options, demands significant capital investment.

Stakeholders and prior studies emphasize replacing chemical-based materials with alternatives as a viable solution. Implementing this strategy require stakeholder education and outreach, as well as substantial financial investment. Therefore, conducting feasibility study that incorporates financial considerations is essential to ensure the successful adoption of these environmentally sustainable practices.

Table 14. Strategies to address potential environmental impacts on acidification

Issue solved	Strategy selected	Supporting Literature	Validator	Agency/ Organization	Approval
Acidification	1. Electric: 1) Evaluation of energy use 2) Optimize equipment usage 3) Invest in renewable energy types	(ESDM, 2012) (Xia et al., 2023) (Gelyaman et al., 2020) (Mesnage, 2022) (Wu et al., 2021) (Oni et al., 2019)	Edi Musah Amirullah	Coffee Plantation Manager SMI Owner	Confirm point 2. 2) and point 3 Confrim point 1. 1) and 2), 2. 2) and 3)
	2. Herbicides: Replace herbicides with more environmentally friendly types, such as organic herbicides				
	3. Organic fertilizer They control the amount of fertilizer dosage, practice organic fertilizer management correctly, and use alternative fertilizers such as biochar. Organic fertilizer.				
	4. Transportation Replace the use of transportation types with environmentally friendly transportation and optimize the use of transportation.	(Chen et al., 2022; Soelistianto et al., 2024) (Raslavičius et al., 2014) (LEMIGAS, 2024)			
	5. LPG Gas Optimize the use of LPG in stages and recommend using natural gas as an alternative.				

5. Conclusion

Based on the results and analysis of this study, we found that the environmental impacta associated with coffee production in SMI Coffee were quantified for specific categories. The findings indicate is global warming potential at 1,380 kg CO_2-eq, acidification at 6.91 kg SO_2-eq, and marine water ecotoxicity at 42,300 kg 1.4-DB-eq. To mitigate these environmental aspects, several recommendations are proposed. These include optimizing transportation usage, exploring alternative transportation methods, and improving the efficiency of equipment and machinery powered by electricity. Additionally, investments in alternative energy resources should be considered to enhance energy generation sustainably. Future research could build upon these findings by exploring and systematic strategies for decision-making. This could include integrating system dynamics modeling to inform policy development and support the implementation of the Sustainable Development Goals (SDGs). Such advancements would enable more objective approaches to mitigating environmental impacts in coffee production.

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