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An evaluation of life cycle assessment and cost-benefit analysis of an ecoprint fabric micro, small, and medium enterprise in Yogyakarta

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ABSTRACT
The rapid growth of the fashion industry has led to the emergence of fast fashion, which often overlooks its environmental impacts. In contrast, environmentally conscious practices are being adopted by some enterprises, including an MSME located in Yogyakarta, Indonesia, specializing in ecoprint fabric production. To evaluate its environmental and economic performance, this study conducts a Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA) focusing on green production, green transportation, and green packaging. LCA results show that the use of LPG in the steaming process has notable environmental impacts, particularly in fossil depletion (0.00076), climate change–human health (0.000359), and human toxicity (0.0000956). Based on these findings, Solar PV was evaluated as an improvement condition to reduce dependence on LPG and mitigate environmental impacts across several categories. However, human toxicity increased from 9.56E-05 to 0.00164, indicating environmental trade-offs throughout the life cycle. The CBA results indicate that the existing production system is economically feasible, with NPV of IDR 58,781,312, IRR of 9%, BEP of 2,136.34 units (IDR 534,084,829.96), Payback Period of 5.52 years, and BCR of 1.40. This implies that the project is already economically feasible under current LPG use, while the substitution with Solar PV further enhances its sustainability and overall benefits.

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1. INTRODUCTION

Micro, Small, and Medium Enterprises (MSMEs) play a crucial role in Indonesia's economy, including in Yogyakarta. One of the rapidly growing MSME sectors in Yogyakarta is the creative industry, particularly ecoprint fabric. Ecoprint is a fabric dyeing technique that has recently gained popularity among fashion entrepreneurs and textile producers. This technique utilizes natural materials that are easily accessible in the surrounding environment, and the production process is considered environmentally friendly [1]. Ecoprint involves transferring color and patterns onto fabric through direct contact, using plant parts that contain pigments such as leaves, flowers, bark, and other organic materials to create unique textile designs [2]. According to Salma and Eskak [3], the use of tannin-containing plants to generate color and motifs positions ecoprint as a sustainable craft industry. This is attributed to the reliance on natural, renewable resources, with additional materials designed to minimize pollution and promote environmental stewardship (eco-art). Although ecoprint has been known for some time, it has recently expanded due to its economic value and relatively simple production process. Ecoprint fabrics are valued for their distinctive aesthetic and high marketability, as each piece is handmade and unique. The term "ecoprint" derives from "eco" (ecology) and "print" (to imprint). The technique was pioneered by India Flint, who applied plant materials containing pigments directly to natural fiber fabrics, followed by boiling or steaming in large vessels. Only plants with high sensitivity to heat are suitable for this process, as heat is essential for extracting pigments. As such, ecoprint is widely recognized as an eco-fashion technique that supports sustainable fashion products [4].

Due to Indonesia's high biodiversity, ecoprint fabric exhibits significant variation. According to Jamilah et al [1], identified two commonly used ecoprinting techniques: pounding and steaming. The pounding technique involves placing leaves or flowers on the fabric and striking them with a wooden mallet (*ganden*) to transfer patterns. Meanwhile, the steaming technique requires rolling fabric layered with plant materials, covering it with a blanket or plastic, binding it tightly, and then steaming it in large pots [5]. Both methods are performed individually and in small batches, making each fabric unique and reflective of the artisan's craftsmanship [6].

This study focuses on an MSME located in Yogyakarta, Indonesia, specializing in ecoprint fabric production. The enterprise has implemented green attributes and claims to operate on a zero-waste basis. First, in terms of green production, the business employs organic materials such as leaves, flowers, and twigs as raw inputs, reuses solid waste as compost, and manages liquid waste through absorption wells that remain safe for irrigation. Second, its green packaging strategy relies on paper bags and cardboard boxes, which are biodegradable and environmentally friendly. Finally, its green transportation approach emphasizes local sourcing, as natural dyes are obtained from home gardens and other materials such as fabric, alum, lime, and ferrous sulfate (*tunjung*) are purchased from nearby suppliers, thereby minimizing transportation-related environmental impacts. This study focuses on a single MSME because an in-depth case study of the production process is required to accurately identify the stages that have the greatest environmental impact, a level of precision that is difficult to achieve in multi-MSME designs given the heterogeneity of scale, technology, and operational practices, thus enabling the formulation of targeted improvement recommendations.

The objective of this research is to evaluate the environmental impact across the entire life cycle of ecoprint fabric production in this micro-industry. Specifically, the study aims to identify which stages of the production process generate the most significant environmental burdens. In addition, the study assesses the economic feasibility of the enterprise by applying Cost–Benefit Analysis (CBA) alongside Life Cycle Assessment (LCA). LCA is a method for evaluating potential environmental impacts and resource use throughout a product's life cycle from raw material acquisition, production, and use, to waste management. In this study, LCA is applied across all attributes of Green Supply Chain Management (GSCM), including production, transportation, and packaging, to determine their respective contributions to environmental impacts. Meanwhile, CBA provides an economic perspective by comparing monetary costs and benefits [7]. The combination of LCA and CBA ensures that the enterprise is not only environmentally sustainable but also financially viable, thereby supporting long-term business resilience.

The contribution of this study lies in the use of LCA and CBA as complementary approaches to evaluate the environmental and economic aspects of ecoprint fabric MSMEs. Although both methods have been widely applied across various sectors, research examining environmental and economic performance simultaneously in the context of ecoprint fabric MSMEs remains relatively limited. This study applies LCA to identify the production stages that contribute most significantly to environmental impacts and uses these findings as a reference for proposing improvement scenario through the substitution of LPG with solar photovoltaic (Solar PV) technology, which is then evaluated based on environmental and economic aspects using LCA and CBA. By comparing existing condition and improvement scenario from environmental and economic perspectives, this study is expected to provide a more comprehensive understanding of strategies for enhancing sustainability in ecoprint fabric MSMEs.

2. GREEN SUPPLY CHAIN MANAGEMENT

GSCM represents an evolution from traditional supply chain management by explicitly integrating environmental considerations into supply chain activities. The quality revolution of the late 1980s and the supply chain revolution of the early 1990s marked a turning point that encouraged firms to become more environmentally conscious [8]. Since then, GSCM has gained increasing attention from both academics and practitioners as an effective approach to reducing waste while maintaining product quality and preserving natural resources. Practices such as eco-efficiency and remanufacturing have emerged as essential components in achieving best practices within green supply chains [8], [9]. In addition to internal efficiency goals, external drivers such as global market demands and governmental regulations have played a significant role in accelerating the adoption of GSCM [10]. Walton et al. emphasized that increasing governmental regulations and stronger public demands for environmental accountability have elevated environmental issues to the level of strategic decision-making within organizations [11]. As a comprehensive concept, GSCM encompasses several key attributes, including green procurement, green production, green transportation and logistics, green packaging, and reverse logistics [12].

2.1. Green Production

Green production refers to manufacturing processes that minimize environmental impacts while maintaining operational efficiency. Growing concerns from stakeholders regarding environmental preservation have encouraged firms to adopt environmentally friendly production practices [13]. Consumer pressure has been identified as a critical driver in this transition, as monitoring and demand for sustainable products compel companies to address environmental challenges across production and distribution activities [14]. Previous studies consistently highlight the influence of external stakeholders on green production strategies. Shubham et al [15] and Huang et al [16] demonstrated that consumer expectations significantly shape firms' environmental initiatives, particularly in production-related decisions. Moreover, Gualandris and Kalchschmidt [17] argued that firms failing to respond to customer demand for environmentally friendly products risk losing market share, which can ultimately reduce sales and profitability. These findings indicate that green production is not only an environmental obligation but also a strategic necessity for maintaining competitiveness.

2.2. Green Transportation

Transportation and logistics activities have long been recognized as major contributors to environmental degradation, making them a critical focus area within GSCM [18]. As integral components of the supply chain, logistics and transportation involve the movement and storage of materials and products across different stages [19]. Green transportation aims to reduce the environmental impacts associated with these activities while balancing economic, environmental, and social objectives [20]. Empirical evidence suggests that the adoption of green transportation practices leads to improvements in both environmental performance and business outcomes. Lai and Wong [21] confirmed that green transportation management enhances environmental quality and overall firm performance, while regulatory pressures play a crucial role in motivating organizations to implement sustainable logistics practices.

2.3. Green Packaging

Green packaging, often referred to as sustainable packaging, has attracted growing attention due to its role in reducing waste and supporting sustainable consumption. It is considered a key element in achieving the Sustainable Development Goals (SDGs) and contributes positively to social and economic dimensions of sustainability [22], [23]. In response to increasing consumer awareness, many companies have adopted reduce, reuse, and recycle principles in their packaging strategies. To effectively implement green packaging, firms must identify and understand the factors associated with environmentally friendly practices [24]. This understanding enables the selection of appropriate materials and the development of innovative packaging designs that minimize environmental impacts while meeting functional and market requirements.

2.4. Life Cycle Assessment (LCA)

LCA is a methodology for evaluating potential environmental impacts and resource use throughout the life cycle of a product from raw material extraction and production phases to use and waste management [25].

This approach enables companies to allocate environmental management costs across specific periods and provides rankings according to the environmental contributions of activities [12].

Figure 1 presents the LCA framework used in this study, which illustrates the interrelationship between the stages of goal and scope definition, inventory analysis, impact assessment, and interpretation in supporting the evaluation of environmental impacts throughout a product's life cycle.

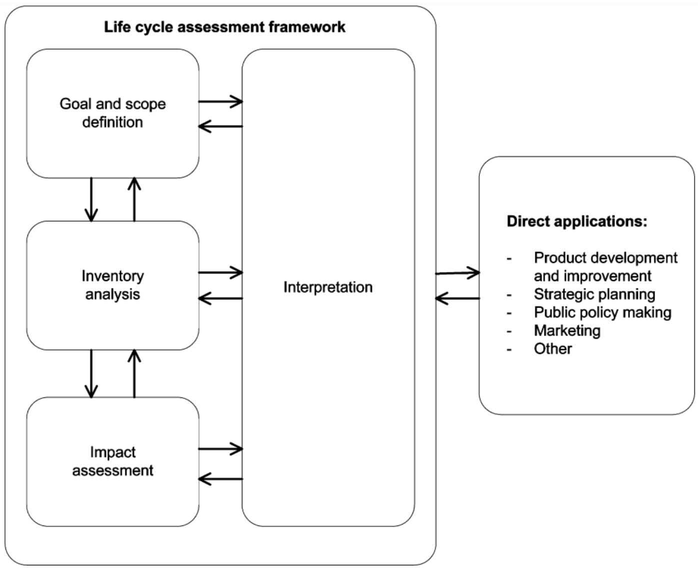

Figure 1. Life cycle assessment framework [25]

2.5. Cost-Benefit Analysis (CBA)

CBA is a policy recommendation method that enables analysts to compare and propose policies by calculating total costs and total benefits in monetary terms [7]. To evaluate the overall economic feasibility of business activities, several investment criteria have been developed [26]. These criteria employ discounted present values of benefits and costs over the project's lifespan. The primary indicators of investment feasibility are as follows:

1. Benefit Cost Ratio (BCR): BCR measures the benefits obtained per unit of project expenditure. A project is deemed feasible if BCR > 1; otherwise, it is not feasible.
2. Net Present Value (NPV): NPV is the net difference between the present value of benefits and costs. A project is considered feasible if NPV > 0.
3. Payback Period (PP): PP indicates the time required to recover the initial investment. A shorter payback period is generally more favorable.
4. Internal Rate of Return (IRR): IRR is the discount rate at which the present value of benefits equals the present value of costs (NPV = 0). A project is feasible if IRR exceeds the prevailing market interest rate.
5. Break-Even Point (BEP): BEP represents the point at which total revenue equals total costs, resulting in neither profit nor loss. It is crucial for managerial decision-making, such as whether to withdraw, expand, or discontinue certain business operations.

3. MATERIALS AND METHODS

This research was conducted at an MSME located in Yogyakarta, Indonesia, specializing in ecoprint fabric production, which has been operating since 2017. Data collection for LCA and CBA analysis was conducted in two stages: field visits and structured interviews with the business owner. Field visits were conducted to determine the production flow, material consumption, energy use, and waste generation at each stage of production. Observations were conducted from May 10 to May 31, 2024, so that the collected data could represent actual operational conditions. Interviews with MSME owners ensured the suitability of the data used for the data processing.

Data processing was divided in two stages: an environmental impact analysis using the LCA method and an invesment feasibility analysis using the CBA method, both for the MSME's existing conditions and improvement scenario to reduce environmental impacts resulting from the production process.

3.1. Life Cycle Assessment

To assess the environmental impact of ecoprint fabric production under existing conditions, this study employs a LCA approach using SimaPro 9.4 software. The method applied is the ReCiPe (H) method, which aggregates environmental impacts at each stage of the product's life cycle into broader hierarchical categories. ReCiPe (H) consists of four main impact categories: human health, ecosystem quality, resources, and climate change. The databases used in the analysis are those integrated within SimaPro, including Ecoinvent, Agri-footprint, Industry Data 2.0, and the U.S. Life Cycle Inventory Database. Referring to ISO 14040, the LCA methodology follows four main phases:

1. Goal and Scope Definition

This stage defines the objectives and scope of the research. The purpose of this study is to evaluate the environmental impact of the life cycle of eco-printed fabric at each stage and to propose improvement scenarios to mitigate these impacts. The scope of this study is defined by establishing the functional unit as one sheet of ecoprint fabric with dimensions of 1.15 m × 2.3 m. The observed system boundaries are cradle-to-gate, encompassing the life cycle assessment of a portion of the product, from raw material preparation (including extraction, processing, and transport to the factory) to the company's or production facility's exit, before the final product is distributed to consumers. The product's use and disposal phases are excluded from this scope. In accordance with ISO 14044, allocation procedures were considered for processes generating more than one output. In this study, ecoprint fabric production generates organic solid waste that is reused internally as compost and does not have direct economic value. Therefore, no mass-based or economic allocation was applied, and all environmental burdens were fully allocated to the main product, namely the ecoprint fabric, in line with a cut-off approach. The system boundaries in this study are divided into eight processes: raw material preparation, drying, dyeing, patterning, steaming, fixing, drying, and packaging, as shown in Figure 2.

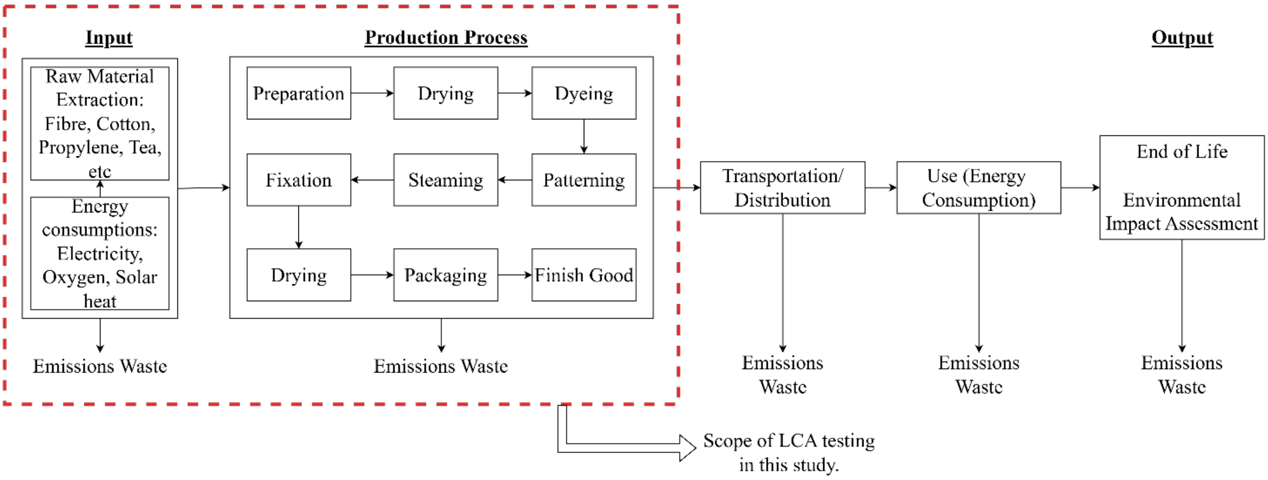

Figure 2. System scope

2. Life Cycle Inventory (LCI)

The LCI is the process of quantifying the inputs of raw materials and energy, as well as the emissions and waste released into the environment throughout the entire life cycle of a product, process, or activity [27]. In this phase, all relevant input and output flows for each process within the defined system boundaries are collected and analyzed. These data flows include material components, energy requirements, waste, and emissions released into the environment.

3. Life Cycle Impact Assessment (LCIA)

The LCIA phase evaluates the potential environmental and human health impacts resulting from the life cycle of a product, including effects on ecosystems and resource availability [27]. The outcomes of LCIA involve the classification of impact categories and the quantification of impact indicators, allowing for comparison through standardized units. Table 1 presents the inventory data flows for each process, which serve as the basis for environmental impact calculations using SimaPro software.

Table 1. Life cycle inventory data for ecoprint fabric production

No	Day	Process	Material	Amount	Unit
1	1	Fabric Preparation	Cotton fabric	3.5267	kg
2			Alum	1	kg
3			Lime	0.1	kg
4			Ferrous sulfate (*Tunjung*)	0.0667	kg
5			Soda ash	0.0267	kg
6			Water	0.6667	liter
7			Transportation from Supplier	74.2	km
8	2	Drying	Result of Fabric Preparation Process	1	p
9	3		Sunlight and Wind		
10	4	Coloring	Result of Drying Process	1	p
11			Dye (Tea)	1	kg
12			Water	10	liter
13			Transportation from Supplier	41.7	km
14	4	Pattern Application	Result of Coloring's Process	1	p
15			Leaves (Tea)	0.7	kg
16	4	Steaming	Result of Pattern Application Process	1	p
17			Plastic 0,3mm	10.6667	kg
18			Raffia rope	0.009	kg
19			Water	2.6667	kg
20			LPG	0.3383	liter
21			Transportation from Supplier	3.7	km
22	4	Fixation	Result of Steaming's Process	1	p
23			Alum	0.025	kg
24			Water	1	liter
25	5	Second Drying	Result of Fixation's Process	1	p
26			Sunlight and Wind		
27	6	Packaging	Kraft paper 350gsm	0.05705	kg
28	7	Distribution	Transportation to Distributor	50.9	km

4. Interpretation

Interpretation is a systematic technique used to identify, quantify, examine, and evaluate information derived from the results of the LCI and LCIA, and to communicate those findings effectively [27]. Life cycle interpretation represents the final phase of the LCA process, aiming to analyze the overall results in order to draw conclusions and provide recommendations for improving the assessed system.

3.2. Cost-Benefit Analysis

CBA is an approach for policy recommendations that allows the analysis to compare and propose a policy by calculating the total costs and the total benefits [7]. In order to evaluate the overall quality of a business activity, various indices have been developed, known as investment criteria [26]. Each of these indices utilizes the discounted present value of the benefits and cost flows throughout the life of the project. The economic feasibility assessment of the investment is conducted as follows:

1. Benefit-Cost Ratio (BCR)

BCR is calculated to determine the benefits received by a project for every unit of expenditure incurred. BCR is obtained by dividing the total present value of benefits by the total present value of costs. A project is considered feasible if the BCR is greater than 1 (BCR > 1). However, if the BCR is less than 1 (BCR < 1), the investment is deemed infeasible.

$$BC\ Ratio = \frac{Total\ Benefit}{Total\ Cost} \tag{1}$$

2. Net Present Value (NPV)

NPV is the net value calculated as the difference between the present value of benefits and the present value of costs. An investment is deemed feasible if the NPV is greater than zero. NPV is defined as the difference between the present value (PV) of cash flows and the PV of investments over the investment period, or, in other words, it represents the estimated future cash flows discounted to the present. The NPV can be calculated using the following Eq. (2):

$$NPV = -I + \sum_{j=1}^{n} \frac{CF_j}{(1+i)^j} \tag{2}$$

where NPV is the net present value (with NPV > 0 indicating feasibility), I represents the initial investment, CF_j denotes the cash flow in the j-th period, and i is the interest rate.

3. Payback Period (PP)

PP is the duration required to recover the initial investment, calculated as the period in which the investment is recouped. A shorter PP indicates a more favorable investment.

$$PP = N + \frac{k_n - I}{k_{n+1}} \tag{3}$$

where PP denotes the Payback Period, N represents the final year during which the cash flow is insufficient to cover the investment cost, nk refers to the cumulative cash flow up to year n, and nk+1 represents the cumulative cash flow up to year n+1.

4. Internal Rate of Return (IRR)

IRR is the interest rate at which the present value of benefits (receipts) equals the present value of costs (expenditures), resulting in a NPV of zero. Thus, the IRR indicates a project's ability to generate returns, or the level of profitability it can achieve [28]. An investment is considered feasible if the IRR exceeds the prevailing interest rate.

$$IRR = i_{NPV(+)} + \frac{NPV_{(+)}}{(NPV_{(+)} - NPV_{(-)})}\ x\ (i_{NPV(-)} - i_{NPV(+)}) \tag{4}$$

where IRR is the internal rate of return, iNPV(i^+) represents the interest rate at which the NPV is positive, iNPV(i^-) represents the interest rate at which the NPV is negative, NPV($^+$) denotes the positive NPV value, and NPV($^-$) denotes the negative NPV value.

5. Break-Even Point (BEP)

BEP is defined as the stage at which a company neither makes a profit nor incurs a loss. The BEP is critical for management decisions, such as whether to withdraw or further develop a product or to close an unprofitable subsidiary. In other words, an enterprise is said to be at break-even when its total revenue equals its total costs, or when the contribution margin is only sufficient to cover fixed costs.

$$BEP\ (Units) = \frac{FC}{P - VC} \tag{5}$$

$$BEP\ (Rupiah) = \frac{FC}{1 - \frac{VC}{S}} \tag{6}$$

where FC represents the fixed cost, VC denotes the variable cost, P stands for price, and S indicates the sales volume.

4. RESULTS AND DISCUSSION

This study aims to identify the environmental impacts of ecoprint fabric production using the LCA method, as well as to evaluate the economic viability of the ecoprint fabric business through CBA. In this study, the LCA and CBA methods are used as complementary approaches to assess environmental and economic aspects. LCA is used to identify the production stages that contribute most significantly to environmental impacts, while also serving as a reference for proposing improvement scenario. Subsequently, CBA is used to evaluate economic feasibility under both existing condition and the proposed improvement scenario, to ensure that the recommended improvement is not only environmentally friendly but also financially viable.

The object of this research is a micro, small, and medium enterprise (MSME) located in Yogyakarta that produces ecoprint fabric. The supply chain network implemented by the MSME is illustrated in Figure 3, encompassing various stages from raw material procurement (supplier selection), the ecoprint fabric production process, to the marketing of finished products. Raw materials such as leaves and flowers used as natural dyes are sourced from plants grown in the owner's yard and through the empowerment of local communities. Other materials such as fabric, alum, ferrous sulfate (*tunjung*), lime, plastic, and kraft paper are obtained from suppliers located near the MSME's premises, in an effort to minimize carbon emissions generated from the transportation of raw materials. The procurement locations (suppliers) of the raw materials used in ecoprint fabric production at the selected MSME are presented in Table 2.

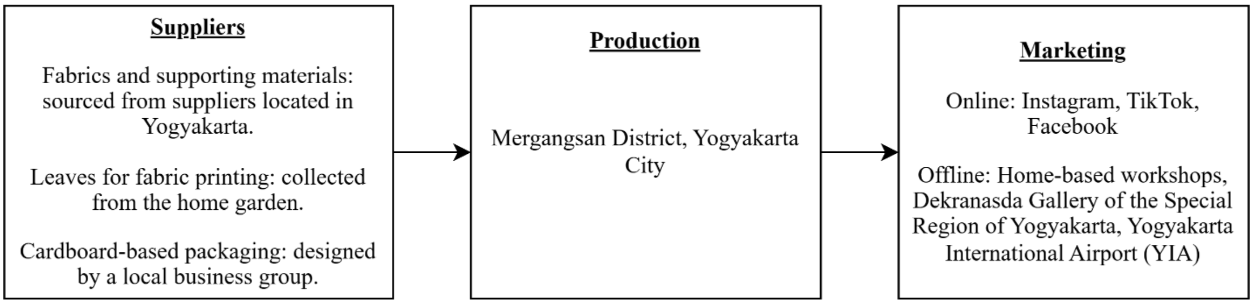

Figure 3. Supply chain network of the selected ecoprint fabric MSME

Table 2. Raw material procurement locations (suppliers) for the selected MSME

Material	Supplier	Location
Cotton fabric	Supplier 1	Laweyan District, Surakarta City
Alum (*Tawas*), Lime	Supplier 2	Jetis District, Yogyakarta City
Ferrous sulfate (*Tunjung*), Soda ash	Supplier 3	Kraton District, Yogyakarta City
Tea	Supplier 4	Samigaluh District, Kulon Progo Regency
Plastic 0,3mm, Raffia rope	Supplier 5	Wirobrajan District, Yogyakarta City
LPG	Supplier 6	Mergangsan District, Yogyakarta City
Kraft Paper 350 gsm	Supplier 7	Wirokerten, Bantul Regency

The selected MSME has currently implemented green attributes in the operation of its ecoprint fabric business, ensuring that the production process is not only sustainable but also environmentally friendly. The first green attribute is Green Production, which at the selected MSME refers to the process of creating ecoprint fabric that prioritizes the use of natural materials and the application of a zero-waste approach. The raw materials used for patterning the fabric are derived from leaves, flowers, and twigs, while the coloring agents are extracted from plants. All patterning and dyeing materials are obtained from plants grown in the backyard or sourced through community empowerment initiatives. These practices ensure that the production process does not harm the ecosystem, as the plants used are renewable. Moreover, solid waste from production residues is processed into compost, while liquid waste is directed into the MSME infiltration well to prevent water pollution. This liquid waste is still within safe limits for use in watering plants.

The second green attribute is Green Transportation, which refers to the minimization of the negative environmental impact resulting from both raw material procurement and the distribution of finished products. Raw materials such as leaves, flowers, and twigs are sourced from the backyard, while other materials are purchased from nearby suppliers located close to the selected MSME site. This strategy significantly reduces carbon emissions associated with long-distance transportation. Additionally, finished products are distributed directly through sales at the Provincial Dekranasda Gallery of the Special Region of Yogyakarta and at Yogyakarta International Airport, as well as via a make-to-order system, where customers pick up their orders directly from the selected MSME.

The third green attribute is Green Packaging, which involves the use of environmentally friendly materials for packaging ecoprint fabric products. The selected MSME utilizes paper bags and cardboard boxes designed by local business groups in Yogyakarta City. These packaging materials are biodegradable and do not cause environmental pollution. Paper bags are primarily used for packaging fabrics intended for local consumers in Yogyakarta City, while cardboard boxes are used for packaging souvenirs or ecoprint fabric displayed in galleries. Figure 4 below shows an illustration of the packaging used by the selected MSME.

Figure 4. Packaging used by the selected MSME

4.1. Life Cycle Assessment

Prior to conducting the LCA of the entire ecoprint fabric production process at the selected MSME, it is essential to understand the material and energy flows involved throughout the product's life cycle. A flowchart is employed to visualize the production stages and the resource flows occurring from the beginning to the end of the ecoprint fabric production process. This flowchart aids in identifying the stages that contribute to environmental impacts and in assessing resource consumption. The complete flowchart of the ecoprint fabric production process at the selected MSME is presented in Figure 5 below.

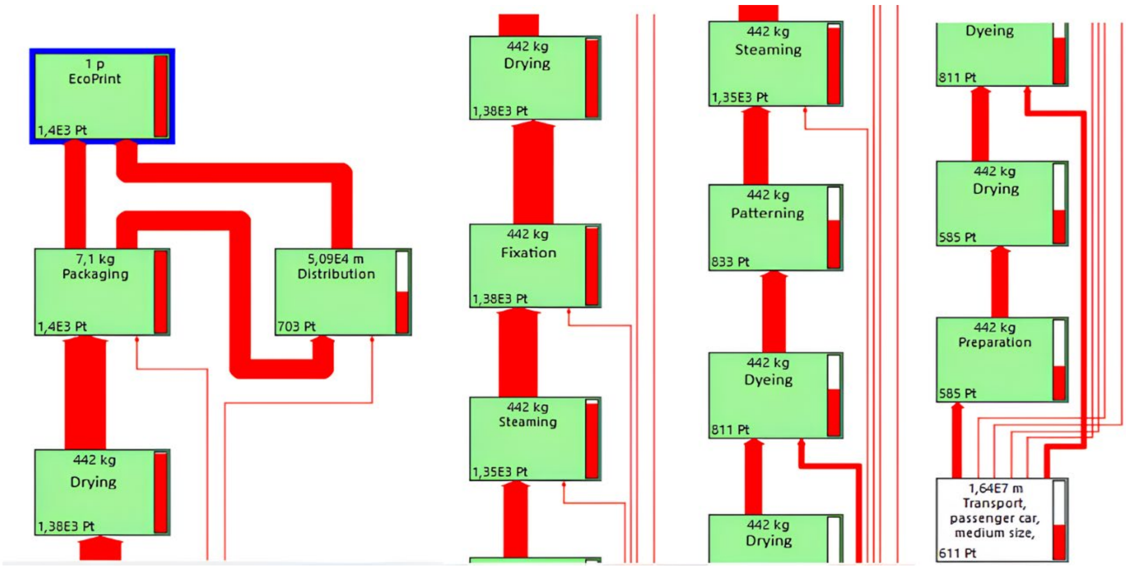

Figure 5. Process flow diagram of ecoprint fabric manufacturing

The flowchart presented above illustrates the entire ecoprint fabric production process from start to finish. The process begins on the far right with the fabric preparation stage, followed by first drying, and proceeds leftward through dyeing, patterning, steaming, fixation, second drying, until it becomes a finished product, after which packaging and distribution are conducted. This flowchart not only provides a clear depiction of the production stages but also serves as a foundational tool for evaluating environmental impacts through the LCA method. Several steps are involved in the LCA analysis, as detailed below:

4.1.1. Goal and Scope

The objective of the LCA analysis under the current conditions is to determine the magnitude of the environmental impact generated across the entire life cycle of ecoprint fabric products. This facilitates the identification of the specific stage(s) that contribute the most to environmental degradation.

4.1.2. Life Cycle Inventory

The LCI encompasses all raw materials used, the energy consumed, and the carbon emissions generated throughout the product's life cycle. The complete life cycle inventory for ecoprint fabric production is presented in Table 1.

4.1.3. Life Cycle Impact Assessment

The LCIA aims to identify and evaluate the potential environmental impacts associated with the entire product life cycle of ecoprint fabric at the selected MSME. This assessment provides a comprehensive overview of how each production stage contributes to various environmental impact categories. Using the SimaPro software for the LCA analysis, the resulting impact assessment is shown in Figure 6. To facilitate result interpretation in Figure 6 - 11and Figure 12 - 16, each bar in the figure represents an impact category, while the different colors within each bar indicate the contribution of individual processes in the ecoprint production system.

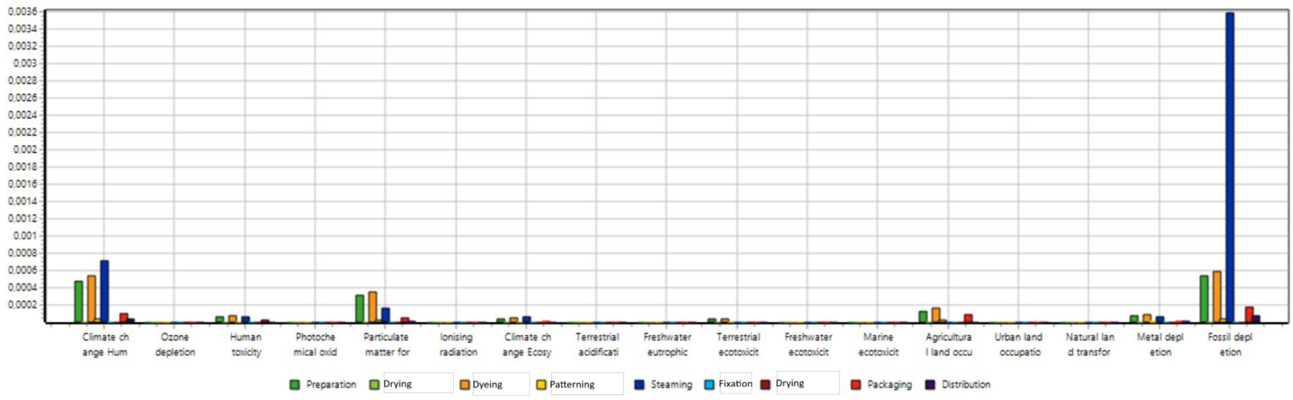

Figure 6. Normalized impact assessment per category under current conditions

Figure 6 shows that the ecoprint fabric process stage with the highest environmental impact is Steaming. A key contributor to this impact is the use of LPG gas as the primary energy source for the steaming process. Figure 7 presents the characterization results of environmental impacts specific to the steaming process, indicating the proportional contribution of each environmental impact category. The results suggest that this process significantly affects climate change impacts on human health and ecosystems, also indicating a potential risk to human health.

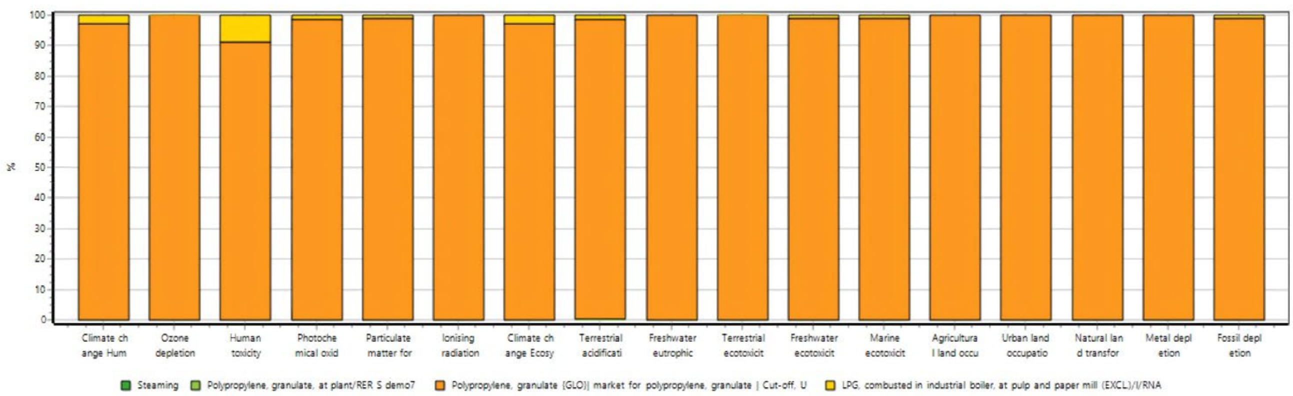

Figure 7. Characterization of environmental impact in the steaming process under current conditions

Figure 8 displays the normalized impact assessment results for the steaming process. The Resources category has an impact score exceeding 0.0040, while the Human Health category reaches nearly 0.0015. Figure 9 highlights the normalized environmental impact assessment for the Fossil Depletion category in the steaming stage. The results demonstrate a significant impact due to the dominant contribution of LPG use, with a score of 0.00076. Figure 10 presents the environmental impact assessment normalized for the Climate Change – Human Health category during the steaming process. The steaming stage shows a considerable impact due to the use of LPG, with a dominant contribution of 0.000359.

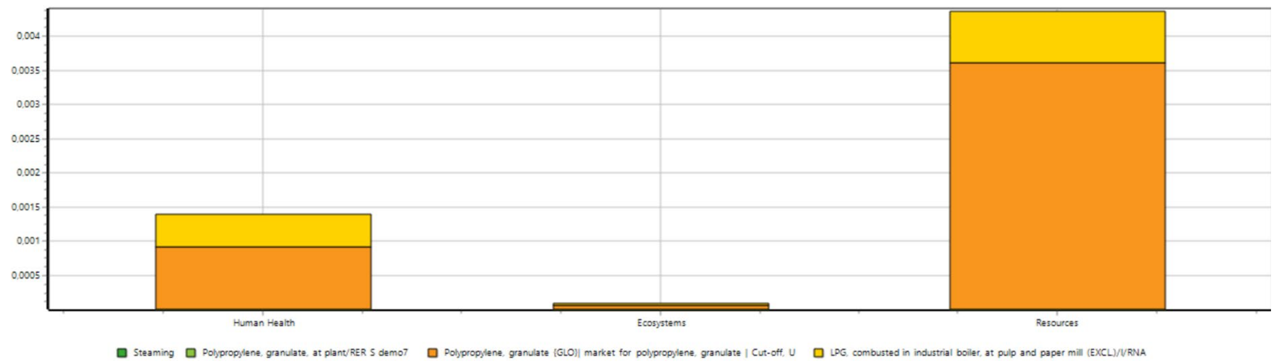

Figure 8. Normalized impact assessment for the steaming process under current conditions

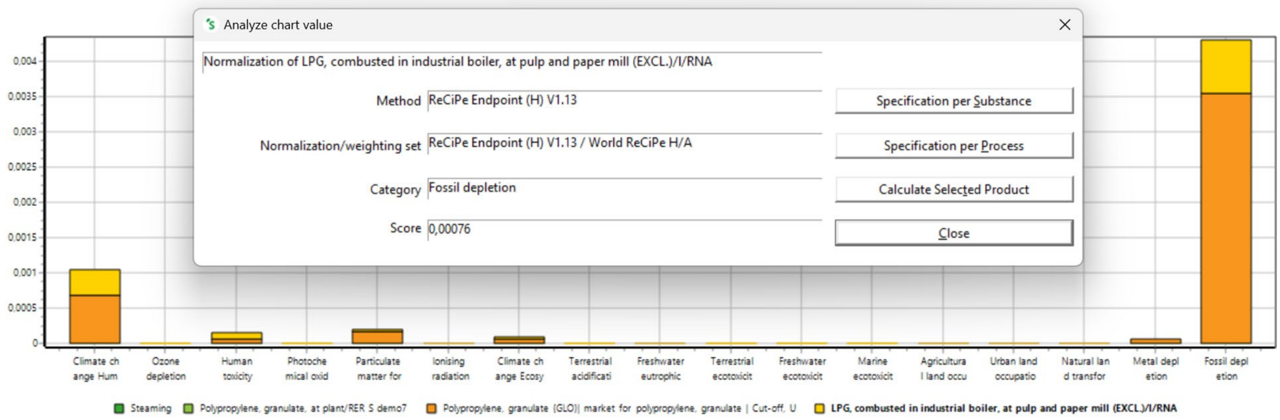

Figure 9. Normalized impact assessment: fossil depletion in the steaming process under current conditions

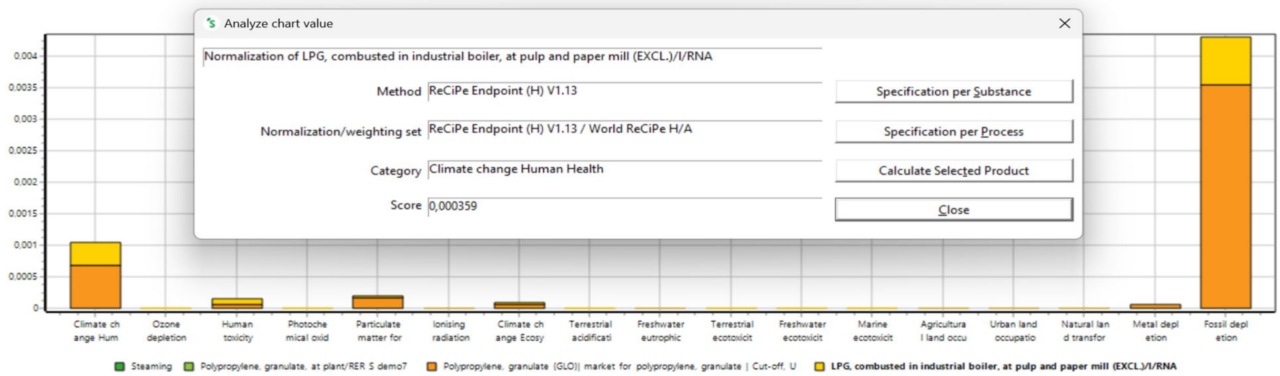

Figure 10. Normalized impact assessment: climate change – human health in the steaming process under current conditions

Figure 11 provides the normalized environmental impact results for the Human Toxicity category. The steaming process exhibits a significant impact in this category, also primarily due to the use of LPG, with a score of 0.0000956.

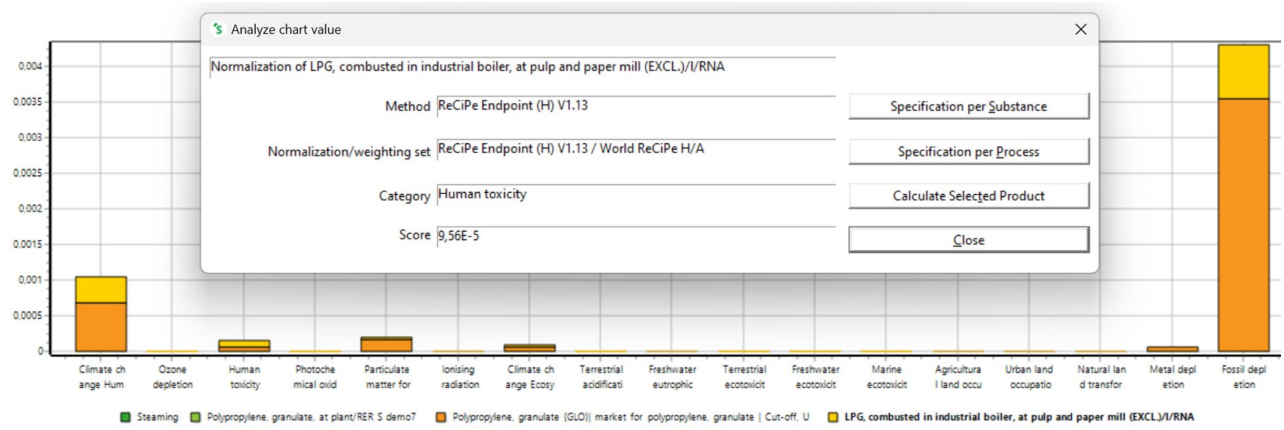

Figure 11. Normalized impact assessment: human toxicity in the steaming process under current conditions

4.1.4. Interpretation of Life Cycle Impact Assessment

Based on the results of the LCA of the ecoprint fabric production process at the selected MSME, it was found that the steaming process has the greatest environmental impact, primarily due to the use of LPG as the main energy source. Compared to other production stages, such as washing, drying, and packaging, the steaming process requires significantly more energy and relies directly on the combustion of fossil fuels to generate heat. This situation makes LPG the primary contributor to the environmental impacts resulting from the observed production process. As shown in Figure 6, the steaming process is the dominant contributor to the overall environmental burden of the ecoprint fabric production system.

This dominance is evident in the impact categories of Fossil Depletion, Climate Change – Human Health, and Human Toxicity. The Fossil Depletion category represents the largest impact because the steaming process is highly dependent on the use of LPG, a non-renewable fossil fuel. The LCA results show a Fossil Depletion score of 0.00076, the highest among the identified impact categories, reflecting the substantial consumption of fossil fuel-based energy during the steaming process. Fossil depletion measures the use of non-renewable fossil resources such as oil, natural gas, and coal [29]. The use of fossil fuels poses significant environmental concerns, including carbon emissions and unsustainable resource extraction. The Climate Change – Human Health category represents the second most significant impact, closely tied to the amount of greenhouse gases that trap heat in the atmosphere over a 100-year timeframe, relative to carbon dioxide. With a score of 0.000359, this category indicates that emissions generated from LPG combustion contribute considerably to climate change-related impacts affecting human health. The Climate Change – Human Health category is used to assess these impacts [30]. Greenhouse gas emissions contribute directly and indirectly to global warming, which poses severe threats to human well-being. Lastly, the Human Toxicity category also indicates a substantial environmental impact. Although the Human Toxicity score of 0.0000956 is lower than those of Fossil Depletion and Climate Change – Human Health, it indicates potential human health risks associated with emissions and chemical substances generated from fuel use [29]. The release of toxic compounds can endanger workers and nearby communities, with long-term exposure potentially causing cancer, respiratory diseases, or reproductive disorders. These findings indicate that the environmental burden associated with the steaming process is influenced not only by its high energy demand but also by the fossil-based characteristics of the energy source used.

Similar findings from a study by Murugesh and Selvadass [31], indicate that steam production and fuel combustion are the primary contributors to the environmental impact of textile dyeing and finishing processes. This supports the findings of the present study, in which the steaming process was identified as the primary contributor to the environmental impact resulting from the intensive use of LPG as a thermal energy source. The consistency of these findings indicates that thermal processes with high energy demands tend to be the primary contributors to environmental impacts in textile-based production systems. Therefore, efforts to reduce LPG consumption through substitution with renewable energy sources have the potential to be an effective strategy for lowering the environmental impact of the ecoprint fabric production process.

4.2. Cost Benefit Analysis

Based on the components of initial investment, cost, and revenue that have been inventoried for the selected MSME. A CBA was conducted to assess the viability of the business using five methods: Net Present Value (NPV), Internal Rate of Return (IRR), Break Even Point (BEP), Payback Period (PP), and the Benefit-Cost Ratio (BCR). The calculations were performed using Microsoft Excel based on Eq. (1) through (6). To assess the investment feasibility for the selected MSME, the first step involved identifying the cash flows, both receipts and expenditures, from each transaction over a specific period, as shown in Table 3-5. Based on these cash flows, an economic feasibility evaluation will be conducted employing the CBA approach.

Table 3. Initial investment components

No	Investment Components	Amount (IDR)
1	Warehouse and Equipment	257,356,000
2	Materials	44,172,000
3	Operational	156,000,000
4	Deprecation	2,000,000
5	Maintenance	12,000,000
	Total Investment	471,528,000

Table 4. Expenditure component (cost)

No	Component	Total	Unit	Price (IDR)	Amount (IDR)/year
			Initial Investment		
1	Gallery	1	Unit	100.000.000	100.000.000
2	Gas Stoves	4	Unit	589.000	2.356.000
3	Vehicles	1	Unit	125.000.000	125.000.000
4	Infiltration well	1	Unit	30.000.000	30.000.000
				Total	257.356.000
			Materials		
1	Cotton	1 per month	roll	750.000	9.000.000
2	Alum	1 per month	sack (25 Kg)	130.000	1.560.000
3	Chalk	5 per month	Kg	10.000	600.000
4	Ferrous sulfate	5 per month	Kg	125.000	7.500.000
5	Soda ash	5 per month	Kg	16.000	960.000
6	Plastic	1 per month	roll	800.000	9.600.000
7	LPG	4 per month	tube	175.000	8.400.000
8	Kraft paper	100 per month	sheet	3.500	4.200.000
9	Raffia rope	1 per month	roll (Kg)	21.000	252.000
10	Cormorant	4	Unit	525.000	2.100.000
				Total	44.172.000
			Operational Cost		
1	Employee Salary	5	Person/month	2.200.000	132.000.000
2	Electricity	1	Month	1.000.000	12.000.000
3	Fuel oil	1	Month	1.000.000	12.000.000
				Total	156.000.000
			Depreciation Expenses		
1	Vehicle	1	Unit	2.000.000	2.000.000
				Total	2.000.000
			Others		
1	Maintenance	1	Month	1.000.000	12.000.000
				Total	12.000.000

Table 5. Components of revenue

No	Component	Total	Unit	Price (Rp)	Amount (Rp)/year
			Initial Investment		
1	Product sales	100	Units per month	250.000	300.000.000
				Total	300.000.000

According to the results of the CBA presented in Table 6, the NPV is used to determine whether an investment will generate a value that exceeds or falls short of the incurred costs while considering the time value of money. An NPV value of 58,781,312 was obtained, where it is positive (NPV > 0), indicating that the project is feasible. The IRR is the discount rate at which the NPV of all the project's cash flows (both positive and negative) equals zero. This rate reflects the project's ability to generate returns or the level of profitability it can achieve. The IRR value obtained is 9%, which is considered acceptable and favorable since it exceeds the prevailing interest rate of 6%. The BEP is the point at which the total revenue of a project or business equals the total costs incurred. It is observed that, under the current conditions, to achieve breakeven—where total revenue equals total cost, and the company experiences neither losses nor gains—the BEP (in units) must reach 2,136.34, which is approximately 2,136 units, while the BEP (in Rupiah) amounts to Rp 534,084,829.96. The PP is defined as the period required to recover the initial investment from the cash flows generated by the project.

Table 6. Cost benefit calculation for existing

COST BENEFIT ANALYSIS CALCULATION				
TOTAL INITIAL INVESTMENT	=	IDR 471.528.000		
INTEREST RATE	=	6%		
TAX	=	0,5%		
INTEREST RATE (IR)=10 %		**CASH FLOW**	**DCF**	**NPV**
INVESTMENT - YEAR	0	(471.528.000)	1	(471.528.000)
CASH FLOW - YEAR	1	85.398.860	0,943396226	80.564.962
CASH FLOW - YEAR	2	85.398.860	0,88999644	76.004.681
CASH FLOW - YEAR	3	85.398.860	0,839619283	71.702.530
CASH FLOW - YEAR	4	85.398.860	0,792093663	67.643.896
CASH FLOW - YEAR	5	85.398.860	0,747258173	63.814.996
CASH FLOW - YEAR	6	85.398.860	0,70496054	60.202.826
CASH FLOW - YEAR	7	85.398.860	0,665057114	56.795.119
CASH FLOW - YEAR	8	85.398.860	0,627412371	53.580.301
	∑ NPV			58.781.312
	IRR			9%
∑ NPV (+) & IRR>6% = INVESTMENT FEASIBLE				
INFLOW	=	Total Revenue per Year		Rp. 300.000.000
OUTFLOW	=	Total Cost per Year		Rp. 214.172.000
CASH FLOW				Rp. 85.398.860
NPV	=	∑ (CASH FLOW*DCF)		
PP	=			
		5,52		
BC Ratio	=	1,40		
BEP (Unit)	=			
		2.136,34		
BEP (IDR)	=	Rp. 534.084.829,96		
DCF	=	$\frac{1}{(1+IR)^n}$; n = periode		

It can be observed that the PP is 5.52 years, which means it will take approximately 5.52 years to recover the initial investment of Rp 471,528,000 from an annual cash flow of Rp 85,398,860. Meanwhile, the BCR compares the present value of the benefits generated by the project to the present value of the costs incurred. If the BCR is greater than 1, the project is considered feasible because the benefits outweigh the costs; if the BCR is equal to 1, the project is regarded as breaking even since the benefits are equal to the costs; and if the BCR is less than 1, the project is deemed unfeasible because the costs exceed the benefits. The obtained BCR value is 1.40, indicating that the project is considered viable.

4.3. Recommendation for Improvement

Following an LCA analysis of the ecoprint fabric production process, the steaming process was identified as the stage with the greatest environmental impact. One of the main factors contributing to this high impact is the use of LPG as the primary energy source in the steaming process. According to research by Sanaye and Sarrafi [32], the use of LPG can be partially substituted with solar photovoltaic (Solar PV)-based solar energy as an alternative energy source to reduce dependence on fossil fuels. However, the environmental benefits of Solar PV must be considered comprehensively. While it has the potential to reduce fossil fuel use and greenhouse gas emissions, Solar PV also generates environmental impacts in certain categories that arise throughout its life cycle. Therefore, the implementation of Solar PV needs to be evaluated from a life cycle perspective to understand the environmental benefits and trade-offs that arise. Based on these considerations, this study proposes the use of Solar PV as an alternative to LPG for the selected MSME. The environmental impacts and economic benefits of this improvement scenario are further evaluated using the LCA and CBA approaches.

4.3.1. Life Cycle Impact Assessment

After obtaining the inventory values for the steaming process, the next step is to evaluate the data processing results in SimaPro. The purpose of this LCA analysis is to determine the environmental impact of using Solar PV as a substitute for LPG during the steaming process. Figure 12 shows the impact assessment characterization results for the steaming process after improvement. The yellow color indicates the Solar PV components, while the orange color indicates the plastic components used for steaming process. The LCI for the steaming process after improvement is shown in Table 7.

Table 7. LCI for the steaming process for improvement condition

Material	Amount	Unit
Plastik 0,3 mm	10.66666667	Kg
Raffia rope	0.009	Kg
Water	2.66666667	Kg
Solar PV 1 kWh	0.556	P

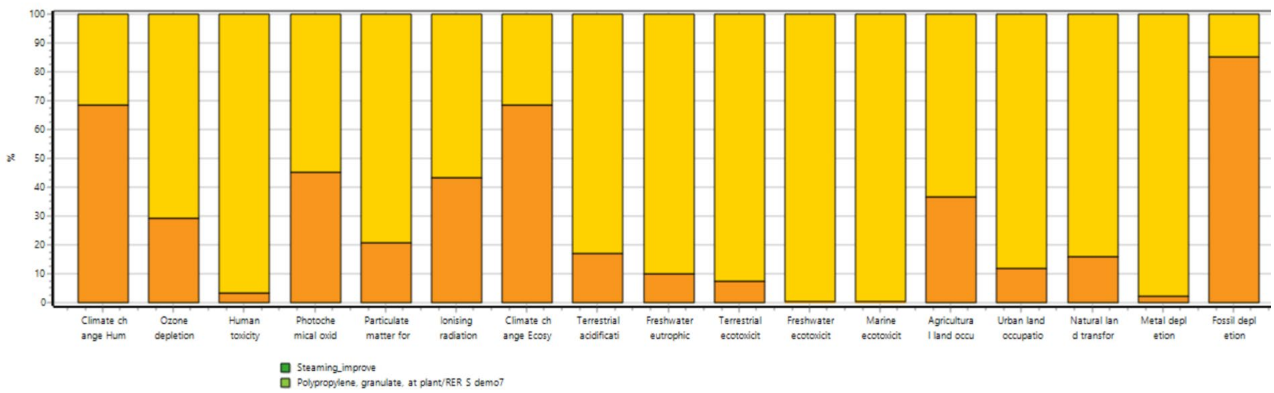

Figure 12. Characterization of environmental impact in the steaming process for improvement conditions

Figure 13 shows the normalized impact assessment results for the steaming process after improvement. The figure shows that the environmental impact value for the resources category is greater than 0.007, while the human health category is nearly 0.0035. Figure 14 shows the specific values in the Fossil Depletion category, which is included in the resources category. For the Solar PV component (replacing LPG), it received a score of 0.00062. The Climate Change – Human Health category for the Solar PV component received a score of 0.000316. This is shown in Figure 15. Meanwhile, for the Human Toxicity category, the Solar PV component received a score of 0.00164, as shown in Figure 16.

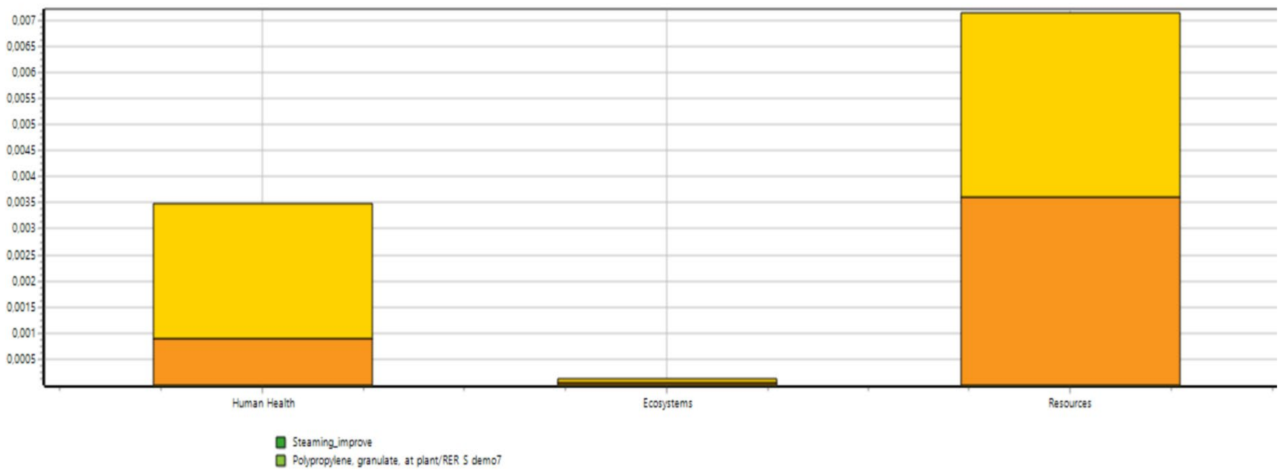

Figure 13. Normalized impact assessment for the steaming process for improvement conditions

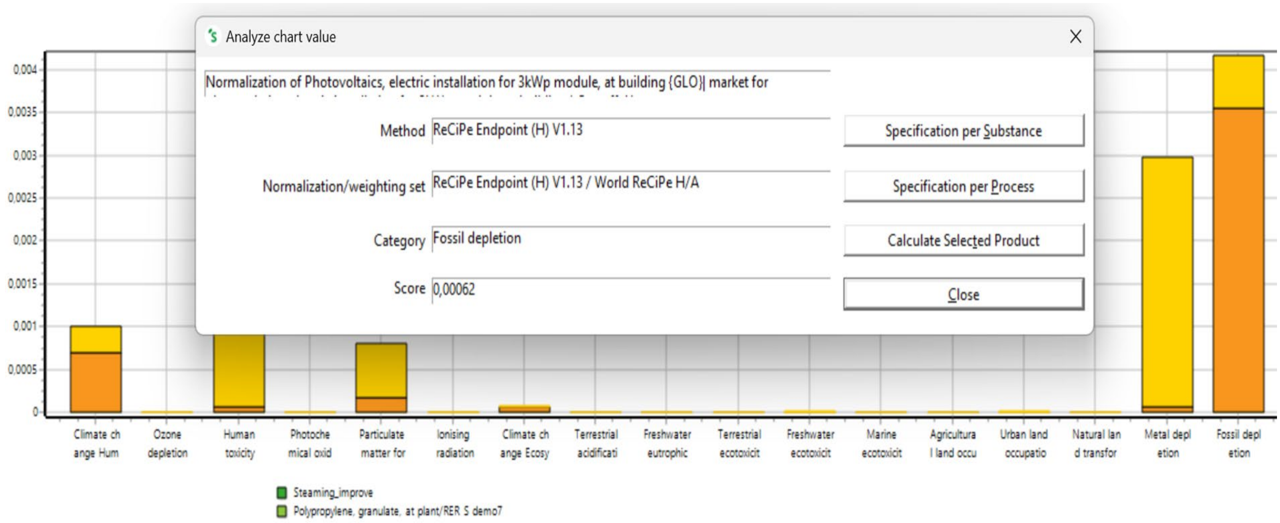

Figure 14. Normalized impact assessment: fossil depletion in the steaming process for improvement conditions

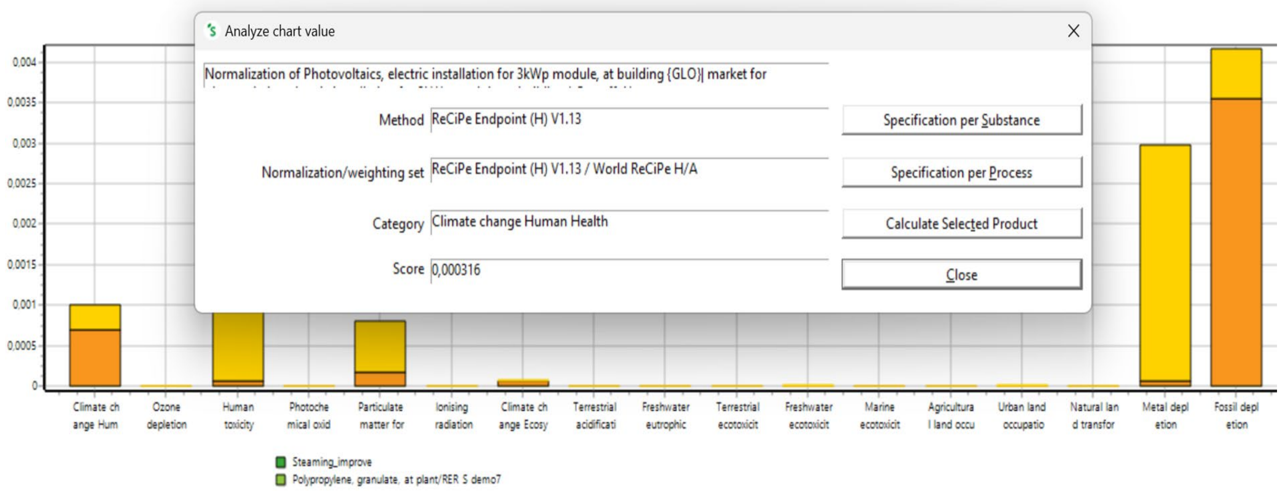

Figure 15. Normalized impact assessment: climate change – human health in the steaming process for improvement conditions

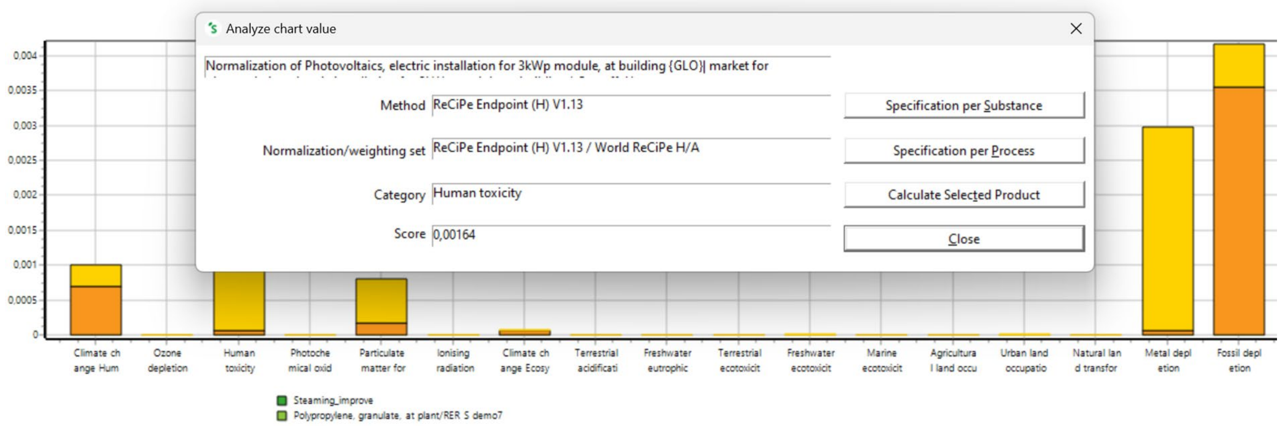

Figure 16. Normalized impact assessment: human toxicity in the steaming process for improvement conditions

Based on the results of the LCA impact assessment of the Solar PV components used in the steaming process, the impact scores were 0.00062 for Fossil Depletion, 0.000316 for Climate Change – Human Health, and 0.00164 for Human Toxicity. These categories represent the environmental burdens associated with the implementation of Solar PV in the steaming process, including raw material extraction, component manufacturing, operation, and end-of-life management. Among the assessed categories, Human Toxicity recorded the highest impact score, which may be associated with the materials and manufacturing processes required for photovoltaic component production. These findings suggest that while Solar PV has the potential to support cleaner energy supply and reduce dependence on fossil fuels, its implementation also presents environmental trade-offs that need to be thoroughly considered.

4.3.2. Cost Benefit Analysis

The CBA calculation for ecoprint fabric production at the selected MSME shows that the most impacted category is the use of resources, specifically LPG as an energy source in the steaming process, with the most significant environmental impact on the fossil depletion category, with a score of 0.00076. Therefore, one proposed improvement effort is to convert energy by utilizing alternative sources, namely New and Renewable Energy (NRE), Solar PV. This effort is certainly in line with the government's target of increasing the use of NRE as an energy source by 25%, especially in industrial processing activities. The results of the CBA calculation for the improvement condition are shown in Table 8.

Table 8. Cost benefit calculation for improvement

COST BENEFIT ANALYSIS CALCULATION				
TOTAL INITIAL INVESTMENT	=	IDR 471.528.000		
INTEREST RATE	=	6%		
TAX	=	0,5%		
INTEREST RATE (IR)=6 %		**CASH FLOW**	**DCF**	**NPV**
INVESTMENT - YEAR	0	(471.528.000)	1	(471.528.000)
CASH FLOW - YEAR	1	85.398.860	0,943396226	80.564.962
CASH FLOW - YEAR	2	85.398.860	0,88999644	76.004.681
CASH FLOW - YEAR	3	85.398.860	0,839619283	71.702.530
CASH FLOW - YEAR	4	85.398.860	0,792093663	67.643.896
CASH FLOW - YEAR	5	85.398.860	0,747258173	63.814.996
CASH FLOW - YEAR	6	85.398.860	0,70496054	60.202.826
CASH FLOW - YEAR	7	85.398.860	0,665057114	56.795.119
CASH FLOW - YEAR	8	85.398.860	0,627412371	53.580.301
CASH FLOW - YEAR	9	348.046.860	0,591898464	206.008.402
CASH FLOW - YEAR	10	374.346.860	0,558394777	209.033.331
	∑ NPV			473.823.045
	IRR			19%

COST BENEFIT ANALYSIS CALCULATION			
∑ NPV (+) & IRR>6% = INVESTMENT FEASIBLE			
Existing Condition			
INFLOW	=	Revenue per Year	Rp 300.000.000
OUTFLOW	=	Cost per Year	Rp 214.172.000
CASH FLOW	=	Inflow - Outflow	Rp 85.398.860
Condition after Improvement in the 9th Year			
INFLOW	=	Revenue per Year	Rp 600.000.000
OUTFLOW	=	Cost per Year	Rp 223.772.000
CASH FLOW	=	Inflow - Outflow	Rp 374.346.860
NPV	=	∑ (CASH FLOW*DCF)	
PP	=	5,52	
BC Ratio	=	2,68	
BEP (Unit)	=	2.371,71	
BEP (IDR)	=	592.927.678,52	
DCF	=	1/(1 + IR)^ PERIODE	

According to the calculation using CBA for the improvement condition, we perceived that the NPV is Rp 473,823,045, which is positive (NPV > 0). That result indicates that the improvement is feasible and more profitable in the long run compared to the existing condition. The IRR is 19%, showing a significant increase from the previous condition, and is considered highly viable since it exceeds the prevailing interest rate of 6%. The BEP is achieved at 2,371.71 units (≈2,372 units) or Rp 592,927,678.52, representing the minimum production level required for the business to avoid losses. The PP remains at 5.52 years, meaning the initial investment of Rp 471,528,000 can be recovered within that timeframe through annual cash inflows of Rp 85,398,860. Furthermore, the BCR is 2.68, which confirms that the benefits significantly outweigh the costs, making the improvement financially feasible.

4.3.3. Difference Analysis Before and After Improvement

A comparison of the LCA results before and after the implementation of the improvement scenario is shown in Table 9. The comparison focuses on the steaming process because, prior to the implementation of the scenario, this stage was identified as the process with the greatest environmental impact in the ecoprint fabric production system. The analysis results show that the implementation of Solar PV as a substitute for LPG use is able to reduce the impact values in the Fossil Depletion category from 0.00076 to 0.00062 and in the Climate Change – Human Health category from 0.000359 to 0.000316, indicating a reduced dependence on fossil-based energy sources as well as a decrease in environmental impacts related to greenhouse gas emissions. However, the Human Toxicity category showed increased from 9.56E-05 to 0.00164 following the implementation of Solar PV, which may be associated with the materials and manufacturing processes required in the production of photovoltaic components. These findings suggest that the proposed improvement scenario can provide environmental benefits in some impact categories, but also presents trade-offs in other impact categories. Nevertheless, the environmental burden associated with Solar PV can be minimized through end-of-life management, such as the implementation of reverse logistics and recycling processes, so that materials that still have utility value can be reused.

Table 9. Comparison of the environmental impact of the steaming process before and after improvement

Environmental Impact Steaming Process	Score Existing Condition	Score Improvement Condition
Fossil Depletion	0.00076	0.00062
Climate Change – Human Health	0.000359	0.000316
Human Toxicity	9.56E-05	0.00164

A comparison of the CBA for existing and improved conditions can be seen in Table 10. The only component being compared is the shift in energy use for the steaming process from LPG to an electric stove utilizing a 1000-watt on-grid Solar PV.

Table 10. Comparison of the CBA before and after improvement

Method	Existing Condition	Improvement Condition
NPV	Rp 58,781,312	Rp 473,823,045
IRR	9%	19%
Payback Period	5,52	5,52
BC Ratio	1,40	2,68
BEP (in Units)	2,136.34	2,371.71
BEP (in Rupiah)	Rp 534,084,829.96	Rp 592,927,678.52

The NPV for both conditions is greater than 0 (>0), indicating feasibility. The NPV after the improvement increased significantly based on projections of an increase in production capacity from 100 to 200 pieces of ecoprint fabric per month following the implementation of Solar PV, particularly in the steaming process. The annual revenue under the existing condition was estimated based on the selected MSME's actual production capacity of 5 ecoprint fabric sheets per day and an average selling price of Rp. 250,000 per sheet. Assuming 20 working days per month, the selected MSME produces approximately 100 sheets per month, generating monthly revenue of Rp 25,000,000. Accordingly, the annual revenue was estimated at Rp. 300,000,000 and was used as the basis for the economic feasibility analysis.

The projected revenue of Rp 600,000,000 in the ninth year is supported by the historical growth trend of Indonesia's textile and apparel industry. According to data published by the Ministry of Industry of the Republic of Indonesia (Kemenperin), the textile and apparel industry recorded a growth rate of 8.73% in 2018, surpassing the national economic growth rate of 5.17% in the same year [33]. Applying this growth rate to the existing baseline revenue of Rp 300,000,000, the projected revenue by the ninth year reaches approximately Rp 637,000,000, as detailed in Table 11, indicating that the assumed revenue of Rp 600,000,000 is in fact a conservative estimate within this growth trajectory.

Table 11. Revenue forecast based on 8.73% annual growth rate of Indonesia's textile and apparel industry

Year	Projected Revenue (IDR)
1	326,190,000
2	354,666,387
3	385,628,763
4	419,294,154
5	455,898,533
6	495,698,475
7	538,972,952
8	586,025,291
9	637,185,299
10	692,811,575

This conversion scenario is projected to take place in the ninth year, based on the potential for increased production capacity supported by an electric evaporation system, market demand, and the company's historical sales growth trends, which indicate opportunities for business expansion. It should be noted that the projected revenue of Rp 600,000,000 represents a conservative scenario; even under a moderate growth assumption, the projected revenue by year nine exceeds this figure, suggesting that the investment remains feasible even under more cautious projections. Additionally, the implementation of Solar PV is expected to reduce reliance on LPG and operational constraints related to energy shortages. Similarly, the IRR, which is greater than the interest rate (6%), is also considered feasible, increasing from 9% to 19%. The PP for both conditions is relatively similar, at around 5.5 years, because the cash flow in the pre-improvement (existing condition) is less than 9 years of operation, contributing positively. Therefore, installing an electric stove using solar power plants does not negatively impact overall cash flow; instead, it will increase revenue due to increased production and sales capacity. For both conditions, the BCR is above 1, indicating feasibility. Meanwhile, the BEP, both in units and Rupiah, does not differ significantly. For the existing condition, the minimum number of units sold to recover the investment capital is 2,136 units, with a value of Rp 534,084,829.96, while 2,371 units in their improved condition were sold for Rp 592,927,678.52.

4.3.4. LCA-CBA Analysis

The LCA-CBA analysis was conducted by considering the results of the LCA and CBA to provide complementary environmental and economic perspectives. LCA results are used to identify environmental hotspots and evaluate the environmental implications of the proposed improvement scenario, while CBA results are used to assess their economic feasibility and financial performance. By considering environmental and economic aspects simultaneously, this analysis provides a broader perspective for evaluating the sustainability implications of the proposed improvement scenario. To facilitate the interpretation of these findings, Table 12 presents a summary of the environmental and economic assessment results and their implications for sustainability-oriented decision-making.

Table 12. Summary of environmental and economic findings from the LCA-CBA analysis

Assessment Dimension	Key Findings	Interpretation
Environmental Assessment (LCA)	Fossil Depletion decreased (0.00076 to 0.00062); Climate Change-Human Health decreased (0.000359 to 0.000316); Human Toxicity increased (9.56E-05 to 0.00164).	The implementation of Solar PV reduces impacts in the Fossil Depletion and Climate Change-Human Health categories, while the increase in Human Toxicity indicates environmental trade-offs.
Economic Assessment (CBA)	NPV increased (Rp 58,781,312 to Rp 473,823,045); IRR increased (9% to 19%); BCR increased (1,40 to 2,68).	The proposed improvement scenario is economically feasible and provides improved long-term financial performance than the existing condition.
Sustainability Consideration	Environmental benefits and trade-offs identified through LCA; economic feasibility evaluated through CBA.	Environmental and economic assessments provide complementary insights for sustainability-oriented decision-making.

Several previous studies have emphasized the importance of integrating environmental and economic aspects simultaneously to support a more comprehensive evaluation of sustainability. For example, Bruno et al [34] on anaerobic digestion (AD) facilities in Italy applied LCA and CBA as complementary approaches, in which environmental impacts were identified through LCA and evaluated alongside economic feasibility through CBA. Similarly, Lam et al [35] on food waste management at Hong Kong International Airport employed both LCA and CBA and helped identify improvement strategies capable of balancing environmental performance and economic viability. These findings underscore the importance of considering environmental and economic aspects simultaneously when evaluating sustainability improvement efforts.

The environmental assessment reveals both benefits and trade-offs arising from the proposed improvement condition, while the economic assessment indicates that the investment remains financially viable. In this context, the results of the LCA and CBA provide complementary perspectives to support more comprehensive and balanced decision-making for the selected MSME in adopting more sustainable production practices. Beyond environmental and economic aspects, the proposed energy transition has the potential to deliver social benefits. Reducing LPG use can lower exposure to emissions associated with fossil fuel-based energy sources that may affect health and workplace safety [36], while the implementation of Solar PV can support capacity building for MSME operators and strengthen local energy resilience. These implications suggest that the proposed improvement condition is not only relevant from environmental and economic perspectives but also has the potential to provide social benefits that support the broader sustainability of the selected MSME.

4.4. Uncertainty and Sensitivity Considerations

Uncertainty is inherent in LCA, particularly in small-scale MSME case studies where primary data availability and analytical tools are limited. In this study, formal quantitative uncertainty and sensitivity analyses were not conducted due to the absence of specialized software and probabilistic input data. Nevertheless, uncertainty in LCA results is addressed qualitatively through a scenario-based sensitivity consideration of key input parameters. Energy consumption and raw material usage are identified as the most influential contributors to environmental impacts across the assessed life cycle stages. Variations in these parameters may affect the magnitude of environmental impacts; however, this qualitative assessment supports the interpretation of dominant impact sources within the defined system boundaries. Future studies are recommended to apply quantitative sensitivity or uncertainty analysis methods to further enhance the robustness.

Economic evaluation using CBA is also subject to uncertainty, particularly with respect to financial assumptions and market-related parameters. To address this, a quantitative sensitivity analysis was conducted by varying the most influential parameter in the CBA model: production volume. This parameter was selected because it directly determines annual inflow, which has the greatest impact on NPV and IRR outcomes. Three scenarios were defined to test the robustness of the projected improvement condition: optimistic (200 pcs/month, representing full capacity utilization after Solar PV implementation), moderate (150 pcs/month, representing 75% of target capacity), and pessimistic (100 pcs/month, representing no capacity increase from the existing condition). The results are presented in Table 13.

Table 13. Sensitivity analysis of production volume on CBA outcomes

Scenario (Production Volume)	Annual Inflow (IDR)	Cash Flow Year 9 (IDR)	NPV (IDR)	Feasibility
200 pcs/month	600,000,000	376,228,000	143,626,014	Yes
150 pcs/month	450,000,000	226,228,000	80,011,371	Yes
100 pcs/month	300,000,000	76,228,000	16,396,729	Yes

As presented in Table 13, varying production volume from 100 to 200 pieces per month results in NPV ranging from Rp 16,396,729 to Rp 143,626,014. Notably, even in the pessimistic scenario where no capacity increase occurs, the NPV remains positive. This is partly attributable to the accumulated positive cash flows generated during years 1 - 8 under the existing condition (∑NPV = Rp 58,781,312), which already contribute substantially toward recovering the initial investment prior to the improvement scenario in year nine. As a result, even the pessimistic scenario, where production volume and inflow remain unchanged from the existing condition, generates a marginal but positive NPV, confirming the baseline viability of the investment independent of the improvement outcome. This demonstrates that the feasibility conclusion is not solely dependent on the optimistic revenue assumption of Rp 600,000,000, but holds across a range of production outcomes. Sensitivity testing for energy prices and discount rates was not conducted quantitatively due to data constraints on detailed energy cost components. However, it is acknowledged that variations in these parameters may influence NPV and IRR outcomes. The implementation of Solar PV is expected to reduce energy-related costs, which would further improve cash flow beyond the projections presented. Future studies are recommended to incorporate quantitative sensitivity testing across a broader range of parameters to further strengthen the robustness of the economic analysis.

4.5. Social Sustainability Considerations

Although this study primarily focuses on environmental and economic sustainability through LCA and CBA, social sustainability aspects are also considered qualitatively. Due to the case-study design and the absence of primary quantitative social data, these aspects are not measured numerically but are discussed systematically based on field observations and relevant literature. In the selected MSME, ecoprint fabric production relies on manual and skill-based processes, contributing to skill development and craftsmanship preservation. The selected MSME provides employment opportunities for local residents, with significant participation of women, reflecting the inclusive nature of small-scale creative enterprises. Furthermore, the use of locally sourced natural dyes and materials strengthens community engagement and supports local livelihoods. These social dimensions complement the environmental and economic sustainability of the selected MSME, although future studies are recommended to incorporate quantitative social indicators or a Social Life Cycle Assessment (S-LCA) approach for a more comprehensive sustainability evaluation.

5. CONCLUSION

Based on the results of the LCA, the steaming process was identified as the stage with the greatest environmental impact in the production of ecoprint fabric. In the improvement scenario, substituting LPG with Solar PV reduces impacts in the Fossil Depletion category (0.00076 to 0.00062) and Climate Change – Human Health (0.000359 to 0.000316). However, the impact in the Human Toxicity category increased (9.56E-05 to 0.00164), reflecting the environmental impacts associated with the materials and manufacturing processes of photovoltaic components. These findings indicate that the implementation of Solar PV can reduce the environmental burden in several impact categories, but also involves environmental trade-offs that need to be considered in sustainability evaluations.

Furthermore, based on the results of the CBA, the existing conditions have demonstrated economic viability with an NPV of Rp 58,781,312, an IRR of 9%, a BEP of 2,136 units (Rp 534,084,829.96), a PP of 5.52 years, and a BCR of 1.40. Meanwhile, the improved scenario demonstrates better economic performance with an NPV of Rp 473,823,045, an IRR of 19%, a BEP of 2,371 units (Rp 592,927,678.52), a PP of 5.52 years, and a BCR of 2.68. These results indicate that the proposed energy transition has the potential to improve economic performance and strengthen the long-term financial viability of the selected MSME.

Overall, the results of the LCA-CBA analysis indicate that Solar PV can be considered a promising alternative to support the sustainability of ecoprint fabric MSMEs, as it provides environmental benefits across several impact categories while improving economic performance. However, the increased impact in the Human Toxicity category suggests that these benefits are accompanied by environmental trade-offs that must be considered in decision-making. Given that this study is based on a single MSME case study and uses scenario-based economic assumptions, the results should be interpreted with caution. Further research is recommended to include a broader data scope and quantitative sensitivity analysis to enhance the robustness of the sustainability assessment results.

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DECLARATION OF AI-TOOL USAGE

The authors used ChatGPT (OpenAI) and DeepL Translator to assist with language editing, grammar checking, and improving the clarity and readability of the manuscript. All content has been reviewed and revised by the authors. The authors take full responsibility for the accuracy and originality of the work.