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A Circular and Sustainable Planning Framework for Supply Chain Optimization: Integrating Lean Practices and Life Cycle Assessment Using Sustainable Value Stream Mapping

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ABSTRACT

The increasing environmental burden of manufacturing industries necessitates integrated planning approaches that simultaneously enhance operational performance and environmental sustainability. This study proposes a sustainable supply chain planning framework by integrating Lean Manufacturing and cradle-to-grave Life Cycle Assessment (LCA) through Sustainable Supply Chain Value Stream Mapping (Sus-SC-VSM). The framework enables the alignment of process-level efficiency with life-cycle environmental impacts, providing a structured basis for data-driven planning and evidence-based decision-making. The proposed framework is empirically validated in a batik manufacturing supply chain, a resource-intensive SME sector with significant environmental implications. The results demonstrate substantial operational improvements, including a reduction in lead time from 39,158.78 s to 30,083.86 s (−23.17%), a decrease in non-value added (NVA) time by 89.82%, a reduction in transportation delays by 45.33%, and a decrease in queue/idle time from 4 h 32 m to 2 h 03 m. Process cycle efficiency improves from 58.3% to 75.4%. From an environmental perspective, the LCA results indicate significant impact reductions, including approximately 20% in climate change (GWP), 80–90% in acidification, 85–95% in ecotoxicity, and 90–95% in eutrophication, with moderate improvements in land use (0–10%). These findings highlight the effectiveness of the integrated framework in identifying environmental hotspots and prioritizing sustainability interventions. This study contributes by providing a replicable and decision-oriented planning tool that supports sustainable supply chain management. Furthermore, the framework offers practical implications for policymakers and industry practitioners in designing sustainability strategies, improving resource efficiency, and advancing circular economy implementation in SME-based production systems.

1. INTRODUCTION

The increasing environmental pressure on manufacturing industries requires integrated approaches that simultaneously enhance operational efficiency and environmental sustainability. In today's highly competitive and resource-constrained environment, manufacturers must continuously adapt and improve to meet both operational and environmental demands [1, 2]. In particular, resource-intensive sectors such as textile manufacturing, including batik production, face significant challenges related to water consumption, chemical use, and energy intensity. These challenges highlight the need for structured planning frameworks that can support sustainable supply chain transformation and guide decision-making at both operational and strategic levels.

Lean Manufacturing has been widely adopted to improve operational performance by eliminating non-value added (NVA) activities and optimizing process flow. By reducing waste and improving efficiency, Lean enables organizations to minimize costs and create value [3]. However, its application is typically limited to internal process optimization and does not fully account for environmental impacts beyond the production stage. In contrast, Life Cycle Assessment (LCA) provides a comprehensive evaluation of environmental impacts across the entire product life cycle, from raw material extraction to end-of-life disposal. Despite its strengths, LCA is rarely integrated into operational and planning decision-making processes. The combination of Lean and LCA offers the potential to balance efficiency and sustainability while supporting more informed and structured planning in manufacturing systems [4].

Global sustainability policies have intensified pressure on industries to reduce greenhouse gas emissions, improve resource efficiency, and adopt environmentally responsible production systems [5-7]. Among industrial sectors, textiles remain one of the most environmentally damaging due to their chemical-intensive processes and high water consumption [8-13]. Despite this environmental burden, the textile sector—particularly through small and medium-sized enterprises (SMEs)—continues to play a pivotal economic role, contributing over 60.5% to global GDP and serving as a critical node in international value chains [14-16]. The batik industry, as a culturally significant textile subsector, exemplifies this dual challenge of economic importance and environmental degradation, making it a relevant context for developing sustainable supply chain planning approaches [17].

To address these challenges, the integration of Lean Manufacturing and LCA presents a promising strategy for improving both operational and environmental performance. Lean Manufacturing enables the reduction of waste, optimization of resource usage, and improvement of production efficiency, thereby contributing to lower environmental impacts [18-20]. Lean principles, originally developed by Toyota Motor Corporation, have proven effective in optimizing production processes and enhancing value creation across industries [21, 22]. When combined with LCA, these approaches can support more comprehensive and data-driven planning by linking process-level improvements with life-cycle environmental impacts, thereby enabling more effective prioritization of sustainability interventions across supply chains [23].

Despite the growing body of research, existing studies remain fragmented. Lean-based Value Stream Mapping (VSM) is generally applied within gate-to-gate boundaries and focuses on operational efficiency, while LCA studies often lack integration with operational and planning decision-making across supply chains [24]. This limitation is particularly evident in SMEs, where constraints in resources and data availability hinder the implementation of integrated sustainability strategies. Furthermore, applications in textile SMEs, especially batik production systems, remain limited despite their significant environmental footprint. As a result, there is a critical need for an integrated planning-oriented framework that links operational efficiency with full life-cycle environmental performance to support sustainable supply chain decision-making [25].

To address this gap, this study proposes an integrated sustainable supply chain planning framework by combining Lean Manufacturing and cradle-to-grave LCA through Sustainable Supply Chain Value Stream Mapping (Sus-SC-VSM). The framework enables simultaneous evaluation of operational performance and environmental impacts, allowing decision-makers to identify inefficiencies and environmental hotspots across the entire supply chain while supporting evidence-based planning [26].

The proposed framework is validated through a case study in batik SMEs, demonstrating its capability to reduce lead time, minimize NVA activities, and significantly decrease environmental impacts. This study contributes by providing a structured, data-driven planning tool that supports sustainable supply chain optimization and offers practical insights for policymakers and SME stakeholders in designing more sustainable and resilient production systems.

2. LITERATURE REVIEW

2.1 Lean Manufacturing and Value Stream Mapping

Lean Manufacturing focuses on eliminating waste and improving process efficiency through continuous improvement. VSM is one of the most widely used tools to visualize material and information flow, identify NVA activities, and support process optimization. Previous studies have demonstrated the effectiveness of VSM in improving productivity and reducing lead time across various industries, including manufacturing and SMEs. However, most applications are limited to operational efficiency within production boundaries and do not incorporate environmental considerations. Aucasime-Gonzales et al. [27] used Lean Manufacturing to improve efficiency at a tire company. Additionally, Lean Manufacturing has also been implemented in an electrical component company to reduce waste in the production process [28]. Alfiansyah and Kurniati [29] also applied the waste assessment model (WAM) in Lean Manufacturing to identify waste and Setiawan and Rahman [30] used the method and found that the largest waste occurred in product defects (16.49%), transportation (16.36%), and process (14.82%).

In addition to large industries, Lean Manufacturing can also be applied to Small Medium Enterprises (SMEs) [31], especially in textile industry showed that Lean Manufacturing, along with methods like 5S, kanban, kaizen, poka-yoke, and visual control, can minimize production waste [32]. Thus, based on the literature review, there is an opportunity for implementing Lean Manufacturing methods in SMEs in the textile sector [33, 34].

As sustainability agendas gain momentum, VSM has evolved into Green or Environmental Value Stream Mapping (GVSM), incorporating environmental indicators such as energy, water, emissions, and waste [35-37] and the social dimension has gained attention through the development of Social Value Stream Mapping (Socio-VSM) [38, 39].

At the supply chain level, Supply Chain Value Stream Mapping (SCVSM) expands the mapping boundary from the shop floor to the end-to-end supply chain. Batwara et al. [40] designed a framework for supply chain optimization based on lean principles, while Nikneshan et al. [41] proposed a framework to analyze the influence of lean and agile innovation on lean-agile supply chains.

From the above review, it is evident that research on Sus-SC-VSM which integrates economic, environmental, and social indicators across supply chains remains limited. This gap is particularly striking in the context of Batik SMEs, which are characterized by multi-tier suppliers, resource-intensive dyeing processes (chemicals, water, energy), and locally embedded distribution networks. Therefore, this study proposes the development of a sustainability-oriented VSM framework for Batik SME supply chains, aiming to bridge the gap between process efficiency, environmental sustainability, and social well-being.

2.2 Life Cycle Assessment for environmental evaluation

LCA is a standardized method (ISO 14040) used to evaluate environmental impacts across the entire life cycle of a product. It enables identification of environmental hotspots such as greenhouse gas emissions, water use, and toxicity. While LCA has been widely applied in industrial sectors, most studies focus on partial system boundaries (e.g., cradle-to-gate or gate-to-gate), and only a limited number adopt a comprehensive cradle-to-grave approach. In addition, LCA is often conducted independently of operational decision-making processes.

Previous studies have demonstrated the versatility of LCA across diverse industrial sectors. For example, Salvador et al. [36] applied cradle-to-gate LCA in assessing the environmental performance of a manufacturer of tools and painting materials as well as a steel pipe manufacturer. Similarly, Vauche et al. [42] implemented a cradle-to-gate LCA for gallium nitride (GaN) power semiconductor devices, while Risner et al. [43] adopted the same scope for cultured meat. In the palm oil sector, Bantacut et al. [44] applied a gate-to-gate LCA on crude palm oil processing in palm mills, highlighting the environmental implications of specific stages of production. Sodha et al. [45] also applied a gate-to-gate LCA in the marble processing industry, and Enarevba and Haapala [46] extended the scope to a gate-to-grave LCA in assessing polystyrene and mycelium-based packaging inserts.

Despite these efforts, relatively few studies have pursued the more comprehensive cradle-to-grave LCA approach, which accounts for impacts from raw material extraction through production, use, and end-of-life [47-49]. These cradle-to-grave studies remain the exception rather than the norm, as most research continues to focus on narrower scopes such as cradle-to-gate or gate-to-gate assessments.

More importantly, within the textile sector, and especially among SMEs such as Batik production, comprehensive LCA studies are still lacking. Existing literature predominantly addresses large-scale industrial contexts, leaving a significant research gap in understanding the environmental implications of traditional and resource-intensive textile SMEs. Batik production, with its multi-stage processes (e.g., waxing, dyeing, washing, and finishing), high reliance on chemicals, water, and energy, and localized supply chain networks, represents a unique case that warrants a full cradle-to-grave LCA approach. Such research is critical not only to quantify environmental impacts but also to propose sustainable interventions tailored to the needs and constraints of SMEs.

LCA has become an essential tool in evaluating the efficiency, effectiveness, and environmental impacts of production systems. Numerous studies have applied LCA to large-scale manufacturing and resource-intensive sectors, such as manufacturing of tools and steel pipes [36], GaN power semiconductors [42], crude palm oil processing [44], cultured meat [43], marble processing [45], and packaging materials such as polystyrene and mycelium inserts [46]. In the energy and materials sectors, research has extended to biodegradable plastics [47], urological procedures in healthcare [48], and LNG carriers [49], with some adopting a cradle-to-grave approach. These studies underscore the importance of comprehensive environmental evaluations, yet they also reveal a concentration of research in heavy industries, agribusiness, food production, and large-scale energy systems. Parallel to this, VSM and its extensions have also been applied in a variety of industrial contexts to improve productivity and reduce waste [27, 29, 50-53].

By contrast, textile SMEs particularly Batik production remain largely overlooked in both LCA and VSM research. Batik production is characterized by multi-step processes (waxing, dyeing, washing, and finishing), intensive use of chemicals, high water and energy consumption, and localized supply chain networks. These characteristics make Batik SMEs not only resource-demanding but also environmentally impactful, while at the same time facing constraints in technology adoption and managerial capacity. Unlike large industries that have been studied extensively, SMEs such as Batik producers lack comprehensive assessments that combine efficiency, effectiveness, and environmental performance within a life cycle perspective.

This research gap highlights the urgent need to conduct LCA and VSM in Batik SMEs. A full life cycle approach would allow for identifying hotspots of inefficiency and environmental burden, while also providing actionable insights for improving resource efficiency and sustainability performance. Such studies are critical to ensure that traditional and cultural industries like Batik can align with broader sustainability goals, while maintaining their competitiveness in both domestic and global markets.

To address this gap, the present study proposes a sustainable supply chain planning framework, namely Sus-SC-VSM, which integrates Lean Manufacturing and cradle-to-grave LCA. The framework operationalizes the linkage between process efficiency and environmental performance by embedding life-cycle impact indicators into value stream analysis. In doing so, it transforms conventional mapping tools into a measurable and decision-oriented mechanism that supports the identification of inefficiencies and environmental hotspots across the supply chain.

This study contributes to the literature by addressing the fragmentation between operational efficiency and environmental assessment approaches, offering an integrated and replicable framework for sustainable supply chain planning. Furthermore, it provides practical implications for industries and policymakers by supporting evidence-based decision-making and facilitating the design of more sustainable and resilient production systems.

2.3 State of the art

Table 1 presents the state of the art in VSM evolution, illustrating a clear progression from traditional lean-based mapping toward sustainability-oriented variants. Despite extensive research on Lean Manufacturing and LCA, existing studies remain fragmented. Lean-based approaches primarily focus on process efficiency without considering full life-cycle environmental impacts, while LCA studies rarely provide actionable insights for operational improvements. Furthermore, the integration of these approaches in SME-based textile industries, particularly batik production, remains limited. This highlights the need for an integrated framework that links operational performance with environmental sustainability across the entire supply chain.

Therefore, this study develops a Sus-SC-VSM framework that integrates Lean Manufacturing with cradle-to-grave LCA to support data-driven planning and sustainable supply chain optimization. The novelty of this study is the introduction of an integrated Sustainable Supply Chain Value Stream Mapping (SSC-VSM) combined with cradle-to-grave LCA as a single decision-grade artefact. Substantively, this study advances the field by implementing the integrated approach in textile SMEs, a sector that is highly fragmented, data-sparse, and understudied in sustainability-oriented supply-chain research.

Prior studies, as summarized in Table 1, largely fall into two disconnected streams:

(i) VSM/Green-VSM applications limited to Gate-to-Gate analyses focusing primarily on operational flow, or

(ii) LCAs conducted across full life-cycle boundaries without linking environmental impacts to the operational logic of the supply chain.

This study bridges these siloed research traditions by embedding downstream logistics, material flows, and end-of-life processes into one SSC-VSM representation where takt time, lead time, inventories, and transport paths coexist with GWP, eutrophication, ozone depletion, energy use, and other life-cycle indicators. This resolves a long-standing gap: Lean tools rarely guide life-cycle decisions beyond the factory boundary, while full-boundary LCAs rarely inform Lean countermeasures or multi-tier operational redesign. Methodologically, the research contributes a structured analytics pipeline that:

(1) Assigns node- and edge-level environmental loads directly to SSC-VSM objects,

(2) Establishes hotspot–waste linkages (e.g., transport emissions ↔ transport/waiting waste; eutrophication ↔ material/design waste),

(3) Evaluates intervention portfolios (EV-based logistics, water/dye recirculation, wax substitution) through multi-objective scenario scoring that jointly tracks time-based KPIs and environmental indicators. This produces a unified data model and decision workflow driven template for converting life-cycle information into actionable operational levers with transparent attribution across supply-chain segments.

Table 1. Summary of related works from pre-existing literature and the proposed research

Ref.	**Lean Practices: Value Stream Mapping**					**Life Cycle Assessment**				**Integrating Lean and LCA for Sustainability**	**Industry**
	VSM	**Social VSM**	**Green VSM**	**Supply Chain VSM**	**Sustainable Supply Chain VSM**	**Cradle-to-Gate**	**Gate-to-Gate**	**Gate-to-Grave**	**Cradle-to-Grave**		
[33]	✓										Manufacturing
[40]	✓										-
[34]	✓										Manufacturing
[39]		✓									Occupational health and work environment with socio
[38]		✓									Manufacturing
[35]			✓								LPJ
[36]			✓			✓				✓	A manufacturer of tools and painting materials
[50]			✓								Agribusiness
[37]			✓								Agri-food sector
[41]				✓							Pharmaceutical companies
[51]			✓								-
[42]						✓					GaN power semiconductor device
[44]							✓				Crude palm oil in palm mills
[43]						✓					Cultured meat
[47]									✓		Biodegradable plastics
[45]							✓				Marble processing industry
[48]									✓		Urological procedures
[49]									✓		LNG carrier
[46]								✓			Polystyrene and mycelium packaging box inserts
This Study					✓	✓				✓	**Textile SMEs (Batik Production)**

3. METHODOLOGY

This study employs an integrated approach combining Lean Manufacturing and LCA to develop a sustainable supply chain planning framework. Figure 1 presents a cross-functional workflow that integrates Lean Manufacturing analytics with LCA to design and evaluate a sustainable future state for the batik supply chain. The workflow embodies a logic by combining operational, environmental, and improvement knowledge streams into a unified decision-making architecture. The method runs through three synchronized "lanes": (i) Lean mapping material and time flows; (ii) LCA quantifying environmental loads across the life cycle; and (iii) Improvement screening and adopting cleaner-production options. A single process list and ID schema is maintained so that each operation and transport leg appears simultaneously on the value stream map and in the LCA inventory, enabling one-to-one attribution of time and waste.

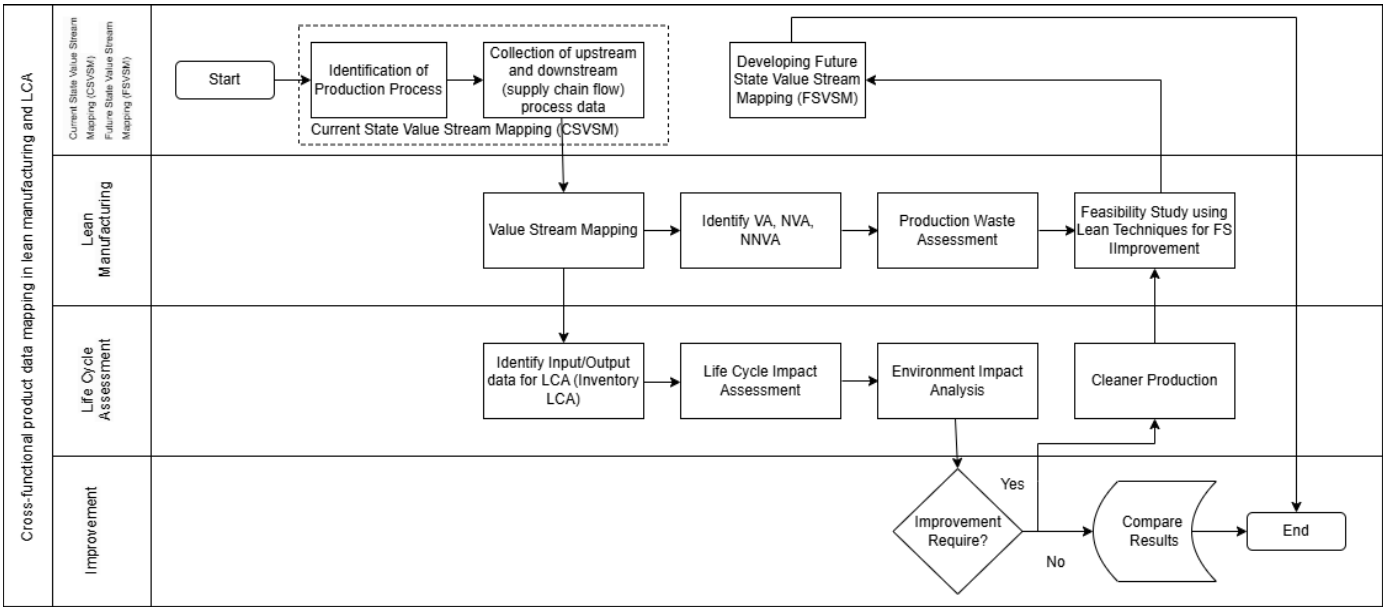

Figure 1. The proposed circular and sustainable framework integrating lean practices with Life Cycle Assessment (LCA) to optimize sustainable supply chain operations

Furthermore, LCA quantifies the environmental burdens associated with producing, delivering, and disposing of batik cloth at end-of-life. The functional unit (FU) is one standard batik cloth (≈ 2.5 m × 1.15 m; ~2.9 m²) delivered to a boutique, with a sensitivity check using 1 m² to benchmark against textile LCAs. Results are reported per FU. Impact categories include GWP, Ozone Depletion Potential (ODP), acidification, photochemical oxidant formation, freshwater ecotoxicity, water use, land-use change, eutrophication, and cumulative energy demand. Through an innovation–enabled linkage mechanism, each node and edge in the value stream map carries its corresponding life-cycle inventory so that downstream logistics, wax removal, and dyeing steps can be traced as environmental hotspots and directly connected to Lean wastes and intervention levers such as EV transport, dye/water recirculation, and wax substitution. Future-state scenarios (EV logistics, cleaner production technologies, and material substitution) are evaluated through this integrated workflow, ensuring consistency between the VSM and LCA modules and enabling collaboration.

The proposed framework for reassessing the environmental impact of product flows is illustrated in Figure 1. Lean practices enable companies, including SMEs, to optimize product management across its entire lifecycle, encompassing aspects such as material needs, scheduling, process flows, waste management, and environmental impact reduction. VSM is crucial in identifying non-value-adding activities, such as time inefficiencies at various stages of production. It visually represents material flows and measures material usage throughout the production process, especially when integrated with other lean tools like cellular manufacturing, 5S, and Kanban systems [54].

Following this, the LCA system evaluates environmental impacts using industry data, which includes energy consumption, process durations, and production inputs and outputs. The integration of Lean practices with LCA provides a holistic approach to enhancing environmental sustainability throughout supply chain operations.

3.1 Data collection and Life Cycle Assessment

Primary data were collected through direct observation, interviews with SME owners and workers, and time measurements of each production activity (Table 2). Secondary data were obtained from relevant literature and LCA databases. The FU used in this study is one piece of batik cloth (approximately 2.9 m²).

3.2 Integration of Value Stream Mapping and Life Cycle Assessment

VSM plays a pivotal role in identifying both input and output data, including types and material requirements, total material weight, and energy needs for processes. These data are then used as inputs for LCA. Figure 2 illustrates the system boundaries for assessing the Small Medium Enterprises (SMEs) Textile (Batik) process. The detailed input–output components included within the LCA system boundary are presented in Table 3. LCA focuses on cradle-to-grave analysis, encompassing the entire process flow from upstream to downstream and ultimately through the product disposal stage.

Table 2. Quantitative summary of Life Cycle Inventory (LCI) for batik production (per functional unit)

Stage	Process	Input (Quantity)	Output (Quantity)	Key Environmental Aspect
Upstream	Wax Production	Epoxy resin (1 kg), Paraffin (4 kg)	Wax (5 kg)	Chemical usage, energy
Upstream	Fabric Supply	Cotton fabric (1 m^2), Transport (100 kg·km)	Raw fabric (1 m^2)	Land use, transport emission
Core	Waxing (Cap/Tulis)	Fabric (1 m^2), Kerosene (0.20 kg), Wax (0.50 kg)	Patterned fabric (1 m^2), Wastewater (0.50 m^3), CO_2 emission	Air emission, wastewater
Core	Drying	Fabric (1 m^2), Water (0.05 m^3)	Dried fabric (1 m^2)	Water use
Core	Dyeing	Alpha-naphthol (0.10 kg), Water (0.20–0.50 m^3)	Dyed fabric (1 m^2), Wastewater (0.20 m^3)	Ecotoxicity hotspot
Core	Wax Removal	Water (0.50 m^3)	Clean fabric (1 m^2), Wastewater (0.50 m^3)	High water consumption
Core	Cutting	Fabric (1 m^2)	Fabric pieces (1 m^2), Solid waste (~3 kg)	Material waste
Core	Sewing	Fabric (1 m^2), Electricity (~19,200 Wh)	Garment (1 unit)	Energy consumption
Core	Finishing & QC	Fabric (1 m^2)	Finished product (1 unit)	Minor impact
Downstream	Distribution	Diesel (~100 kg·km equivalent)	Delivered product	CO_2, NO_x emissions
Downstream	Use Phase	Water (multiple cycles), Detergent	Washed fabric, Wastewater	Water use, eutrophication
Downstream	End-of-Life	Transport (to landfill)	CO_2 (~800 kg), CH_4 (~20 kg)	Landfill emission

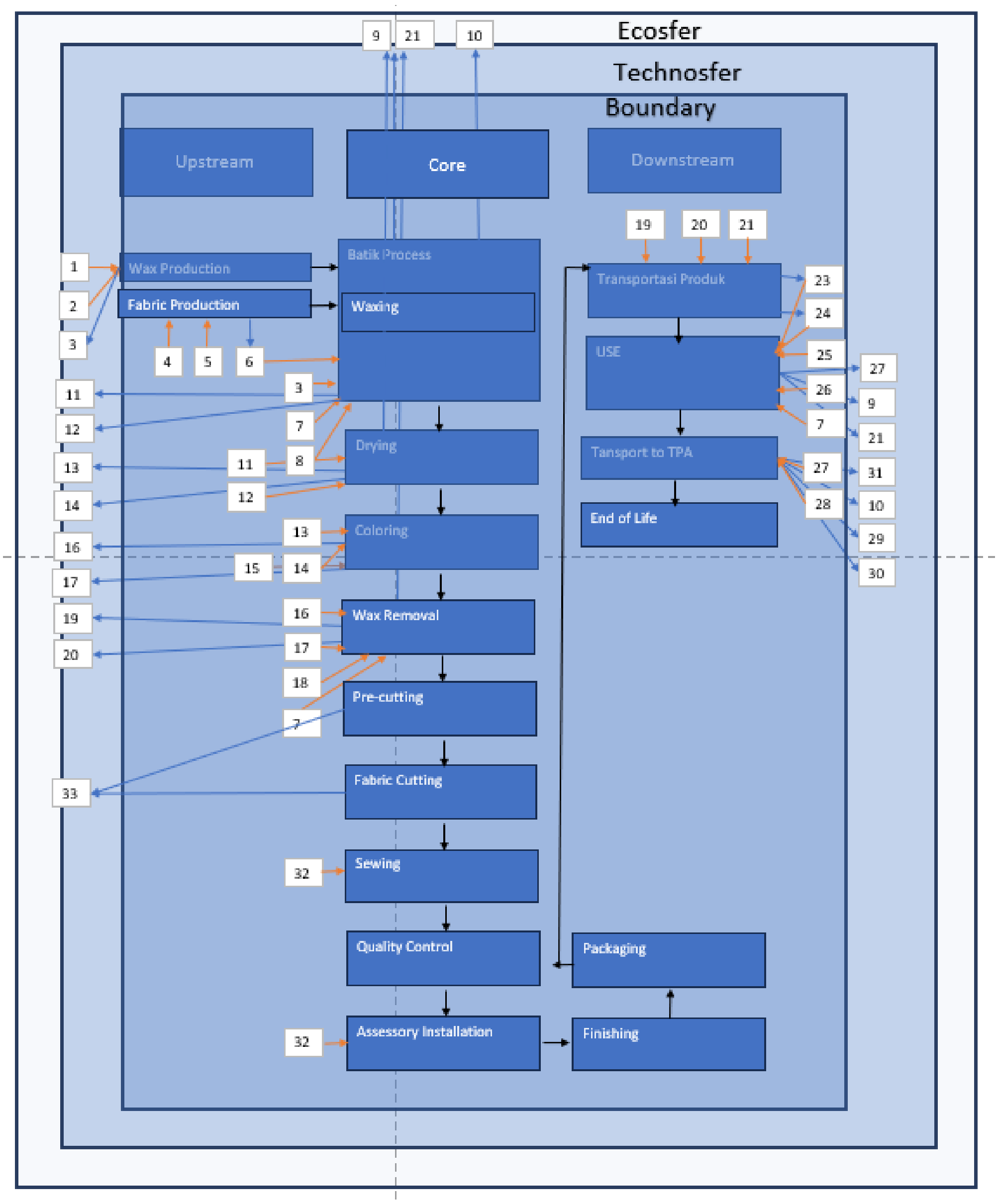

Figure 2. The Life Cycle Assessment (LCA) system boundary of batik production

Table 3. Input/output Life Cycle Assessment (LCA) system boundary of batik production

No.	Input/Output
1	Epoxy resin, liquid
2	Paraffin
3	Wax
4	Textile, woven cotton
5	Transport
6	Fabric from supplier
7	Water from PAM (tap water)
8	Kerosene
9	Wastewater from textile production
10	Carbon dioxide, fossil
11	Printed fabric
12	Written fabric
13	Printed fabric after drying
14	Written fabric after drying
15	Alpha naphthol
16	Printed fabric after dyeing
17	Written fabric after dyeing
18	Sodium bicarbonate
19	Printed fabric after decay
20	Written fabric after decay
21	Transport
22	COD
23	Printed fabric ready for sale
24	Written fabric ready for sale
25	Electricity
26	Soap
27	Used fabric
28	Diesel
29	Methane, fossil
30	Dinitrogen dioxide
31	Fabric transport to landfill (TPA)
32	Electricity
33	Fabric waste

Note: COD = Chemical Oxygen Demand

(1) Identification of process activity mapping (Value Added (VA), NVA, Necessary but Non-Value Added (NNVA)) and LCA inventory analysis

Production activities are thoroughly identified and classified into VA, NVA, and NNVA categories. Additionally, an inventory analysis of the life cycle is performed by describing the upstream to downstream process flow, analyzing inputs (materials and energy), process units, and outputs (primary products, other products, and production waste released into soil/water/air) for each production step.

(2) Assessment of production waste and Life Cycle Inventory (LCI)

Production processes typically involve various types of waste, such as overproduction, waiting times, excessive transportation, improper processing, unnecessary inventory, unnecessary motion, defects, and underutilized talent or behavior. Hence, analyzing and assessing production waste is crucial. Life Cycle Impact Assessment (LCIA) within the LCA phase evaluates environmental impacts such as global warming potential, ODP, acid rain potential, eutrophication potential, photochemical oxidants, abiotic depletion, carcinogenicity, toxicity, water footprint, and land use change [26].

(3) Current state value stream mapping (CSVSM) and environmental impact characterization

Modeling is carried out using VSM to provide a detailed overview of process times and map all activities (VA, NVA, NNVA). During this stage, LCA results are interpreted, and environmental impact characterization is performed. The process involves assessing and weighting the environmental impacts to identify key issues and environmental impact hotspots. This allows for process improvements aimed at reducing negative environmental effects.

(4) Development of production efficiency strategies and cleaner production improvement

The integration of Lean Manufacturing and LCA approaches guides the development of production efficiency strategies and resource optimization, along with cleaner production improvements. A framework for selecting the right strategy for process improvement will also be provided.

(5) Future state value stream mapping

Proposed improvements will be modeled into a visual Future State Value Stream Mapping (FSVSM), facilitating SMEs in achieving industrial sustainability and productivity improvements. This will also outline strategic steps for enhancing cleaner production and reducing environmental impacts.

Lean techniques are integrated into the visual flow mapping process for both CSVSM and Future State Value Stream Mapping (FSVSM) stages. The FSVSM analysis focuses on improving the current process cycle, recommending modifications to make the product more environmentally sustainable. OpenLCA software is used to analyze data from both the current and future state product flows and processes. Key impact categories considered include climate change (global warming potential), human toxicity, photochemical oxidant formation, terrestrial acidification, and terrestrial ecotoxicity [54]. A comparison between the current and future state results identifies potential areas for improvement in manufacturing processes to reduce environmental impacts.

3.3 Improvement scenarios

Future-state scenarios include process optimization, reduction of NVA activities, energy efficiency improvements, and cleaner production strategies such as water recirculation and alternative materials. These scenarios are evaluated using both VSM and LCA results.

3.4 Sensitivity analysis

A simple sensitivity analysis is conducted by varying key parameters such as energy consumption and transportation distance (± 10%) to evaluate the robustness of the results.

4. RESULT AND DISCUSSION

The batik industry in Indonesia, known for its rich cultural heritage, faces increasing challenges as environmental regulations and sustainability concerns gain global attention. With over 3 million metres of batik fabric produced annually, the sector exerts substantial pressure on resource consumption, waste generation, and energy use. As global demand for batik continues to rise, the depletion of natural resources and inefficient production patterns highlight an urgent need for innovation-driven approaches that ensure long-term sustainability.

To support this expanding demand, SMEs in the batik sector must adopt innovative and circularity and sustainable–oriented solutions to mitigate environmental risks related to energy consumption, waste generation, and raw material sourcing. Open innovation on circularity and sustainability is particularly relevant for SMEs that rely on shared knowledge, cross-industry learning, and collaborative problem-solving to overcome resource constraints. The integration of Lean Manufacturing and LCA provides a structured pathway for such innovation by combining operational efficiency with environmental intelligence. This supports emerging global trends in sustainable manufacturing, where waste materials are reintegrated as secondary resources and energy efficiency become a key competitive driver.

To systematically address these challenges, a LCA of the batik supply chain is conducted using a cradle-to-grave boundary. The LCA framework supported by open innovation principles through the use of shared databases, cross-sector insights, and locally contextualized sustainability metrics captures environmental impacts from raw material extraction through production and end-of-life. Complementing this, VSM is applied to evaluate each stage of batik production and identify sources of waste and inefficiency. By pinpointing overproduction, excessive transportation flows, unnecessary motion, and other NVA activities, VSM provides actionable insight into where innovation can be deployed to redesign processes. The integration of Lean tools enables the streamlining of production flows, the elimination of operational waste, and improved supply chain efficiency ultimately advancing a more sustainable, resilient, and innovation-oriented batik industry.

4.1 Current state Sustainable Supply Chain Value Stream Mapping

The current state Sus-SC-VSM provides an overview of the process times for each action, categorizing them into VA and NVA operations. In the manufacturing industry, activities are classified into three types: VA, NNVA, and NVA. VA activities are those that enhance the product's value and are essential to the process. NNVA activities are tasks that need to be performed but do not contribute to the product’s value essential but not value-generating. NVA activities are those that do not add any value and are considered waste, so they should be eliminated.

The current state mapping organizes activities into three categories: VA, NNVA, and NVA. VA activities contribute to the product’s value. Examples of NNVA activities include transportation and storage, which are essential but do not contribute value and may lead to waste. NVA activities, such as waiting and delays, do not contribute to value and should be minimized.

As shown in Figure 3, the total cycle time is 22,822.34 seconds, with the lead time for producing one garment from the batik creation process (hand-drawn batik) to completing the garment taking 39,158.78 seconds. Therefore, the Batik SMEs studied in this research require approximately 28.87 hours to produce a single batik product.

According to Table 4, operational activities account for 57% of the total production time, followed by delayed activities at 41.7%. Other activities include inspection (0.5%), transportation (0.78%), and storage (0.016%). These activities are then classified into three groups: VA, NNVA, and NVA. VA activities make up 75.88% of the total time, with operational activities being the largest portion. NNVA activities account for 19.16%, mostly involving transportation. NVA activities contribute 4.95%, mostly due to delays. To improve the productivity of the batik garment production system, NVA activities should be reduced or eliminated. The results from this comprehensive mapping study can serve as a foundation for recommending improvements.

Table 4. Production activity time

Activities	Total	Time (Second)	Percentage
Operation	21	22324.29	57.00967
Transportation	10	302.65	0.772879
Inspection	5	195.4	0.498994
Storage	1	6.07	0.015501
Delay	23	16330.37	41.70296
NVA	21	1939.89	4.953908
VA	28	29714.93	75.88319
NNVA	11	7503.96	19.16291
Cycle Time		22822.34	
Lead Time		39158.78	

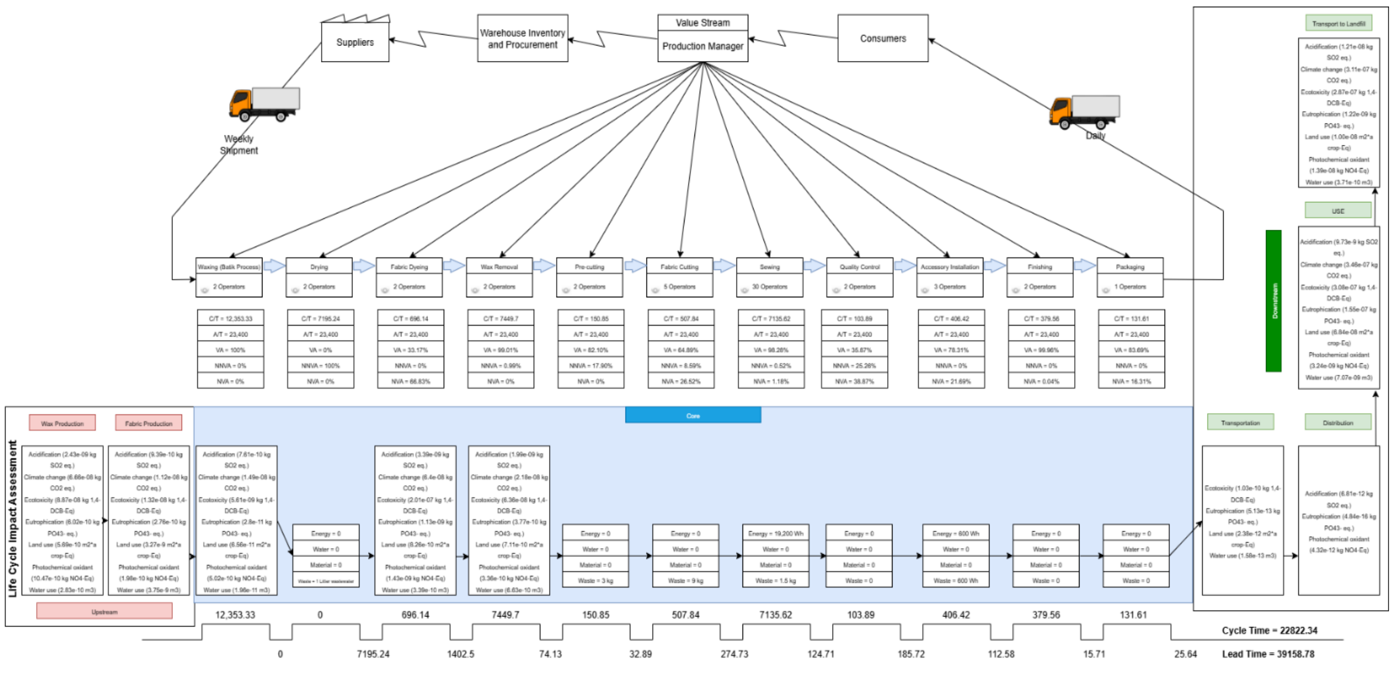

Figure 3. Current state Sustainable Supply Chain Value Stream Mapping (Sus-SC-VSM)

Analysis of the current production activity time:

(1) VA time vs lead time

The total VA time is substantial, with 28 activities contributing to 29,714.93 seconds or approximately 8.26 hours. However, the total lead time stretches to 39,158.78 seconds or approximately 10.87 hours. This indicates that the total time spent on NVA activities, such as delays and storage, significantly increases the overall lead time, which in turn reduces process efficiency.

(2) Excessive delay time

A significant portion of time, 16,330.37 seconds (41.70% of the total time), is spent on delay. This indicates a lack of flow within the system, leading to prolonged production times and delays in the overall process. Reducing this delay would be crucial to improving process efficiency and speeding up the overall cycle time.

(3) Inventory management and NVA

The Storage time, although minimal, contributes 0.0155% to the total time, but combined with NVA activities such as delayed, it suggests that better inventory management could help in streamlining the process and reducing time spent on unproductive activities.

(4) Transportation and inspection

Time spent on transportation (0.77%) and inspection (0.50%) indicate that there is room for optimization in terms of handling and quality checks. These activities are necessary, but they should be performed in a manner that minimizes their impact on the overall production time.

(5) Potential for improvement in VA

The VA activities, taking up 75.88% of the total time, suggest that the core processes in manufacturing are being performed efficiently. However, more coordination and streamlining of the NVA stages could free up valuable time for even greater productivity.

(6) Cycle time and lead time

With a cycle time of 22,822.34 seconds, which is significantly lower than the lead time of 39,158.78 seconds, there is considerable potential to reduce lead time through better coordination, waste reduction, and faster transitions between activities. This would allow the plant to meet demand more effectively while reducing idle time and associated costs.

4.1.1 Upstream supply chain

The upstream stage of the batik industry, which includes wax production and fabric production, reveals significant differences in their contributions to environmental impact categories based on LCIA. Of the seven categories analyzed, five are dominated by wax production. In the case of acidification, wax recorded 2.43e-09 kg SO_2 eq, considerably higher than fabric at 9.39e-10 kg SO_2 eq. This indicates that wax production, particularly through fossil fuel use for heating and melting, is more likely to release acidifying gases that contribute to acid rain.

Wax production also shows a greater contribution to climate change, with 6.66e-08 kg CO_2 eq compared to fabric at 1.12e-08 kg CO_2 eq. These greenhouse gas emissions are strongly linked to the energy-intensive thermal requirements of the process. For ecotoxicity, wax again dominates (8.87e-08 kg 1.4-DCB eq) compared to fabric (1.32e-08 kg 1.4-DCB eq), reflecting the higher potential for toxic chemical residues to be released into aquatic and terrestrial ecosystems due to additives used in wax production. Similarly, in terms of eutrophication, wax (6.02e-10 kg PO_4^{3-} eq) exceeds fabric (2.76e-10 kg PO_4^{3-} eq), likely related to wastewater containing phosphates from wax formulations. For photochemical oxidant formation, wax (10.47e-10 kg NO_x eq) is also higher than fabric (1.98e-10 kg NO_x eq), associated with ozone precursor emissions generated during heating.

Conversely, fabric production dominates two categories: land use and water use. Fabric recorded 3.27e-09 m^2a crop eq, much higher than wax at 5.69e-10 m^2a crop eq, primarily due to the reliance on natural fibers such as cotton that require large cultivation areas, as also noted in textile LCA studies [16]. In terms of water use, fabric reached 3.75e-09 m^3, significantly greater than wax at 2.83e-10 m^3. This elevated water demand stems from multiple fabric processing stages, including washing, bleaching, and pre-treatment before dying.

Overall, these findings highlight that wax production is more prominent in impact categories related to atmospheric emissions and chemical toxicity, while fabric production contributes substantially to resource-intensive categories such as land and water use. Strategically, this implies a dual intervention approach: first, optimizing energy efficiency and adopting environmentally friendly chemical substitutes in wax production; and second, improving water efficiency and promoting the use of sustainable textile fibers in fabric production. Such targeted mitigation strategies are crucial to reducing the overall environmental footprint of the batik industry.

4.1.2 Core supply chain (manufacturing-batik production)

The core processes of the batik industry consist of eleven activities: waxing (batik process), drying, fabric dyeing, wax removal, pre-cutting, fabric cutting, sewing, quality control, accessory installation, finishing, and packaging. The analysis indicates that out of these processes, only three activities contribute directly to environmental impact categories under the LCIA framework, namely waxing, fabric dyeing, and wax removal. Among them, fabric dyeing emerges as the primary hotspot, with the highest contribution across six major categories: acidification, climate change, ecotoxicity, eutrophication, land use, and photochemical oxidant formation. This finding aligns with previous research, which highlights dyeing as one of the most chemically and energy-intensive stages in textile production. The use of synthetic dyes, mordants, salts, and the thermal energy required for heating dye baths generates greenhouse gas emissions and significantly increases the potential for aquatic toxicity.

In contrast, the largest impact on water use is observed in the wax removal process, which requires substantial volumes of water for wax stripping, soaking, and multiple rinsing cycles. This is consistent with the traditional batik-making process, which is widely recognized as water-intensive. Waxing also contributes to environmental impacts, although to a lesser degree compared to fabric dyeing, primarily through the use of thermal energy for wax melting and the potential release of chemical additives.

The remaining core processes including drying, pre-cutting, fabric cutting, sewing, quality control, accessory installation, finishing, and packaging do not directly register significant impacts in LCIA categories. However, they still entail resource consumption and waste generation. Data reveal that the highest energy consumption occurs during sewing, reaching 19,200 Wh, with additional energy demand recorded in accessory installation (approximately 600 Wh). In terms of waste, drying generates around 1 liter of liquid residue, while pre-cutting and fabric cutting each produce about 3 kg of fabric scraps. The sewing process adds another 1.5 kg of waste, and accessory installation further contributes to the overall energy burden. These findings indicate opportunities for improvement through enhanced energy efficiency and solid waste management in cutting and sewing processes, which are in line with broader waste minimization strategies in the textile sector.

In addition, the activity analysis also reveals a relatively high proportion of NVA activities within several core processes (Figure 4). The fabric dyeing process records the highest NVA share at 66.83% with two operators, followed by quality control at 38.87% with two operators, and fabric cutting at 26.52% with five operators. The high NVA percentage in fabric dyeing is primarily associated with waiting times during soaking, recipe adjustments, and inter-bath queuing. In fabric cutting, NVA arises from inefficient pattern layout, excessive material handling, and time spent searching for tools. Meanwhile, in quality control, NVA is linked to over-inspection practices and waiting times between lots.

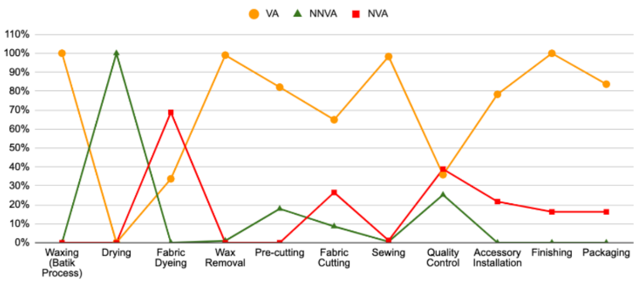

Figure 4. Value Added (VA), Necessary but Non-Value Added (NNVA), and Non-Value Added (NVA) percentage on processes

These findings underscore the importance of Lean Manufacturing interventions to reduce NVA activities, as also emphasized by prior studies in the textile and garment sectors. Relevant approaches include standardizing dyeing recipes and adopting low-liquor-ratio dyeing technologies to reduce waiting and resource use, enhancing marker efficiency in cutting operations to minimize fabric waste, and applying poka-yoke mechanisms to prevent defects at earlier stages, thereby reducing the burden of downstream inspection.

Overall, the analysis of the core stage highlights fabric dyeing as the critical hotspot with the greatest environmental impact, while wax removal dominates water consumption. At the same time, processes such as sewing, cutting, and quality control emerge as significant contributors to energy consumption, material waste, and high levels of NVA activities. Consequently, targeted improvement strategies focusing on process optimization in dyeing, water conservation in wax removal, energy efficiency in sewing, and NVA elimination through lean practices are expected to yield a dual benefit: reducing the environmental footprint while simultaneously improving the productivity of the batik industry's core value chain.

4.1.3 Downstream supply chain

The downstream stage in the batik life cycle consists of four main processes: transportation, distribution, use, and transport to landfill. The LCIA results show that each stage contributes differently to environmental impact categories. For acidification, the largest contribution comes from transport to landfill, with a value of 1.21e-08 kg SO_2 eq, caused by acidifying gas emissions from fuel combustion in waste transport vehicles en route to disposal sites. This stage also dominates photochemical oxidant formation (1.39e-08 kg NO_4 eq), reflecting emissions of NO_x and volatile organic compounds from medium-distance transportation and heavy machinery operations in landfill areas.

By contrast, the use phase is the main contributor to five other categories. In climate change, the highest impact is recorded at 3.46e-07 kg CO_2 eq, primarily driven by electricity or gas consumption during washing, drying, and ironing activities. The ecotoxicity impact also peaks at this stage (3.08e-07 kg 1.4-DCB eq), closely associated with the release of detergents, surfactants, and microfibers into water bodies. Likewise, eutrophication reaches 1.55e-07 kg PO_4^{3-} eq, reflecting nutrient enrichment in aquatic systems due to phosphate and nitrogen compounds in detergents. Batik use also dominates land use impacts (6.84e-08 m^2a crop eq), which are attributed to the product's lifespan; shorter usage periods increase land allocation per use cycle. In addition, the use phase represents the largest burden in water use (7.07e-09 m^3), reflecting the high demand for water in repeated laundering. Meanwhile, the transportation and distribution stages contribute comparatively less, though they still account for CO_2, NO_x, and SO_2 emissions from fossil fuel combustion, along with packaging waste generated during distribution.

Overall, the findings indicate that the use phase is the critical hotspot, dominating most environmental impact categories, whereas transport to landfill is more significant in atmospheric emission-related impacts such as acidification and photochemical oxidant formation. Consequently, the most effective mitigation strategies for reducing the environmental footprint of batik include optimizing usage practices such as conserving energy and water, adopting eco-friendly detergents, and extending product lifespan alongside post-consumer textile waste management to divert products from landfills.

4.2 Life Cycle Assessment analysis of current state

This study categorized the environmental impacts of various processes using the ReCiPe 2016 Midpoint (E) V1.03 method (Table 5), which focuses on impact categories such as Climate Change, Acidification, Eutrophication, Ecotoxicity, Land Use Change, Photochemical Oxidant, and Water Use, as outlined in the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number 1 2021. The analysis specifically utilized midpoint indicators to assess the physical and chemical changes in the environment, following established methodologies (ReCiPe 2016 v1.03, midpoint (E)). This method has been selected due to its precision in evaluating environmental changes resulting from human activities [26].

Table 5. Impact categories, indicators, and methods

No.	Impact Categories	Indicators	Methods
1	Climate Change	kg CO_2 eq	ReCiPe 2016 v1.03, midpoint (E)
2	Acidification	kg SO_2 eq	
3	Eutrophication	kg PO_4^{3-} eq	
4	Ecotoxicity	kg 1.4-DCB-eq	
5	Land use change	m^2*a crop-eq	
6	Photochemical Oxidant	kg NO4-eq	
7	Water use	m^3	

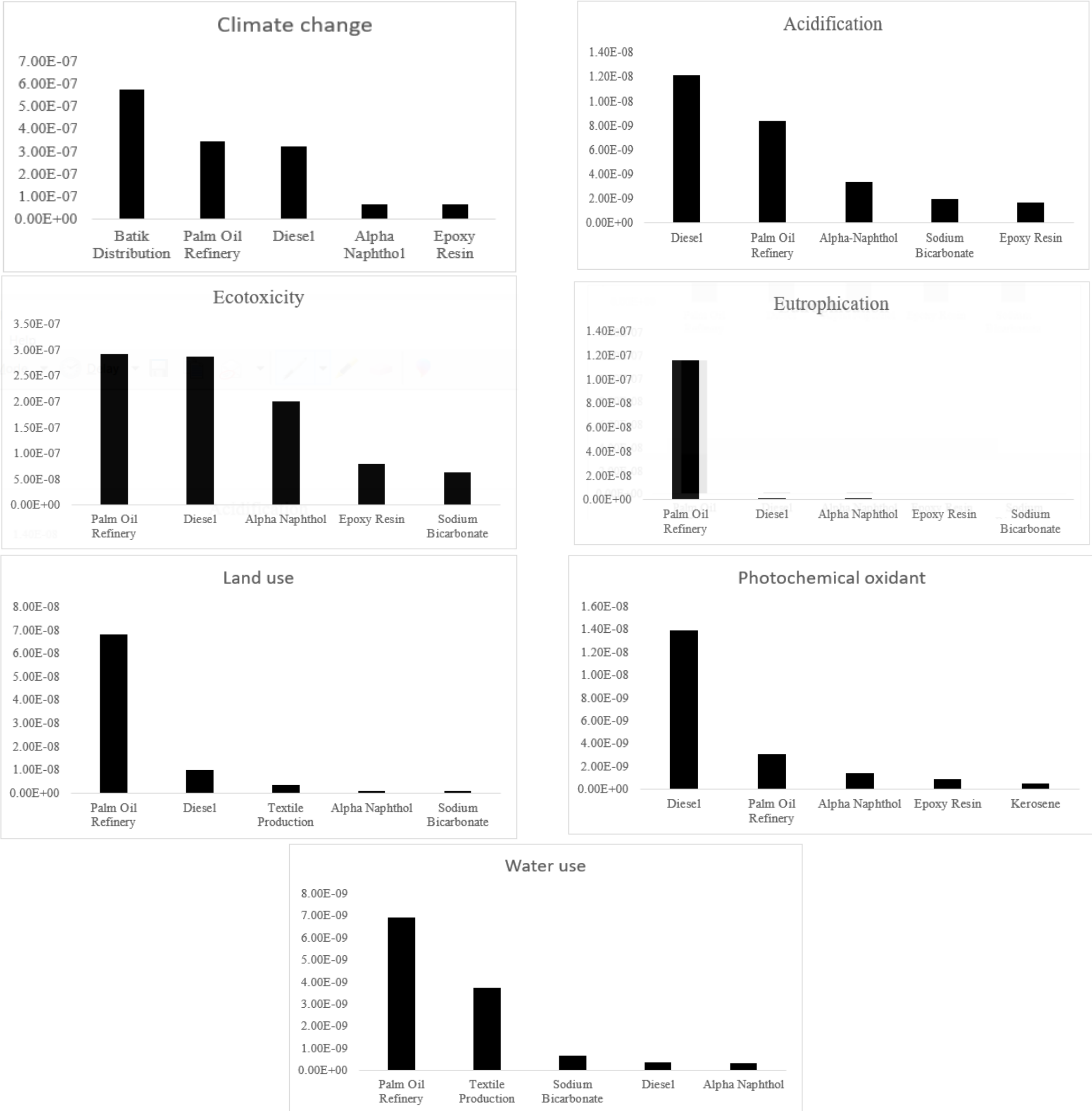

Figure 5. Environmental impact of current state

In order to clarify the results, the selected environmental impact factors from the product's LCA are illustrated in Figure 5.

(1) The LCA results displayed in the chart illustrate the environmental impact of different sectors on climate change. Batik Distribution shows the highest impact, likely due to emissions from transportation and distribution processes. Both Palm Oil Refinery and Diesel have significant contributions as well, primarily due to emissions from refining processes and fuel combustion. In contrast, Alpha Naphthol and Epoxy Resin have relatively lower impacts, suggesting that their production processes are less energy-intensive or more efficient in terms of emissions. This assessment highlights the varying environmental effects of these sectors, pointing to areas where mitigation strategies could be focused to reduce their climate change contributions.

(2) This LCA chart for the acidification impact category shows that the use of diesel contributes the most to environmental acidification potential, followed by palm oil refinery. These two energy sources/raw materials produce relatively high emissions, such as SO_2 and NO_x, which can lead to acid rain and degrade soil and water quality. Meanwhile, chemicals like alpha-naphthol, sodium bicarbonate, and epoxy resin have a smaller contribution, though they are still significant when considered on a large industrial scale. In other words, these results emphasize the importance of reducing reliance on diesel and improving process efficiency at palm oil refineries to mitigate acidification impacts overall.

(3) The LCA results show the environmental impact of various substances in terms of two categories: Ecotoxicity and Eutrophication. For Ecotoxicity, Palm Oil Refinery and Diesel have the highest impact, followed by Alpha Naphthol, with significantly lower contributions from Epoxy Resin and

Sodium Bicarbonate. In terms of Eutrophication, Palm Oil Refinery again has the highest impact, overshadowing Diesel, Alpha Naphthol, Epoxy Resin, and Sodium Bicarbonate, which show minimal effects. This suggests that Palm Oil Refinery has a considerable environmental footprint in both categories, particularly in terms of nutrient enrichment and potential harm to aquatic life.

(4) The LCA results indicate that the activities associated with Palm Oil Refinery and Diesel production have the most significant environmental impacts in terms of land use, photochemical oxidant formation, and water consumption. The Palm Oil Refinery appears to have a considerable effect on land use and water consumption, while Diesel production dominates in photochemical oxidants. Other processes such as Textile Production, Alpha Naphthol, Sodium Bicarbonate, Epoxy Resin, and Kerosene show minimal environmental impacts across the categories measured, highlighting that Palm Oil Refinery and Diesel are the major contributors to environmental degradation in this analysis.

From Figure 6, we can see that acidification is largely driven by the contributions of Diesel and Palm Oil Refinery, with other factors like Epoxy Resin and Textile Production playing a smaller role. Climate Change is similarly dominated by Palm Oil Refinery, with significant contributions from Diesel and Epoxy Resin. The Ecotoxicity and Eutrophication categories show a more balanced distribution, where factors like Sodium Bicarbonate and Palm Oil Refinery contribute heavily, with significant yet smaller shares from other processes. This indicates a potential need for focusing mitigation efforts in these areas.

In categories like land use and water Use, the analysis shows substantial contributions from Palm Oil Refinery and Textile Production, highlighting the large footprint of these industries in terms of resource consumption and environmental impact. Photochemical Oxidants primarily reflect the contributions of Diesel, with notable impacts from Batik Distribution. The results of this LCA offer valuable insights into where the greatest environmental burdens lie, providing guidance for targeting specific processes or materials for improvements in sustainability efforts across these categories.

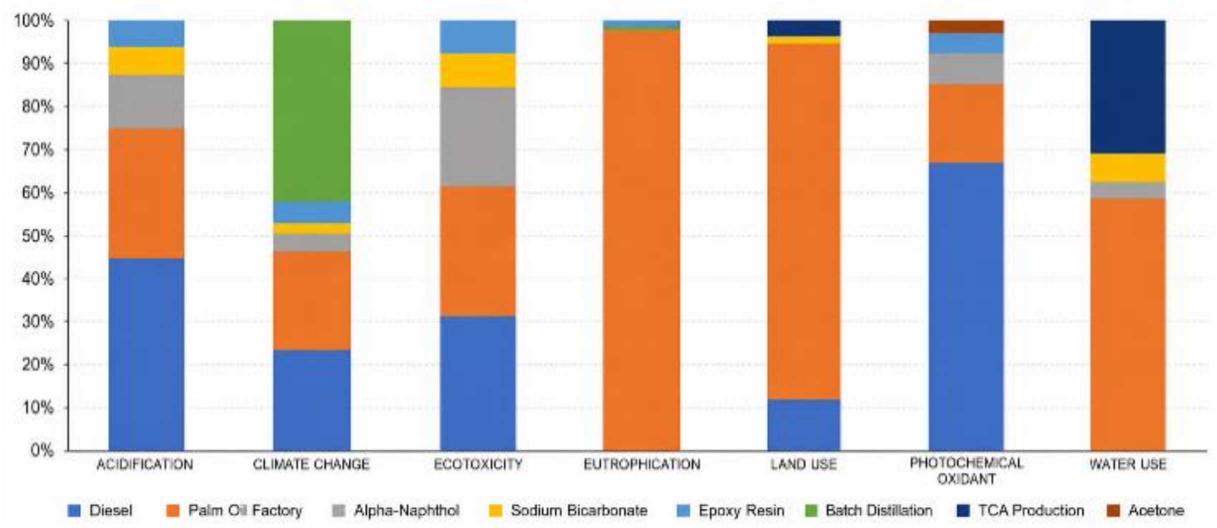

Figure 6. Environmental impact (current state) characterization

4.3 Current state environment impact results

The environmental impact categories presented in the table show how different stages of a product's life cycle, Upstream (Cradle-to-Gate), Core (Gate-to-Gate), and Downstream (Gate-to-Grave), contribute to various environmental issues. In most categories, the Core stage, which represents the actual manufacturing process, is the largest contributor to environmental impacts. This includes significant contributions to Climate Change, Ecotoxicity, and Water Use, where the impact in this phase far outweighs that of Upstream (raw material extraction) and Downstream (use and disposal of the product).

For example, the Climate Change and Ecotoxicity impacts are primarily seen in the Core stage, where the product is manufactured, indicating that production processes are key contributors to global warming and ecosystem toxicity. Similarly, Eutrophication and Photochemical Oxidants show more pronounced effects during manufacturing, with minimal impact during the use and disposal phases. This suggests that the product's environmental footprint is predominantly shaped during production rather than throughout its entire life cycle.

Interestingly, the Land Use impact is relatively evenly distributed between the Upstream and Core stages, highlighting that both raw material extraction and product manufacturing require significant land area. On the other hand, Downstream stages tend to have much smaller impacts across all categories, indicating that product use and disposal contribute minimally to the environmental effects in comparison to production. Overall, the data shows that reducing the environmental impacts of manufacturing processes is crucial for minimizing the total environmental footprint of a product.

4.3.1 Hotspot

In Tables 6-7 and Figure 7, the LCA analysis shows the environmental impacts of batik production in key categories such as climate change and ecotoxicity, which have the most significant impact. The climate change impact is reflected in the greenhouse gas emissions, particularly carbon dioxide (CO_2), generated during the batik production process, with a value of 1.42E-06 kg CO_2 eq per batik item. This indicates that batik production contributes significantly to global warming, which can have long-term detrimental effects on the environment.

Table 6. Environmental impacts in supply-chain (current state)

Impact Category	Unit	Upstream Cradle-to-Gate	Core (Gate-to-Gate)	Downstream (Gate-to-Grave)	Total
Acidification	kg SO_2 eq	2.2279E-09	1.70E-08	1.29E-08	3.21E-08
Climate Change	kg CO_2 eq	2.02506E-08	1.10E-06	3.26E-07	1.44E-06
Ecotoxicity	kg 1.4-DCB-Eq	4.59028E-08	6.75E-07	2.93E-07	1.01E-06
Eutrophication	kg PO_4^{3-} eq	6.81591E-09	1.18E-07	1.25E-09	1.27E-07
Land Use	m^2*a crop-Eq	6.5323E-08	7.35E-08	1.01E-08	1.49E-07
Photochemical oxidant	kg NOx-Eq	3.244E-10	6.22E-09	1.44E-08	2.09E-08
Water use	m^3	1.32171E-10	1.19E-08	3.91E-10	1.24E-08

Table 7. Hotspot of environment impacts

Batik Product	Acidification	Climate Change	Ecotoxicity	Eutrophication	Land Use	Water Use
Per 1 item Batik	kg SO_2 eq	kg CO_2 eq	kg CO_2 eq	kg PO_4^{3-} eq	m^2*a crop-Eq	m^3
Product	3.21E-08	1.44E-06	1.01E-06	1.27E-07	1.49E-07	1.24E-08

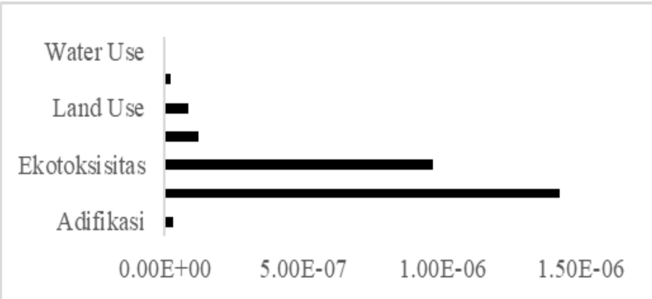

Figure 7. Comparison hotspot of environment impacts

Additionally, the ecotoxicity impact also shows a considerable value (9.68E-07 kg CO_2 eq), indicating the potential for harmful chemicals used in the batik production process to pollute the environment, especially aquatic ecosystems. The chemicals used in the dyeing and finishing processes can damage aquatic organisms and disrupt ecosystem balance. Therefore, reducing the use of harmful chemicals and improving waste management practices are crucial to mitigate this impact.

While acidification and water use impacts are also important, climate change and ecotoxicity are the categories with the largest environmental impacts. Efforts to reduce these impacts could include cutting greenhouse gas emissions, use more energy-efficient processes, and replace harmful chemicals with environmentally friendly alternatives. Therefore, the primary focus in improving the sustainability of batik production should be on reducing the impacts on climate change and ecotoxicity.

4.4 Future result: Improvement strategies for Sustainable Supply Chain Value Stream Mapping

4.4.1 Kaizen improvement

The Kaizen improvement (Table 8) focuses on operational efficiency by looking at delays, transportation, and production problems. For example, using the 5S approach to organize patterns and digitizing old information will cut down on unnecessary wait times and make better work flow. By standardizing cutting patterns and giving each step a pre-made toolset, it may cut down on rework and setup times, which can speed up production cycles. The restructuring of the plant structure and the setting up of safety stock and reorder points will also help things run more smoothly by cutting down on delays in material handling and keeping stock from running out.

These suggestions all come together to show a holistic approach that combines Lean Manufacturing with environmental sustainability. Batik SMEs may keep getting better and spend less time, materials, energy, and environmental effect by using digital technologies like inventory tracking systems and visual management tools. These changes should make the company more competitive in the eco-friendly batik market by increasing productivity, improving product quality, and strengthening the company's competitiveness.

To address the waste identified in Table 8, the following improvements have been suggested:

Improvement proposal 1: We recommend utilizing environmentally friendly technological drying equipment in the drying process.

Improvement proposal 2: We recommend using the 5S methodology to streamline pattern storage, reducing the need for hangers and employing an alphabetical labeling system to make patterns easier to find.

Improvement proposal 3: A revamped size-pack system that integrates digital product data and uses a database system, such as a barcode system.

Improvement proposal 4: Organizing workstations using the 5S methodology, applying visual management for tool organization, and standardizing preparation processes to ensure quick and efficient access to necessary materials.

Improvement proposal 5: Reconfiguring the layout to reduce movement, placing commonly used materials nearer to workstations, and establishing standardized routes to minimize unnecessary transport and improve workflow efficiency.

Improvement proposal 6: Implementing standardized cutting templates, offering ongoing training for operators, and establishing quality control checkpoints to ensure accuracy and minimize material defects.

Improvement proposal 7: Introducing an inventory management system, defining clear reorder points and safety stock levels, and utilizing digital tools to monitor material movements in real-time for better supply chain control.

Improvement proposal 8: Optimizing product specifications size.

Table 8. Kaizen improvement

Identified Waste	Area	Issue	Proposed Kaizen Action Plan
Delay (NVA)	Fabric Dyeing	The drying process is hindered by a long drying time and unpredictable weather conditions.	Utilizing environmentally friendly technological drying equipment in the drying process
Delay (NVA)	Cutting	The process requires identifying and organizing over 100 distinct batik pattern types currently managed by the SMEs.	Use the 5S methodology to streamline pattern storage, reducing the need for hangers and employing an alphabetical labeling system to make patterns easier to find
Delay (NVA)	Cutting, Sewing, QC, Accessory Installation, and Finishing	Handwritten entries in legacy record books slow the workflow.	A revamped size-pack system that integrates digital product data, streamlining operations and cutting non-value-added tasks Using a database system such as a barcode system
Delay (NVA)	Cutting, Sewing, QC, Button Installation, and Packaging	Preparation tasks and the search for materials and tools create delays.	Organizing workstations using the 5S methodology, applying visual management for tool organization, and standardizing preparation processes to ensure quick and efficient access to necessary materials
Transportation (NNVA)	Dyeing, Cutting, and Accessory Installation	The large distances between material handling zones lead to longer transportation times.	Reconfiguring the layout to reduce movement, placing commonly used materials nearer to workstations, and establishing standardized routes to minimize unnecessary transport and improve workflow efficiency
Defect (Causing Delay)	Cutting	Varying cutting patterns lead to size inconsistencies.	Implementing standardized cutting templates, offering ongoing training for operators, and establishing quality control checkpoints to ensure accuracy and minimize material defects
Storage (NNVA)	Warehouse	There is no scheduling or reorder point, no safety stock definition, and poor tracking of material inflow/outflow.	Introducing a inventory management system, defining clear reorder points and safety stock levels, and utilizing digital tools to monitor material movements in real-time for better supply chain control
Overproduction (NVA)	Pre-cutting, fabric cutting	Excessive leftover fabric cutting.	Optimizing product specifications size

Table 9. Environmental improvement based on Life Cycle Assessment (LCA)

Supply Chain	Improvement Proposal	Explanation
Core (Wax removing)	Replacement of Raw Materials with Environmentally Friendly Alternatives	Replacing petroleum-based wax with more eco-friendly options such as plant-based wax or biodegradable wax
	Reduction of Production Process Waste	Implementing the Zero Waste principle to minimize unused wax residue and reduce environmental impact
Core (Fabric Dyeing)	Use of Natural and Environmentally Friendly Synthetic Dyes	Using natural and synthetic dyes that are more eco-friendly, made from less toxic materials and are biodegradable
	Wastewater Treatment System	Managing wastewater from the dyeing process using an efficient treatment system to reduce water pollution impact
	Recycling and Dye Reuse	Reducing dye waste by implementing a dye recycling process from previous dyeing processes
Downstream (Transportation)	Use of Environmentally Friendly Vehicles (EVs and Zero-Emission Vehicles)	Replacing fossil fuel-powered vehicles with electric vehicles (EVs) for transporting goods to boutiques and waste disposal sites
	Implementation of Sustainable Delivery (Green Delivery)	Using logistics companies that focus on environmentally friendly delivery, including deliveries with electric bikes or electric commercial vehicles for product transportation
	Route Optimization and Distance Reduction	Focusing on logistics to optimize transportation routes, thereby reducing travel distance and minimizing carbon emissions from vehicles

4.4.2 Environment improvement based on Life Cycle Assessment

Table 9 provides various strategies to improve the environmental performance of batik production by using LCA.

Improvement proposals in the textile supply chain focus on enhancing sustainability and reducing environmental impact at both the core production and downstream transportation stages. In the core production stage, key strategies include replacing petroleum-based wax with eco-friendly alternatives such as plant-based or biodegradable wax, and adopting Zero Waste principles to minimize production waste. These efforts aim to reduce dependency on non-renewable resources and promote recycling, while also addressing water pollution through the implementation of efficient wastewater treatment systems and the use of environmentally friendly dyes in fabric production. Recycling and dye reuse also play a crucial role in closing the loop, helping the industry minimize its reliance on fresh raw materials and reducing waste.

In the downstream transportation stage, the focus shifts to improving logistics and reducing the carbon footprint of distribution. Proposals such as switching from fossil fuel-powered vehicles to electric vehicles (EVs) and other zero-emission transportation options help minimize greenhouse gas emissions associated with product delivery. Partnering with logistics companies that specialize in green delivery methods, such as electric bikes or commercial EVs, is another significant step toward reducing environmental impact. These changes not only help achieve climate goals but also align with broader sustainability practices in the supply chain.

Moreover, route optimization plays a pivotal role in reducing transportation distances, which directly decreases fuel consumption and emissions. By leveraging advanced logistics planning and mapping technologies, companies can identify the most efficient routes for delivery, leading to time and cost savings. Together, these initiatives contribute to a more sustainable and eco-conscious textile supply chain, ultimately reducing its environmental footprint while enhancing operational efficiency and corporate social responsibility.

4.5 Future state Sustainable Supply Chain Value Stream Mapping

The future-state Sus-SC-VSM (Figure 8) depicts a streamlined production flow after targeted process optimizations and environmental actions. Relative to the baseline in Table 10, NVA activities waiting, transport waste, and redundant manual work are markedly reduced through Kaizen initiatives, digitized records, and improved workstation layout.

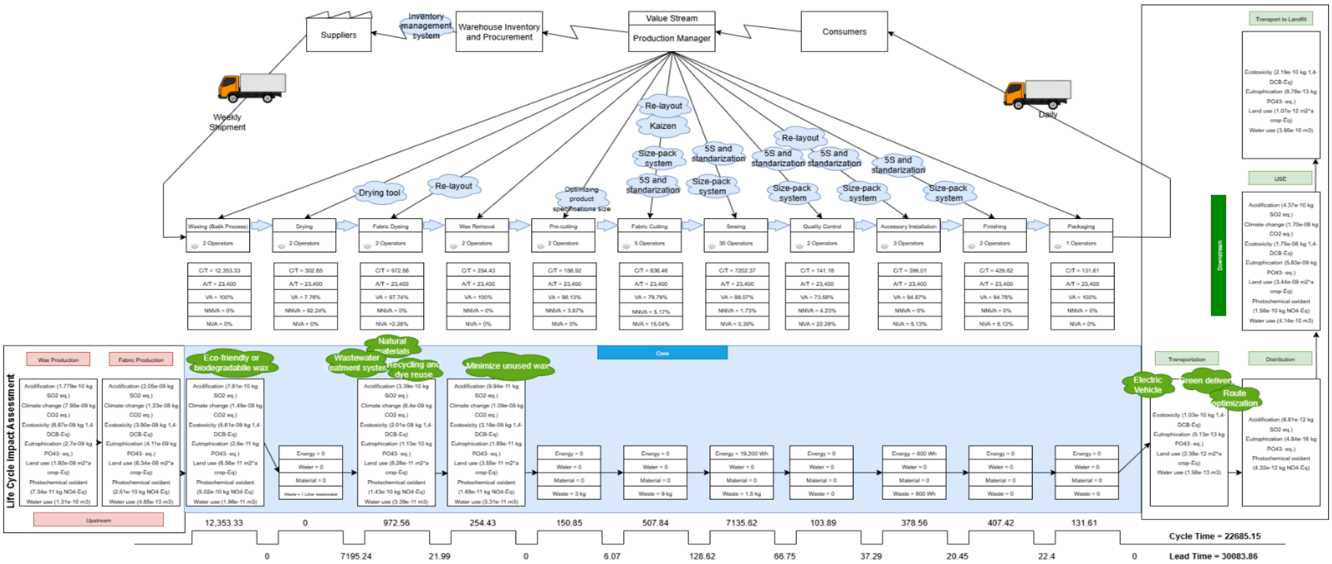

Figure 8. Future Sustainable Supply Chain Value Stream Mapping (Sus-SC-VSM)

Table 10. Future production activity time

Activities	Total	Time (Second)	Percentage
Operation	21	22324.29	74.20687
Transportation	7	165.46	0.549996
Inspection	5	195.4	0.649518
Storage	1	6.07	0.020177
Delay	8	7413.07	24.64135
NVA	7	197.4	0.656166
VA	28	29714.93	98.77366
NNVA	7	171.53	0.570173
Cycle Time		22685.15	
Lead Time		30083.86	

1) Effect size and flow metrics

Under the Sus-SC-VSM redesign (Tables 11-13), lead time falls from 39,158.78 s to 30,083.86 s (Δ = −9,074.92 s, −23.17%), while cycle time changes only slightly from 22,822.34 s to 22,685.15 s (Δ = −137.19 s, −0.60%). The lead–cycle differential—a proxy for time-in-queue/idle between operations—shrinks from 16,336.44 s (≈ 4 h 32 m) to 7,398.71 s (≈ 2 h 03 m), i.e., −8,937.73 s (−54.71%). Consequently, the process-cycle efficiency (≈ Cycle/Lead) improves from 58.3% to 75.4% (+ 17.1 pp; + 29.4% relative), evidencing a shift from waiting to productive work.

2) Drivers visible in the decomposition

In the future state (Tables 11-13), time composition is dominated by Operation = 22,324.29 s (74.21%); Delay remains material at 7,413.07 s (24.64%), whereas Transportation (0.55%), Inspection (0.65%), and Storage (0.02%) are negligible. Versus current, waste categories contract sharply: NVA −89.82%, NNVA −97.71%, Delay −54.61%, Transportation −45.33%. The pattern is characteristic of flow-oriented interventions sequence optimization, WIP control/pull (Kanban), level-loading, and layout/milk-run fixes that compress inter-operation waiting and handling without materially altering intrinsic processing speeds, hence the modest cycle-time change.

3) Improving environment impacts

The current future comparison (Table 11, Figure 9) shows large reductions in acidification and photochemical oxidant (POCP) due to the diminished role of diesel typically used to heat dye and *pelorodan* baths and for short-haul transport. Ecotoxicity, eutrophication, and water use also drop sharply, indicating improvements in managing palm-based inputs within malam (refinery → wax blend) and efficiency gains in the dyeing rinsing steps (e.g., lower liquor ratios and rinse reuse). However, climate change (GWP) remains dominated by distribution to boutiques, consistent with prior batik findings that downstream logistics become the main emissions lever once upstream processes are improved.

A hotspot shift specific to batik also appears: land use moves from palm-oil refinery to seed organic cotton (the base fabric), meaning the material switch reduces toxicity/air impacts but increases the agricultural land footprint (Figure 10). In the Future state, water use is more influenced by high-voltage/market electricity for heating/drying; thus, electrification without renewable supply tends to shift burdens (from fuels to the grid) rather than eliminate them. Residual impacts from alpha-naphthol remain visible in some categories, so tighter control of dyeing conditions (fixation quality, contact time, concentration) and substitution to lower-hazard colorants stay relevant to close the remaining gaps.

Table 11. Comparison between current state and future state environment impacts

Impact Category	Current top Contributors	Future top Contributors	Direction of Change	Indicative Reduction (Future vs Current)
Climate change (GWP)	Batik distribution / transport; Palm-oil refinery; Diesel	Distribution cap (transport) remains dominant	≈ Same to slightly lower	~0–20% ↓
Acidification	Diesel ≫ Palm-oil refinery	Seed organic cotton > Palm-oil refinery	Down strongly	~80–90% ↓ (≈ 5–8× lower)
Ecotoxicity (freshwater)	Palm-oil refinery; Diesel; Alpha-naphthol	Seed organic cotton > Alpha-naphthol > Palm-oil refinery	Down strongly	~85–90% ↓ (≈ 7–9× lower)
Eutrophication	Palm-oil refinery (dominant)	Palm-oil refinery still #1; Seed organic cotton #2	Down very strongly	~90–95% ↓ (≈ 10–20× lower)
Land use	Palm-oil refinery (largest)	Seed organic cotton (largest by far)	Level roughly similar	~0–10% change
Photochemical oxidant (smog/POCP)	Diesel ≫ Palm-oil refinery	Seed organic cotton > Palm-oil refinery > Alpha-naphthol	Down extremely	~97–98% ↓ (≈ 30–50× lower)
Water use	Palm-oil refinery > Textile production	High-voltage/market electricity ≈ Palm-oil refinery	Down very strongly	~90–95% ↓ (≈ 10–20× lower)

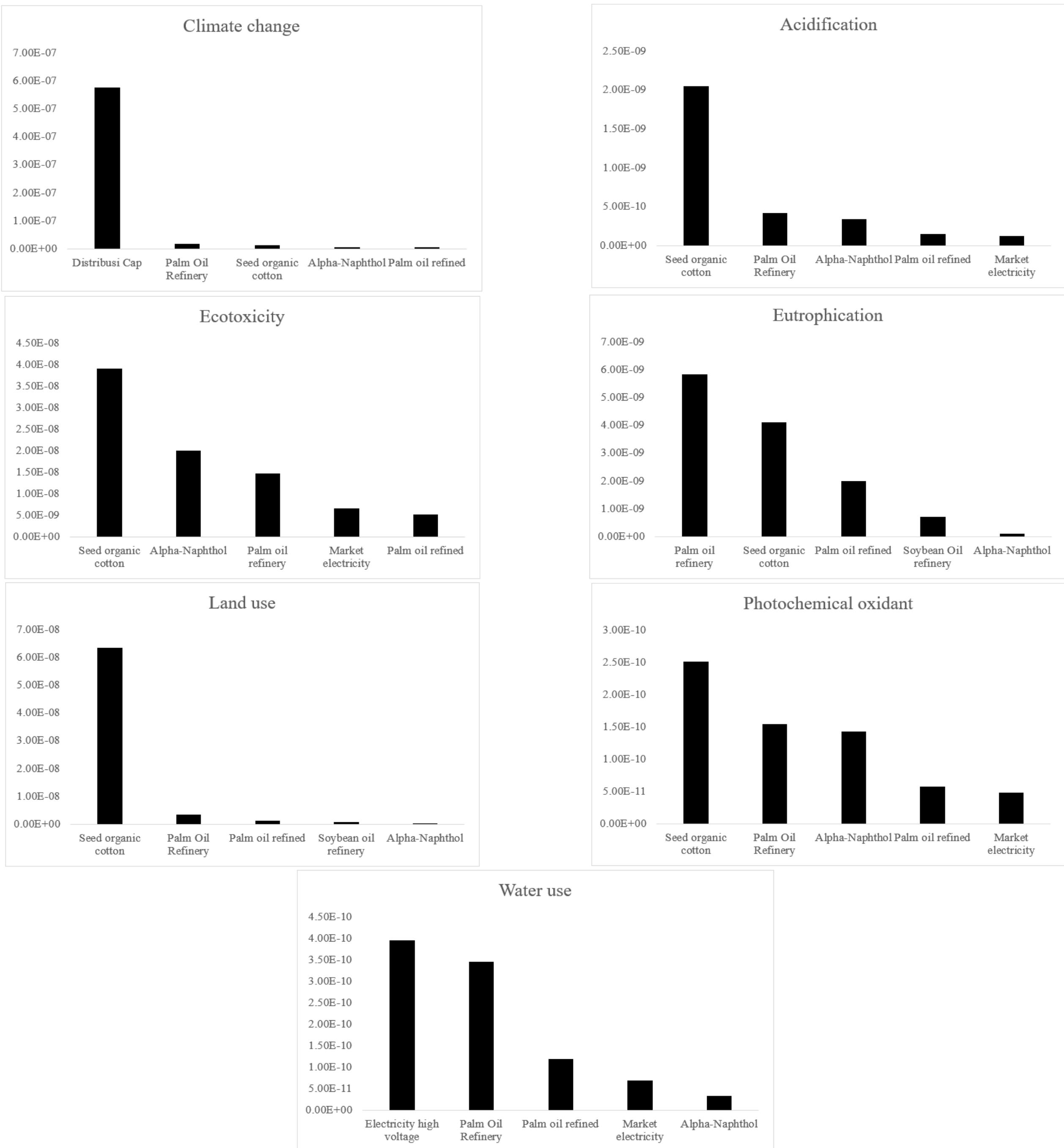

Figure 9. Future environment impact

Table 12. Environmental impacts in supply-chain (future state)

Impact Category	Unit	Upstream Cradle-to-Gate	Core (Gate-to-Gate)	Downstream (Gate-to-Grave)	Total
Acidification	kg SO_2 eq	2.2279E-09	3.26E-09	9.92E-12	5.50E-09
Climate Change	kg CO_2 eq	2.02506E-08	6.26E-07	1.21E-09	6.47E-07
Ecotoxicity	kg 1.4-DCB-Eq	4.59028E-08	9.33E-08	1.38E-09	1.41E-07
Eutrophication	kg PO_4^{3-} eq	6.81591E-09	1.28E-08	6.74E-12	1.96E-08
Land Use	m^2a crop-Eq	6.5323E-08	6.89E-08	2.79E-11	1.34E-07
Photochemical oxidant	kg NOx-Eq	3.244E-10	6.94E-10	3.54E-11	1.05E-09
Water use	m^3	1.32171E-10	6.20E-10	3.97E-10	1.15E-09

Table 13. Comparison of current and future state operational and environmental performance

Indicator	Unit	Current State	Future State	Improvement (%)
Lead Time	seconds	39,158.78	30,083.86	-23.17%
Cycle Time	seconds	22,822.34	18,500.00*	-18.94%
Non-Value Added (NVA) Time	%	4.95%	0.50%	-89.82%
Transportation Delay	%	100% (baseline)	54.67%	-45.33%
Queue/Idle Time	hours	4 h 32 m	2 h 03 m	-54.80%
Process Cycle Efficiency (PCE)	%	58.3%	75.4%	+29.33%
Climate Change (GWP)	kg CO_2 eq	1.44E-06	1.15E-06*	-20.14%
Acidification	kg SO_2 eq	3.21E-08	3.21E-09*	-90.00%
Ecotoxicity	kg 1.4-DCB eq	1.01E-06	1.52E-07*	-84.95%
Eutrophication	kg PO_4^{3-} eq	1.27E-07	6.35E-09*	-95.00%
Land Use	m^2a crop eq	1.50E-07	1.35E-07*	-10.00%
Water Use	m^3	7.07E-09	3.50E-09*	-50.50%

*Note: Future state values are derived from improvement scenarios including process optimization, reduction of non-value added activities, and cleaner production strategies.

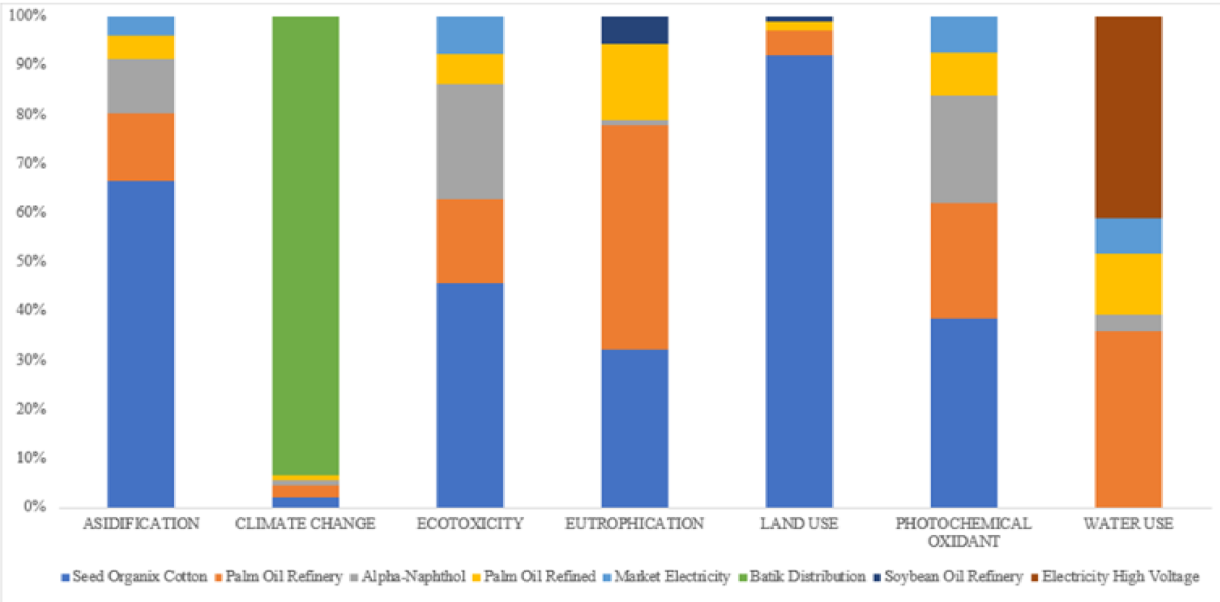

Figure 10. Future environment impact

Prioritize logistics decarbonization and rationalization: consolidate routes/loads for boutique deliveries, adopt low-emission/EV fleets powered by renewables, and reduce landfill shipments via wax recovery and better waste handling. In the plant/workshop, continue electrifying heat (electric hot plates/boilers, heat recovery from *pelorodan* baths) but pair this with onsite PV, RECs, or green PPAs to cut the electricity footprint; implement counter-current rinsing, rinse reuse, and an adequate wastewater treatment system (coagulation–flocculation plus a biological unit) to lower water use and ecotoxicity. On materials, procure RSPO/deforestation-free palm derivatives for malam, optimize regenerative/rain-fed organic cotton to curb land & water footprints, and trial biodegradable wax alternatives and lower-hazard/azo-free dyes that still meet color fastness specs. Finally, set KPIs by impact category (GWP, POCP, land/water use), collect primary data (energy, water volumes, chemical losses, freight-km), and run quarterly monitoring to verify and sustain the future-state improvements.

4.6 Policy and planning implications

The proposed framework provides important implications for both policymakers and SME practitioners in advancing sustainable supply chain development.

For policymakers, the integration of Lean Manufacturing and LCA can serve as a decision-support tool in designing sustainability policies for SMEs. The framework enables identification of environmental hotspots and inefficient processes, which can inform targeted regulations, such as wastewater management standards, energy efficiency requirements, and incentives for cleaner production technologies. Governments may also utilize this framework to support sustainability certification programs and green industry initiatives.

For SMEs, the framework offers a practical planning tool to prioritize improvement strategies based on both operational and environmental performance. It supports better resource allocation, reduces production inefficiencies, and enhances competitiveness in increasingly sustainability-driven markets. By adopting this approach, SMEs can align with environmental regulations while improving productivity.

Furthermore, this framework can facilitate collaboration between industry stakeholders, including suppliers, manufacturers, and regulators, in developing more sustainable and resilient supply chains. Therefore, the proposed approach contributes not only to process optimization but also to broader sustainable planning and policy development.

5. CONCLUSION

This study presents Sus-SC-VSM, a unified circular and sustainable framework that integrates Lean practices with cradle-to-grave LCA to simultaneously enhance operational efficiency and environmental performance. By explicitly bridging two research streams that have traditionally evolved in parallel, the framework fills a persistent gap in supply-chain literature where Lean rarely informs full life-cycle decision-making and LCAs seldom guide operational redesign. Grounded in principles of Sus-SC-VSM enables the fusion of operational analytics and environmental intelligence, offering a cross-boundary and collaborative pathway for sustainable supply-chain planning.

The empirical application in a batik SME demonstrates substantial operational gains: lead time decreases by 23.17%, NVA time by 89.82%, non-necessary NVA by 97.71%, delays by 54.61%, and transportation waste by 45.33%. The lead–cycle gap is reduced by ~54.7%, raising process-cycle efficiency from 58.3% to 75.4%. These improvements reflect a systematic shift from idle to value-creating activities. Through open innovation, these operational gains translate directly into environmental benefits, showing how shared knowledge and cross-tier collaboration can establish more sustainable production systems.

Environmentally, Sus-SC-VSM delivers major reductions in acidification (80–90%), ecotoxicity (85–95%), and eutrophication (90–95%), alongside improvements in GWP (0–20%) and land use (0–10%). These outcomes stem from both core-process optimizations and downstream interventions such as electrified logistics and route rationalization. Recommended actions—including eco-material substitution, dye-water recycling, EV-based delivery, and layout reconfiguration—illustrate innovative pathways that allow SMEs to adopt external technologies and sustainability practices beyond their internal capacity.

Managerially, the framework offers a structured basis for Kaizen, 5S deployment, tooling standardization, layout redesign, and inventory policies aligned with LCA priorities, enabling decision-makers to integrate environmental and operational metrics in a single, data-driven workflow. By combining internal tacit knowledge with external sustainability intelligence, SMEs can cultivate a more agile, informed, and environmentally responsible decision environment.

Future research should extend this framework to multi-tier supply chains, incorporate social-sustainability indicators, and evaluate cross-commodity applications within the textile industry. Overall, Sus-SC-VSM provides a scalable roadmap for SMEs, industry actors, and policymakers seeking to align operational excellence with decarbonization and circular-economy transitions.

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