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Environmental Impact Evaluation of Batik Production through Gate-to-Gate Life Cycle Assessment: Quantitative Evaluation of Energy, Water, and Emission Hotspots in Textile Dyeing

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Abstract

This study presents a gate-to-gate Life Cycle Assessment (LCA) of traditional batik production in Sri Lanka, aimed at quantifying environmental impacts and identifying process-level hotspots. A batch of 16 sarees (4.8 kg) was defined as the functional unit, and impacts were evaluated using the ReCiPe Midpoint (H) method. The normalization results revealed that marine(0.119), freshwater(0.053), and terrestrial ecotoxicity(0.018), along with human non-carcinogenic toxicity(0.023), were the dominant impact categories, primarily driven using synthetic dyes, paraffin wax, and alkaline chemicals. Boiling and washing stages were identified as major energy-related hotspots, while wetting, dyeing, and washing contributed most significantly to ecotoxicity. The persistence of Naphthol and Indigosol dyes, coupled with the presence of heavy metals, further intensified effluent toxicity. The study highlights that implementing heat recovery systems, water recycling, optimized dyeing practices, and natural wax substitutions can substantially reduce the environmental burden. Overall, this work provides a comprehensive environmental profile and practical mitigation strategies for advancing sustainable batik production in small-scale settings.

Keywords: Life Cycle Assessment (LCA), Batik production, Ecotoxicity, Sustainable textiles, Environmental hotspots

1. Introduction

Batik is a traditional Sri Lankan textile craft which uses a wax-resist dyeing technique to produce intricate, vibrant patterns (Senarathna and Rajakaruna, 2021). The industry thrives on individual creativity and benefits economically from integration with export markets and tourism, offering visitors a unique cultural experience (Steelyana, 2012). Batik production is mainly undertaken by small and medium-scale household enterprises (Wijayasenarathene and Thushari, 2022), particularly in tourist areas like Hikkaduwa and Galle, where centers create complex, multi-coloured designs (Wijesekara et al., 2025). For this study, a small scale, home-based batik enterprise was selected as the case study to assess environmental impacts at the household level.

The traditional batik crafting process generally consumes less electricity and water compared to large-scale production, and as a result, the environmental impacts of small- and medium-scale household-based enterprises are often underestimated. However, irrespective of production scale, these industries utilize toxic substances such as synthetic dyes and paraffin-based waxes. Due to the absence of adequate wastewater treatment facilities, effluents from the dyeing process in small- and medium-scale household-based enterprises are frequently discharged untreated into surrounding soils and surface water bodies, thereby posing significant risks to environmental quality (Wijayasenarathene and Thushari, 2022).

Textile wastewater, particularly from the batik industry, poses significant treatment challenges due to its low biodegradability and high pollutant load (Sulthonuddin and Herdiansyah, 2021). This wastewater typically contains paraffin residues and synthetic azo dyes derived from aromatic hydrocarbons such as benzene, toluene, naphthalene, and anthracene, which contribute to elevated chemical oxygen demand (COD) levels (Iqbal et al., 2021). The presence of these complex organic compounds results in a low biochemical oxygen demand to chemical oxygen demand (BOD/COD) ratio, indicating limited biological degradability. Consequently, the direct discharge of such effluents into water bodies can lead to severe environmental contamination and persistence of toxic substances (Iqbal et al., 2021).

Limited research has quantified the environmental impacts of the batik industry in Sri Lanka, with existing studies primarily focused on water footprint analysis or the development of natural dyes to mitigate the environmental burden of conventional dyeing processes. To date, no published studies have assessed the environmental impacts of batik production in Sri Lanka using the Life Cycle Assessment (LCA) methodology. Existing LCA studies have primarily been conducted in countries such as Indonesia, where batik production practices differ considerably from those in Sri Lanka. For example, Indonesian studies have evaluated batik production using natural dyes (Yoshanti and Dowaki, 2017), whereas the commercial batik industry in Sri Lanka predominantly relies on synthetic dyes. Furthermore, these studies have adopted different functional units and system boundaries (Yoshanti and Dowaki, 2017; Asih et al., 2024), limiting the comparability and applicability of their findings to the Sri Lankan context. Therefore, a country-specific LCA is required to accurately assess the environmental impacts of batik production under Sri Lankan production conditions.

This study adopts an exclusively gate-to-gate life cycle assessment (LCA) framework because its primary objective is to evaluate the environmental impacts associated with batik manufacturing processes within a small-scale production facility and identify process-level environmental hotspots for targeted improvement. Small-scale batik

industries often receive limited attention in environmental assessments despite their cumulative contribution to environmental burdens. Therefore, this study focuses on the manufacturing activities directly controlled by the selected facility to provide a detailed understanding of the environmental performance of small-scale batik production.

The system boundary includes fabric preparation, waxing, dyeing, washing, drying, and finishing stages, while upstream processes were excluded. The cotton yarn used in production is imported from India, and fabric manufacturing is carried out at a separate textile manufacturing facility in Sri Lanka before being supplied to the batik manufacturer. Thus, the gate-to-gate approach enables the assessment to specifically capture the environmental impacts arising from the batik manufacturing stage itself.

Unlike previous batik LCA studies that have primarily assessed batik textile production using generalized functional units, this study evaluates the environmental impacts associated with the production of a batch of sixteen complete batik saree. A saree represents a major commercial batik product requiring a substantial amount of fabric, dyes, and processing inputs; however, its environmental footprint has not been previously quantified. Therefore, assessing impacts based on a product-specific functional unit provides a more realistic representation of the environmental burden associated with a commercially relevant batik product in the Sri Lankan context.

Life Cycle Assessment (LCA) is a systematic methodology used to quantify and evaluate the environmental impacts associated with an industrial system or product across all stages of its life cycle, following a "cradle-to-grave" approach (Shi et al., 2017). Incorporating LCA into the batik industry is essential for promoting sustainable production practices and ensuring alignment with the Sustainable Development Goals, especially Sustainable Development Goals(SDG) 12 on Responsible Consumption and Production (Asih et al., 2024).

This study presents a comprehensive environmental impact assessment of batik saree manufacturing using the Life Cycle Assessment (LCA) methodology. The assessment quantifies environmental impacts across different production stages, identifies key environmental hotpots, and provides insights into the processes and resources contributing to environmental burdens. The findings support the development of targeted mitigation strategies to enhance the sustainability of batik manufacturing. The remainder of this paper is organized as follows: Section 2 describes the materials and methods, including goal and scope definition, system boundary, inventory analysis, and impact assessment. Section 3 presents the results and discussion, including impact assessment outcomes, hotspot analysis, and improvement strategies. Section 4 concludes the study by summarizing key findings and recommendations for sustainable batik production.

2. Materials and Methods

2.1. Goal and Scope Definition

The primary objective of this study was to conduct a gate-to-gate Life Cycle Assessment (LCA) of batik manufacturing to quantify its environmental impacts and identify critical intervention points through hotspot analysis. Specifically, the assessment aimed to determine and prioritize the life cycle stages, processes, and input–output flows that contribute disproportionately to the overall environmental burdens of the batik production system. The findings are expected to support process optimization and promote environmentally sustainable practices within Sri Lanka's artisanal textile sector.

2.2. System Boundary and Functional Unit

A small-scale batik manufacturing facility located in the Gampaha District, with a monthly production capacity of approximately 400–500 batik products, was selected for this study. The functional unit was defined as the production of one batch of 16 finished batik sarees, representing the typical production practice of the selected facility. This batch size corresponds to the production capacity of an individual craftswoman engaged in cottage-level batik manufacturing, making it representative of small-scale batik production in Sri Lanka. As material inputs, energy consumption, water use, and emissions are generated collectively during batch-level processing, the selected functional unit provides a realistic representation of the manufacturing system. Accordingly, all life cycle inventory data and environmental impact calculations were based on the production of one batch of 16 finished batik sarees, ensuring consistency throughout the life cycle assessment.

A gate-to-gate system boundary was defined to focus on the environmental impacts generated within the batik manufacturing stage, which is the primary focus of this study. The boundary includes fabric preparation, waxing, dyeing, washing, drying, and finishing processes conducted within the selected facility, while upstream and downstream processes were excluded. The cotton fabric used for batik production is manufactured at a separate textile facility in Sri Lanka using imported cotton yarn from India before being supplied to the batik manufacturer. Therefore, limiting the assessment to the manufacturing stage enables the evaluation of process-specific environmental impacts associated with the selected facility.

2.2.1 Product selection rationale:

Batik sarees were selected as the representative product for this study because they are among the most traditionally produced and economically important products in the Sri Lankan batik industry. Although manufacturers have increasingly diversified into products such as curtains and bags (Ratnavadivel, 2021), batik sarees remain the most standardized product in terms of material composition, production processes, and manufacturing requirements. This process uniformity facilitates reliable life cycle inventory data collection and minimizes variability in the assessment.This uniformity facilitates reliable data collection and reduces variability in the life cycle inventory. In contrast, other batik products, such as shirts, wall hangings, or accessories,exhibit substantial variation in material composition, design complexity and process requirements, which could introduce uncertainty and hinder comparability. Consequently, the selection of batik sarees ensures that the results are both representative of typical artisanal batik production and relevant for informing sustainability improvements across the wider batik sector.

The life cycle model incorporated the following unit processes: transportation of raw materials from local suppliers to the production site, fabric cutting and sewing, wetting, waxing, dyeing, boiling, washing, drying, ironing, and packaging (Figure 1). These processes collectively define the operational boundaries of the batik manufacturing system evaluated in this study.

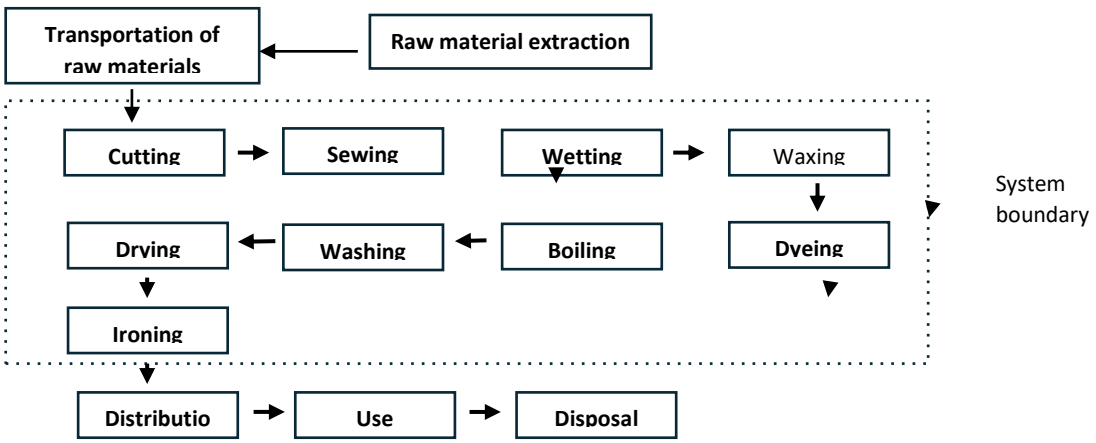


Figure 1: Process flow diagram of batik saree manufacturing, showing the main production stages, including fabric preparation, waxing, dyeing, boiling, washing, drying, and finishing operations considered in the life cycle assessment.

2.3. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase involved systematically collecting and quantifying all relevant environmental inputs and outputs associated with each unit process within the defined gate-to-gate system boundary. Primary data were obtained through onsite measurements and structured interviews with the batik factory owner. A series of interviews and follow-up communications were conducted to collect and verify information related to the batik production process. The collected data included quantities of raw materials (fabric, dyes, and wax), water consumption, electricity use, production time, material losses, and solid waste and wastewater generation and management of waste and wastewater associated with the manufacturing of batik sarees. Onsite measurements were conducted to quantify material inputs and resource consumption during different production stages, while follow-up discussions were used to clarify missing information and confirm data uncertainties. This approach ensured that the datasets accurately reflected small-scale batik manufacturing practices in Sri Lanka during January to June 2024. For electricity consumption, background data were obtained from the SimaPro 10.1.0.6 database, while all other inputs and outputs were measured or estimated directly at the facility. All data were normalized to the functional unit of one batch of sixteen batik sarees, corresponding to 4.8 kilograms of finished product, to ensure consistency across all process stages.

2.4. Life Cycle Impact Assessment (LCIA) Modelling

Life Cycle Impact Assessment (LCIA) was conducted using SimaPro version 10.1.0.6, integrating inventory data to quantify potential environmental impacts across the included unit processes. The ReCiPe 2016 Midpoint (H) methodology was selected because it provides globally representative characterization factors, improved impact assessment models, and incorporates updated impact pathways for key environmental issues, including climate change, water use, particulate matter formation, and terrestrial acidification(Huijbregts et al.,2017). These features make it a scientifically robust and widely accepted method for evaluating the environmental impacts of manufacturing processes.The life cycle inventory modelling was performed using the Ecoinvent version 3.10 database available within SimaPro 10.3, supplemented with primary inventory data collected from the selected batik manufacturing facility. The analysis covered multiple impact categories, including climate change, ozone depletion, terrestrial acidification, freshwater and marine eutrophication, photochemical ozone formation, particulate matter formation, fossil resource depletion, metal resource depletion, and water depletion. This approach enabled the evaluation of the relative contribution of each process to these impact categories and provided the basis for subsequent hotspot analysis.

2.5. Data Quality and Assumptions

The quality of the inventory data was evaluated in terms of completeness, consistency, and representativeness. Primary data on material and energy inputs and outputs were collected through onsite measurements and structured interviews with the factory owner, with follow-up communications conducted to address missing data and confirm uncertainties. This ensured that the datasets reflect typical small-scale batik manufacturing practices in Sri Lanka. Following the gate-to-gate approach, upstream processes such as chemical manufacturing, cotton cultivation, and fabric production were excluded, with electricity generation being the only background process modeled using SimaPro. Variability arising from material losses, evaporation during dyeing, and batch-to-batch differences was acknowledged during result interpretation, although no formal uncertainty analysis was performed.

3.6. Normalization

Normalization of the LCIA results was performed to enable comparison across different process stages and impact categories (Muthukumarana et al., 2017). In this study, external normalization was applied, using published reference data for each impact category (Benini et al., 2014; Prado et al., 2017).The selected normalization reference is based on the global annual environmental impacts per capita as defined in the ReCiPe 2016 methodology. External normalization scales the environmental impacts of each process relative to the total impacts of a chosen reference system, expressed per person, per system, or per region over a defined period. This method facilitated the identification of the most environmentally burdensome processes and supported the prioritization of interventions for enhancing sustainability in batik production.

2.7. Hotspot Analysis

Hotspot analysis was conducted to identify stages and processes within the batik production chain that contribute disproportionately to overall environmental impacts (Montagnini & Nair, 2004). The analysis considered unit processes and associated inputs and outputs, including electricity consumption, biomass fuel use, water, dyes, and wax,to determine which activities impose the greatest environmental burdens across the assessed impact categories. By quantifying the contribution of each process to energy use, water consumption, chemical usage, and emissions, critical areas requiring intervention were highlighted. Hotspot identification was based directly on the LCIA results, enabling prioritization of processes for targeted environmental improvement. This approach provides actionable insights for reducing the

environmental footprint of batik manufacturing and enhancing the overall sustainability of small-scale textile enterprises.

3. Results and Discussion

The collected input–output data for each stage of the batik manufacturing process are presented in Table 1. The system boundary encompasses sequential operations such as cutting, sewing, wetting, waxing, dyeing, boiling, washing, drying, ironing, and packaging. Key inputs include cotton fabric, polyester threads, paraffin wax, dyes, water, electricity, and wood, while outputs consist of the processed fabric, wastewater, gaseous emissions, and ash generated primarily from biomass combustion during boiling. These quantified data formed the basis for the life cycle inventory (LCI) and were subsequently used for impact assessment modelling.

Table 1: Input-output data of batik manufacturing processes

Input	Amount	Unit	Output	Amount	Unit
Cutting					
Cotton fabric	4.80	kg	Cut fabric	4.8	kg
Sewing					
Cotton fabric	4.80	kg	Sewed fabric	5.10	kg
Polyester threads	0.30	kg			
Electricity	5.00	kWh			
Wetting					
Sewed fabric	5.10	kg	Wetted fabric	5.10	kg
Water(well)	16.00	L	Waste water	11.20	L
Waxing					
Wetted fabric	5.10	kg	Waxed fabric	5.10	kg
Paraffin	64.00	kg			
Dyeing					
Waxed fabric	5.10	kg	Dyed fabric	5.10	kg
Naphthol dye	0.24	kg	Waste water		
Aryl dizonium	0.24	kg			
Water(well)	32.00	L			
Boiling					

Dyed fabric	5.10	kg	Boiled fabric	5.10	kg
Water(well)	24.00	L	Waste water	24.00	L
Wood	10.00	kg			
Washing					
Boiled fabric	5.10	kg	Washed fabric	5.10	kg
Water(well)	88.00	L	Wastewater	88.00	L
Sodium tripolyphosphate	0.24	kg			
Drying					
Washed fabric	5.10	kg	Dried fabric	5.10	kg
Ironing					
Ironed fabric	5.10	kg	Ironed fabric	5.10	kg
Electricity	0.80	kWh			
Packaging					
Ironed fabric	5.10	kg	Packed fabric	5.10	kg
Packaging material	0.27	kg			

Table 2: Life Cycle Impact Assessment Results for Batik Production under the ReCiPe Midpoint (H) Method

Impact category	Unit	Total
Global warming	kg CO_2 eq	38.12
Stratospheric ozone depletion	kg CFC11 eq	0.00
Ozone formation, Human health	kg NOx eq	0.13
Fine particulate matter formation	kg PM2.5 eq	0.01
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.12
Terrestrial acidification	kg SO_2 eq	0.22
Freshwater eutrophication	kg P eq	0.01
Marine eutrophication	kg N eq	0.00
Terrestrial ecotoxicity	kg 1,4-DCB	56.46
Freshwater ecotoxicity	kg 1,4-DCB	1.50
Marine ecotoxicity	kg 1,4-DCB	0.46
Human carcinogenic toxicity	kg 1,4-DCB	0.02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.17
Land use	m2a crop eq	0.56
Mineral resource scarcity	kg Cu eq	0.04
Fossil resource scarcity	kg oil eq	7.84
Water consumption	m^3	5.90

In this study, global warming and terrestrial ecotoxicity were identified as the most significant impact categories at the characterization stage (Table 2). However, following normalization, freshwater and marine ecotoxicity emerged as dominant categories (Figure 2). This shift reflects the influence of normalization, which scales each impact relative to its global reference value. While global warming and terrestrial toxicity contribute substantially in absolute terms, their relative importance decreases due to large global background values. In contrast, ecotoxicity-related impacts possess lower global reference values, amplifying their relative significance after normalization. The use of Naphthol dyes, paraffin wax, and Aryl diazonium compounds in the batik process likely intensified these toxicity related impacts, emphasizing that chemical discharges pose a comparatively higher ecological risk to aquatic systems even in small-scale production settings.

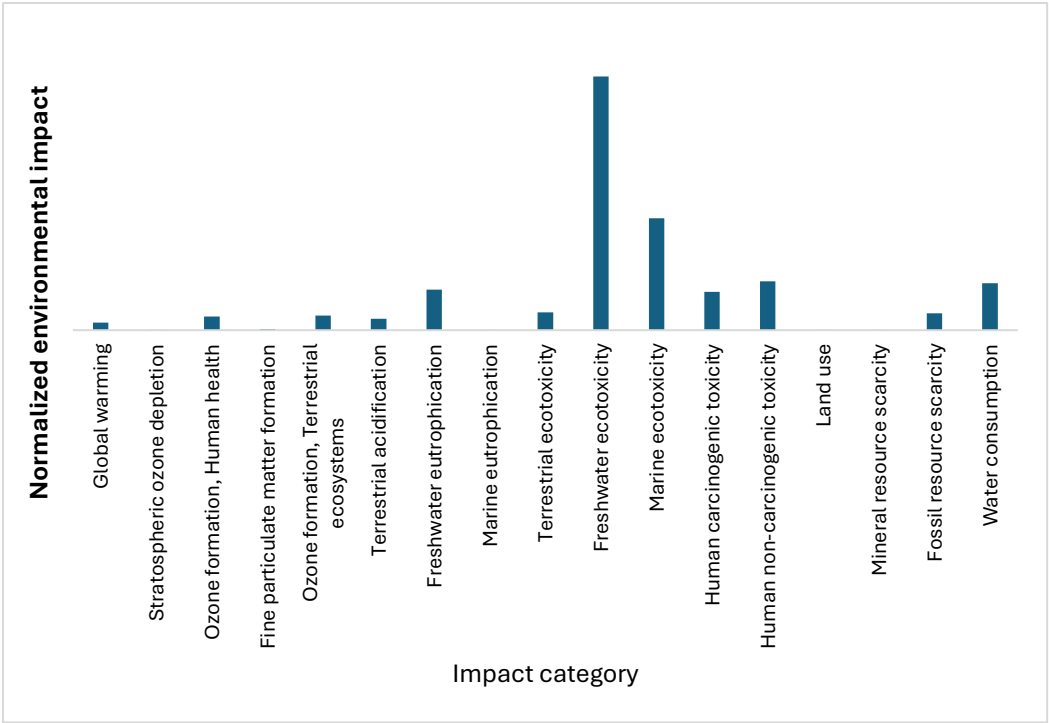


Figure 2. Process-level hotpot analysis showing the percentage contribution of each batik manufacturing stage to the assessed environmental impact categories

Normalized results indicated that freshwater ecotoxicity emerged as the primary impact category, followed by marine ecotoxicity, within the gate to gate scope of

batik manufacturing. These results reflect the substantial environmental burden associated with the use of synthetic dyes, paraffin wax, alkalis, and auxiliary chemicals, particularly during the dyeing and wax removal stages. Although approximately 80% of wax and dye residues are typically recovered for reuse, the remaining fraction is directly discharged onto land, where it can infiltrate soils and enter freshwater systems via runoff or leaching, ultimately reaching rivers and coastal waters. This pathway explains the observed impacts on marine ecotoxicity, despite the initial terrestrial discharge. The persistence of synthetic dyes,especially naphthol-based azo dyes, contributes to elevated ecotoxicity due to their low biodegradability and potential to form toxic aromatic amines during degradation. Additionally, batik effluents have been reported to contain heavy metals, including iron, copper, chromium, cadmium, and lead, further exacerbating environmental toxicity (Aish et al., 2024).

Aish et al. (2024) identified marine ecotoxicity as a major impact category in their gate-to-gate LCA of industrial-scale batik production, primarily driven by the extensive use of chemicals such as sulphuric acid, sodium hydroxide, and sodium carbonate, which readily dissolve in large volumes of water and are discharged directly into aquatic systems. In contrast, the present study demonstrates that marine ecotoxicity also emerges as a significant impact in small-scale, household-level batik production, despite the absence of direct effluent disposal into waterways. This impact is attributed to the indirect transport of chemical residues,including Napthol dyes, paraffin wax, and Aryl diazonium compounds,through soil infiltration and surface runoff, ultimately reaching aquatic environments. These findings suggest that even decentralized, land-based batik operations can contribute to marine ecotoxicity, highlighting the need for integrated mitigation strategies that address both terrestrial and aquatic pollution pathways.

Human toxicity impacts were also identified. Non-carcinogenic toxicity emerged as a key category, associated with workers' and community exposure to hazardous substances such as dyes, alkalis, and finishing chemicals. These compounds can cause respiratory irritation, dermatological disorders, and other chronic health issues. Carcinogenic toxicity, although less significant in relative terms, was linked to trace constituents in dyes and auxiliaries with known or suspected carcinogenic properties. Long-term occupational exposure during manual dyeing and wax removal processes increases the risks of both toxicity categories, particularly in contexts where wastewater treatment and occupational safety measures are limited.

Although global warming potential (GWP) was lower in normalized terms than toxicity-related categories, it remained an important contributor. GWP was primarily driven by biomass combustion for boiling fabric, which released CO_2 and other

greenhouse gases. Electricity use for sewing and ironing contributed marginally. Since the system boundary excluded upstream processes, the reported GWP reflects only direct, on-site energy-related emissions. Water consumption, while relatively moderate compared to chemical-related impacts, is also noteworthy given the large volumes required for boiling, dyeing, washing, and wax removal. Inefficient water use coupled with untreated discharge highlights the need for conservation and recycling strategies in batik production.

The hotpots analysis was conducted to identify the contribution of individual production stages to the overall environmental impacts. The highest contributing process combinations and dominant process stages for each impact category are presented in Table 3. As shown in Table 3, different production stages contributed differently across impact categories, indicating that environmental burdens in batik manufacturing are influenced by both energy-intensive operations and process-related emissions.

Boiling and washing operations were identified as the primary energy-related hotpots, accounting for over 30% of the impacts in categories such as GWP (31.09%), stratospheric ozone depletion (30.17%), ozone formation–human health (35.90%), and human non-carcinogenic toxicity (40.48%).

Table 3: Hot-spot analysis' highest impact percentage for each process

Impact Category	Boiling + Washing (%)	Wetting + Dyeing + Boiling + Washing (%)	Dominant Process Stage	Max % Contribution
Water Consumption	66.06	66.48	Washed cloth	33.16
Human Non-Carcinogenic Toxicity	40.46	58.69	Boiled fabric	20.23
Human Carcinogenic Toxicity	37.73	57.80	Boiled fabric	18.86
Ozone Formation (Human Health)	35.90	57.30	Dyed cloth	17.95
Freshwater Eutrophication	44.15	63.52	Dyed cloth	16.49
Marine Eutrophication	41.22	61.18	Boiled fabric	21.32
Terrestrial Acidification-	39.87	59.80	Boiled fabric	19.93

Freshwater Ecotoxicity-	42.65	62.41	Boiled fabric	20.16
Marine Ecotoxicity	40.33	60.47	Boiled fabric	19.13
Terrestrial Ecotoxicity	38.26	58.33	Boiled fabric	18.36
Global Warming Potential-(GWP)	34.51	57.46	Boiled fabric	17.26

These impacts are directly tied to the energy intensity of water heating, the combustion of biomass, and the associated release of pollutants. Conversely, sewing, wetting, dyeing, boiling, and washing combined were the dominant contributors to ecotoxicity and eutrophication categories, with contributions exceeding 80% for freshwater and marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, and land use. These results highlight the dual burden of batik manufacturing: energy-related emissions driving climate and air-quality impacts, and wastewater discharges driving ecotoxicity and nutrient enrichment.

In contrast to the present study, which identified environmental hotspots based on process-level contributions, Iqbal et al. (2021) conducted a material-based LCA linking environmental impacts directly to raw material inputs such as paraffin, dyes, and refinery gas. Their analysis revealed that paraffin accounted for approximately 68.7% of the total environmental impact, followed by dyes and electricity, emphasizing the need for material substitution to reduce emissions. In the current study, the boiling and washing processes were identified as major hotspots, contributing 31.09% to global warming potential, 35.9% to ozone formation (human health), and 66.16% to water consumption. These results suggest that, unlike Iqbal et al. (2021), where material inputs dominated the impact profile, the process operations themselves are key contributors to environmental burdens in the batik production system. Therefore, while material substitution remains important, optimizing production processes through improved energy efficiency, dye bath management, and wastewater treatment can substantially reduce environmental impacts and enhance sustainability in batik manufacturing.

3.3 Process Optimization Strategies for Sustainable Batik Production

The hotspot analysis highlighted that boiling, washing, dyeing, and waxing stages contribute substantially to environmental impacts due to their high energy intensity, water use, and chemical discharge. Optimizing these processes can significantly mitigate the overall environmental footprint of batik manufacturing.

In the boiling stage, substantial energy savings can be achieved by implementing heat recovery systems that reuse waste heat from condensate or exhaust streams to preheat incoming water. Studies in textile dyeing and finishing industries have shown that heat recovery can reduce energy consumption by 15–25%, with short payback periods (Elahee, 2010). Integrating such systems in batik production can not only lower fuel or electricity demand but also decrease greenhouse gas emissions associated with thermal energy use. Additionally, combining heat recovery with process optimization, such as minimizing water volumes and improving insulation, can further enhance overall energy efficiency. These measures contribute to both economic savings and environmental sustainability in traditional textile manufacturing processes.

For washing and rinsing operations, counter-current washing, which involves the sequential reuse of rinse water across multiple cycles, can further decrease water consumption by approximately 30%(Hashem and Farag,2025). Integrating membrane technologies such as ultra-filtration or reverse osmosis enhances water reuse potential and decreases pollutant concentrations (Zakaria et al.,2023).In laboratory-scale experiments, reverse osmosis (RO) demonstrated high treatment efficiency, achieving 99.6% chemical oxygen demand (COD) reduction and nearly complete color removal under batch operation, while the continuous mode achieved 91.9% COD removal and 96.4% color elimination (Kurt et al.,2012).

In the dyeing process, optimizing parameters such as pH, temperature, and bath ratio improves dye fixation efficiency, minimizing chemical waste. The use of enzymatic or low-salt dyeing techniques and effluent reuse can further reduce fresh water and chemical consumption (Ghaly et al., 2014). Substituting synthetic dyes with biodegradable natural dyes derived from plant or microbial sources can significantly lower ecotoxicity and improve biodegradability.

In line with this approach, replacing conventional petroleum-based paraffin with natural waxes such as beeswax or carnauba wax during the waxing stage can enhance biodegradability and minimize toxicity, promoting a more sustainable and health-conscious batik production process. Ariani and Pandanwangi (2021) developed an eco-friendly cold wax utilizing tamarind seed powder, whose polysaccharide content exhibits strong coagulating properties and can serve as an effective barrier during batik coloring. The incorporation of this natural ingredient not only reduces environmental impact but is also non-toxic and safe for use by all individuals, including children. Enhancing wax recovery systems through mechanical separation or filtration can reduce waste generation and pollutant discharge, complementing advanced pre-treatment strategies. Rashidi et al (2020) developed a sustainable per-treatment approach using a baffle separation tank with nano sodium silicate, which

demonstrated over 95% wax removal within one hour, significantly outperforming conventional methods, while partial removal of other chemicals ranged from 12.5% to 32.4%

Finally, implementing energy and water audits, staff training, and continuous process monitoring can identify inefficiencies and promote long-term sustainability. Cleaner production assessments in textile industries have demonstrated that such measures can reduce energy use by 25–40%, water consumption by 30–50%, and pollutant loads by up to 60%.

Overall, process optimization in batik production can substantially reduce both direct and indirect environmental burdens, complementing material substitution efforts and contributing to a more circular and sustainable production system.

3.4 *Limitations of the study*

This study has several limitations that should be considered when interpreting the results. First, the assessment was limited to a gate-to-gate system boundary and therefore did not include upstream processes, such as cotton cultivation, yarn production, fabric manufacturing, or downstream processes related to product use and end-of-life management. Second, the life cycle inventory was developed using primary data collected from a single small-scale batik manufacturing facility in Sri Lanka. Although the selected facility represents typical cottage-level batik production, variations in production capacities,chemicals usage, resource consumption, and technology among manufacturers may influence the environmental impacts. Third, due to limited availability of detailed upstream inventory data for imported raw materials, particularly cotton fabric, the present study focused on the manufacturing stage to ensure the reliability of the inventory data. Future studies should consider expanding the system boundary to cradle to gate or cradle to grave by incorporating comprehensive supply chain and end of life management data from multiple manufacturing facilities to provide a more complete assessment of the environmental impacts of batik production.

4. Conclusion

The LCA revealed that energy-intensive boiling and washing and chemical,intensive wetting, dyeing, and waxing are the main contributors to environmental impacts in traditional batik production. Persistent synthetic dyes and heavy metals drive ecotoxicity and human toxicity, while biomass combustion contributes to greenhouse gas emissions. Implementing heat recovery, water reuse, optimized dyeing, and natural wax substitution can reduce energy use, water consumption, and pollutant loads significantly. These interventions, alongside cleaner production practices, can

enhance the sustainability of small-scale batik enterprises and support responsible textile production in line with SDG 12.

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