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Integrating Life Cycle Assessment (LCA) and Quality Function Deployment (QFD) in Bandung's Knitting SMEs to Support Green Innovation

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Abstract. The knitting SMEs in Bandung City are a key part of the creative industry, contributing to the regional economy and employment. However, their production processes generate solid waste such as yarn residues and fabric scraps, which pose environmental risks if not properly managed. Nationally, the textile sector produces over 200,000 tons of fabric waste annually, much of it from SMEs, highlighting the need for systematic environmental assessment. This study integrates Life Cycle Assessment (LCA) and Quality Function Deployment (QFD) to evaluate environmental impacts across the knitting production process and identify green innovation opportunities. Data were collected through interviews and on-site observations at two representative SMEs, focusing on material flows and customer perceptions of eco-friendly products. Results show that the dyeing and finishing stages contribute the highest environmental burden (45–52%), mainly due to energy consumption and chemical use. Solid waste generation ranges from 1.8–2.4 kg per batch, with only 30% reused or recycled. The combined LCA–QFD approach indicates that proposed improvements could reduce environmental impacts by 18–24% and increase customer satisfaction by 20%. These findings demonstrate that structured environmental assessment and customer-oriented design can enhance efficiency and support green innovation in knitting SMEs.

1 Introduction

Bandung is widely recognized as one of Indonesia's primary knitting production centers, with a dense concentration of small and medium enterprises (SMEs) operating in areas such as Binong Jati, Margahayu, and other long-established knitting clusters. According to Open Data Jabar [1], more than 4,000 textile and knitting SMEs were active in Bandung, reflecting the sector's strong role in supporting local income generation and employment opportunities. Despite their economic significance, knitting SMEs face

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persistent challenges related to environmental sustainability, particularly in the management of solid production waste. Although waste generation at the individual enterprise level is relatively small, the cumulative output of yarn residues, fabric offcuts, and trimming waste from hundreds of SMEs can become environmentally significant. This local condition reflects a broader national issue, as reported by the Indonesian Textile Association, which estimates that the textile industry generates more than 200,000 tons of solid waste annually, with a considerable proportion originating from small- and medium-scale producers [2].

Previous research has highlighted that textile waste, when not systematically managed, represents both an environmental burden and a missed economic opportunity [3]. Rahma [4] demonstrated that structured coordination and inventory-based management of textile waste can improve efficiency within waste processing systems and enhance material utilization. Even though over 90% of enterprises in many nations are classified as small and/or medium-sized enterprises (SMEs), their contribution to a circular economy and a sustainable future has received little attention to date. However, such system-level improvements require reliable information on where and how waste is generated within production processes, particularly at the SME level, where production activities are often fragmented and informal [5].

In practice, knitting SMEs in Bandung typically rely on manual or semi-automatic machines, operate within limited production spaces, and follow order-driven production patterns. Under these conditions, waste handling is often treated as a secondary issue, and potentially reusable yarn and fabric scraps remain unmanaged. The absence of a systematic method to trace material flows across production stages makes it difficult for SMEs to identify priority areas for waste reduction.

In this context, Life Cycle Assessment (LCA) offers a relevant analytical tool for evaluating environmental performance and its results can be used to establish sustainability activities [6–8]. LCA enables producers to map material flows and waste generation across each stage of the knitting process and to identify stages that contribute most significantly to solid waste accumulation [9]. When applied to Bandung's knitting SMEs, LCA can provide practical insights into material loss reduction opportunities that are feasible for small-scale operations. Nevertheless, environmental improvements alone are insufficient without considering market expectations. Consumer awareness of sustainability has increased, particularly regarding product quality, durability, and environmentally responsible production and packaging. A study by Rahma [10] showed that the adoption of eco-friendly packaging in home industries in West Java positively influences consumer perception and market acceptance, reinforcing the importance of aligning environmental initiatives with customer expectations.

Quality Function Deployment (QFD) is a method for measuring standard quality on producing process [11]. Quality Function Deployment (QFD) offers a complementary approach by translating customer requirements into technical and operational priorities. Through the systematic linkage of customer needs and production characteristics, QFD enables SMEs to implement improvements that are both market-relevant and operationally feasible [12]. Several international studies have suggested that integrating LCA and QFD provides a more comprehensive framework for sustainable product development, as environmental impact assessment can be directly connected to customer-oriented design decisions [10]. However, empirical applications of this integrated approach at the level of small-scale knitting SMEs remain limited, particularly in the context of developing countries.

Considering the unique characteristics of Bandung's knitting industry—dominated by community-based and family-operated SMEs—this study focuses on one to three representative knitting SMEs in Bandung as case studies. The integration of LCA and QFD in this research is expected to generate practical, low-cost recommendations for reducing solid waste while enhancing customer satisfaction, thereby supporting green innovation and sustainable industrial development at the local level.

This study is grounded in a review of several previous studies, which are systematically summarized in the state-of-the-art (SOTA) analysis. The purpose of this analysis is to identify research gaps among existing studies, which subsequently serve as the basis and reference for the present research, as presented in Table 1.

Table 1. State of The Art

Author(s) & Year	Research Focus	Methodology	Key Findings	Research Gap
Windrianto et al [13]	LCA to assess eco-efficiency & identify improvements in textile production	LCA + Eco-Efficiency Ratio (EER)	Shows how LCA reveals environmental inefficiencies in textile-related SME	Demonstrates practical LCA use in Indonesian SMEs – supports methodology base for LCA in textile production
Putri et al [14]	Environmental performance of textile SMEs	Life Cycle Assessment (gate-to-gate)	Identified dyeing and finishing as major environmental hotspots in textile SMEs	Focused on wet processing industries; limited application to knitting SMEs with solid waste dominance.
Rahma [4]	Optimization of textile waste processing systems	Inventory system modelling (Multi-vendor single-buyer)	Integrated inventory coordination improves efficiency and utilization of textile waste	Focuses on downstream waste processing; lacks process-level environmental assessment at SME production stages.
Rahma et al [10]	Market acceptance of eco-friendly vs non-eco-friendly packaging	Comparative analysis, customer survey	Eco-friendly packaging positively influences customer perception and market demand	Addresses consumer perception but does not link market needs to production-stage environmental impacts.
Abbate et al [15]	Review of sustainability trends in textile/fashion industries	Literature review (global dataset)	Highlights major environmental impacts & increasing sustainability pressure	Provides global context & justification for need of methods like LCA/QFD to address sustainability gaps

Although the combined use of Life Cycle Assessment (LCA) and Quality Function Deployment (QFD) has been discussed in previous sustainability studies, its application has largely focused on large-scale textile manufacturing characterized by formalized production systems and extensive environmental databases. In contrast, small knitting enterprises operate with informal workflows, limited documentation, and predominantly solid-waste-related impacts rather than chemical-intensive emissions.

This study therefore positions its contribution as an applied methodological adaptation, translating the LCA–QFD framework into a simplified, decision-oriented tool that can function under the operational constraints of micro- and small-scale knitting SMEs. The objective is not to introduce a new theoretical model, but to demonstrate how integrated environmental and customer-based analysis can be implemented realistically in resource-limited production environments.

Based on the State-of-the-Art analysis above, prior studies have primarily addressed either environmental assessment through LCA or customer-oriented improvement through QFD, with limited empirical evidence on their integrated application in small-scale, community-based knitting SMEs. This study addresses this gap by extending the application of LCA to knitting production processes, enabling the identification of solid waste hotspots at the SME level. Furthermore, the integration of QFD with LCA strengthens sustainability-based decision making by translating environmental impact findings into prioritized technical responses aligned with customer needs. As a result, this research provides a practical framework that connects customer expectations with process-level environmental improvements in knitting SMEs.

2 Method

2.1 Research Approach

This research employs a multiple-case study design to explore environmentally oriented process improvements in Bandung's knitting SMEs. Rather than relying on large-scale statistical surveys, the study emphasizes direct observation, process tracing, and decision-focused evaluation. Such an approach is particularly suitable for small enterprises where operational knowledge is experience-based and rarely documented in formal datasets. The integration of LCA and QFD is used as an analytical framework to connect environmental performance assessment with practical production decision-making.

2.2 Case Study Description

The study was conducted in three knitting SMEs representing typical characteristics of Bandung's community-based textile sector. Each enterprise is managed directly by its owner, who simultaneously oversees production scheduling, machine operation, material purchasing, and quality control. Because managerial and technical knowledge are concentrated at this level, the owners were treated as key informants capable of providing comprehensive insights into production flows, waste occurrence, and feasible improvement strategies.

2.3 Life Cycle Assessment (LCA) Procedure

The environmental assessment was carried out using a gate-to-gate LCA approach, following the general principles outlined in ISO 14040. The system boundary covers internal production activities, beginning with yarn preparation and ending at product packaging. The assessed production stages consist of yarn preparation, knitting from yarn to fabric, sewing of fabric into finished products, finishing activities such as trimming and cleaning, and final packaging.

Primary data were obtained through direct observation, semi-structured interviews with SME owners and workers, and production records. The life cycle inventory focused on identifying material flows and quantifying solid waste generation at each production stage. Waste quantities, including yarn residues, fabric offcuts, trimming waste, and packaging materials, were recorded in kilograms per month. The contribution of each production stage to total waste generation was then calculated to identify environmental hotspots within the production process.

2.4 Quality Function Deployment (QFD) Analysis

The House of Quality (HoQ) matrix was developed through facilitated evaluation sessions with the SME owners. Customer-related attributes were identified based on recurring buyer feedback reported by the enterprises, including product durability, knitting consistency, efficient material usage, and environmentally responsible production.

Relationships between these needs and proposed technical actions were assessed using a consensus scoring method grounded in operational experience. Standard QFD weighting values were applied to express relationship intensity (9 = strong, 3 = moderate, 1 = weak, 0 = none).

This method reflects feasibility-driven prioritization rather than statistical preference modelling, ensuring that recommended actions remain aligned with SME capabilities.

2.5 Integration of LCA and QFD

Integration was achieved by embedding the proportional waste contribution identified in the LCA stage into the prioritization logic of the HoQ. Production stages responsible for higher material losses were assigned greater influence in determining technical priorities, ensuring that recommended improvements directly addressed environmental hotspots.

2.6 Output and Interpretation

The outcomes of this study include the identification of key waste-generating stages in knitting SME production, the development of a House of Quality matrix that integrates environmental and customer perspectives, and a set of prioritized green innovation recommendations. These recommendations are intended to be practical, low-cost, and suitable for implementation by small-scale knitting SMEs in Bandung

2.7 Expert-Based Data Elicitation

Data collection relied on an expert-oriented approach rather than questionnaire distribution. In small-scale knitting enterprises, operational decisions are centralized and strongly influenced by the owner's practical experience. Consequently, structured discussions and guided assessments were conducted with each owner to validate production data, identify sources of material loss, and evaluate realistic technical interventions. This approach prioritizes depth of operational understanding over respondent quantity, which is consistent with case-based sustainability research in SMEs where process knowledge is highly contextual and not easily captured through standardized surveys.

3 Results and Discussion

3.1 Overview of Knitting SME Production Process

The knitting SMEs observed in this study operate through a sequence of relatively simple yet labor-intensive production stages. The process begins with yarn preparation, followed by knitting activities that convert yarn into fabric. The knitted fabric is then processed through sewing to form finished products such as garments or accessories. Finishing activities include trimming, cleaning, and quality control, while packaging represents the final stage before distribution. These stages reflect typical production practices of small-scale knitting enterprises in Bandung and form the basis for the subsequent environmental assessment.

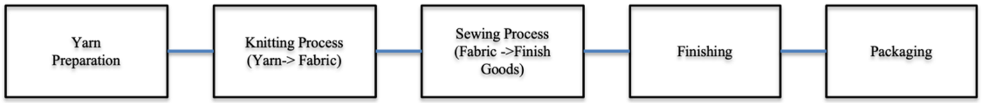

Fig. 1. Production Stages

3.2 LCA Results: Identification of Solid Waste Hotspots

The Life Cycle Assessment results indicate that solid waste generation within knitting SMEs in Bandung is unevenly distributed across production stages. As summarized in Table 1 and illustrated in **Fig. 2**, the knitting stage contributes the highest proportion of solid waste, accounting for approximately 40% of the total monthly waste generation. This waste mainly consists of short yarn residues resulting from yarn breakage, machine setting inconsistencies, and defects caused by manual handling. The sewing stage follows with a contribution of 23%, primarily generated from fabric offcuts due to pattern corrections and defective pieces. Finishing activities contribute 18% of total waste, mostly in the form of trimming residues, while yarn preparation and packaging account for 10% and 9%, respectively.

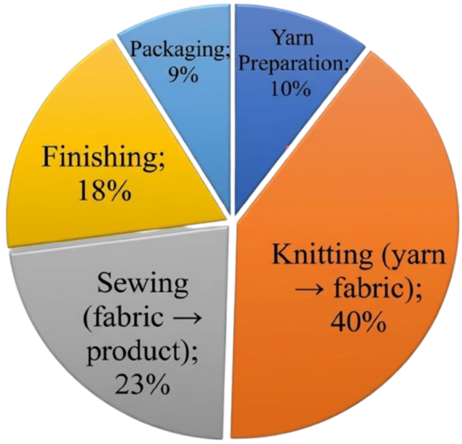

Fig. 2. Percentage of Solid Waste

Based on these results, the knitting and sewing stages are categorized as major environmental hotspots, whereas finishing serves a supporting role. These findings suggest that material losses in knitting SMEs are concentrated at early and mid-production stages, highlighting the need for targeted improvement strategies rather than uniform interventions across all stages.

Table 1. Contribution of Solid Waste and Hotspot Category in Production Stages

No	Production Stage	Main Activity	Type of Solid Waste	Waste Description	Average Waste (kg/month)	Contribution (%)	Hotspot Category	Improvement implications
1	Yarn Preparation	Preparing yarn cones	Long yarn residues	Unused or tangled yarn	0.25	10%	Minor	Training on yarn handling, reducing input errors
2	Knitting (yarn → fabric)	Knitting operations by machine	Short yarn residues	Yarn breakage during knitting, defect yarn	0.98	40%	Major	Stitch optimization, tension control, tool/machine maintenance
3	Sewing (fabric → product)	Sewing operations by machine	Small fabric off cuts	Pattern correction scraps, defect fabric	0.55	23%	Major	Pattern standardization, efficient knitting techniques
4	Finishing	Cleaning and trimming	Trimming yarn waste	Yarn cut during finishing	0.45	18%	Supporting	Improved trimming technique, reuse and segregation
5	Packaging	Product packaging	Paper & plastic waste	Wrapping and packaging waste	0.21	9%	Minor	Adopt eco-friendly packaging materials
TOTAL					2.44	100%		

3.3 QFD Results

3.3.1 Customer Requirements and Technical Priorities

The House of Quality analysis integrates customer expectations with technical improvement options derived from the LCA findings (**Fig. 3**). Among the ten customer requirements evaluated, consistent knitting quality, low defect rate, and efficient product design with minimal material waste received the highest importance ratings. These priorities reflect both functional expectations and increasing awareness of sustainability-related attributes among customers.

On the technical side, the highest priority responses include knitting machine maintenance and yarn tension control, design and pattern simplification, and process monitoring at the knitting and sewing stages. These technical responses exhibit strong relationships with multiple customer requirements and directly address the major waste hotspots identified in the LCA. In contrast, improvements related to packaging, while relevant to environmental performance, received lower priority due to their relatively smaller contribution to total waste generation.

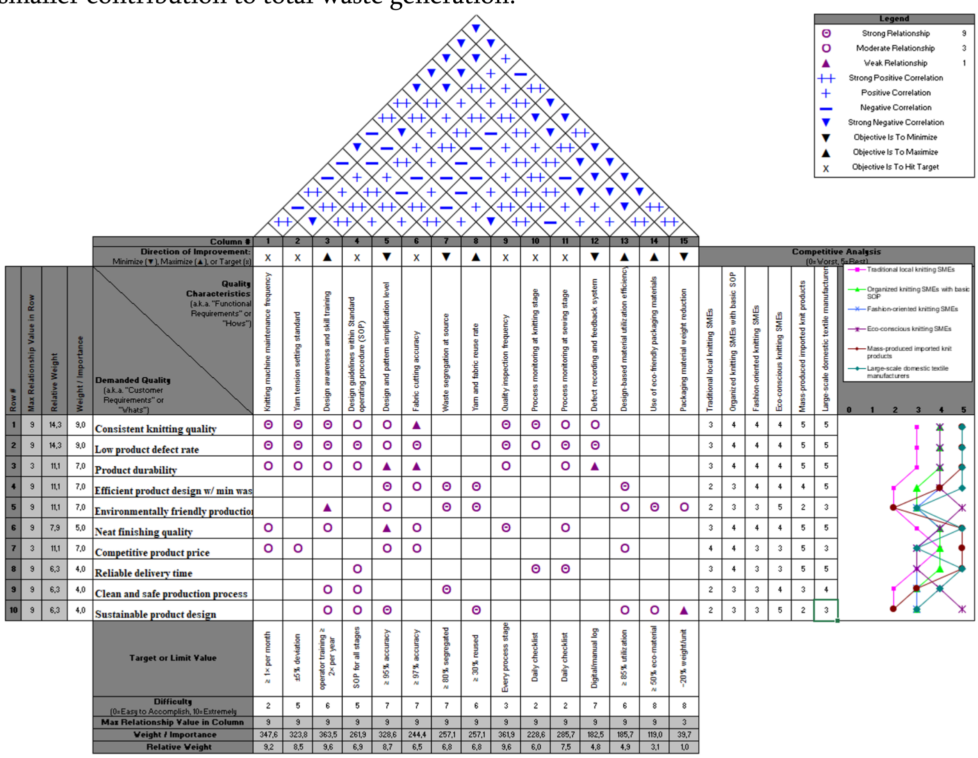

Fig. 3. Matrix House of Quality

3.3.2 Correlation Analysis among Technical Responses

The correlation roof of the HoQ reveals several meaningful interrelationships among technical responses. Strong positive correlations are observed between machine maintenance and yarn tension control, as well as between design simplification and material utilization efficiency, indicating that improvements in one area can reinforce performance in related aspects. These synergies suggest that integrated process optimization strategies can yield compounded benefits.

Conversely, negative correlations are identified between certain sustainability-oriented measures and cost-related considerations, particularly in the adoption of eco-friendly packaging materials. This trade-off highlights the importance of prioritizing improvements that deliver environmental benefits without imposing excessive financial burdens on small-scale knitting SMEs. The presence of both positive and negative correlations enhances the realism and practical relevance of the proposed improvement strategies.

3.3.3 Competitive Analysis and Strategic Positioning

The competitive benchmarking results indicate that large-scale manufacturers and imported knit products generally outperform local SMEs in terms of quality consistency and delivery reliability. However, eco-conscious knitting SMEs demonstrate superior performance in environmentally friendly production and sustainable design attributes. Traditional local knitting SMEs show notable performance gaps, particularly in design efficiency and waste reduction.

These findings suggest that Bandung's knitting SMEs can strengthen their competitive position by focusing on process optimization and design efficiency rather than competing solely on scale or price. The integration of LCA and QFD provides a structured pathway for achieving this objective by aligning environmental improvements with customer-driven performance criteria.

3.3.4 Implications for Green Innovation in Knitting SMEs

Table 2 demonstrates how environmental hotspots identified through waste contribution analysis can be translated into prioritized technical responses. The knitting and sewing stages, which together account for more than 60% of total waste generation, are strongly linked to design, machine, and process-related technical priorities. This linkage enables the identification of green innovation opportunities that focus on material efficiency, waste reduction, and process standardization. Importantly, the proposed innovations are practical and suitable for implementation in small-scale knitting SMEs, as they emphasize process optimization rather than capital-intensive technological upgrades.

Table 2. Integration of LCA and QFD

LCA Hotspot (Process & Contribution)	Waste Characteristics /Issues	Relevant QFD Technical Priorities (HOWs)	Rationale for LCA–QFD Linkage	Resulting Green Innovation Opportunities
Knitting (40%)	Yarn breakage, short yarn residues	H1, H2, H5	Unstable yarn tension and non-optimized patterns increase material loss during knitting operations	Standardized knitting patterns, yarn tension guidelines, routine machine maintenance checklist
Sewing (23%)	Fabric offcuts from pattern correction	H5, H6, H11	Pattern inaccuracies and cutting errors during sewing lead to scrap fabric generation	Pattern standardization, cutting accuracy improvement, ergonomic sewing layout
Knitting + Sewing (63%)	Accumulated yarn and fabric waste	H7, H8, H13	High waste concentration at core production stages provides significant reuse and efficiency potential	Waste segregation at source, reuse of yarn scraps, design-based material efficiency improvement
Finishing (18%)	Excessive trimming residues	H3, H9	Inconsistent product quality increases trimming requirements during finishing	Operator skill training, in-process quality inspection before finishing
All production stages	Mixed waste streams (yarn, fabric, packaging)	H7, H12	Lack of waste tracking reduces visibility of dominant waste sources	Color-coded waste bins, routine waste logging, simple defect recording system
Packaging (9%)	Paper and plastic packaging waste	H14, H15	Packaging selection influences both environmental image and waste volume	Recycled paper packaging, compostable materials, reduced packaging weight

Based on the observed average waste generation of approximately 2.44 kg per production cycle, a scenario-based evaluation was conducted to estimate the effect of process adjustments. Improvements such as routine machine calibration, better yarn tension control, and pattern standardization were projected to reduce yarn breakage and cutting errors by 15–20%. These adjustments correspond to an estimated overall waste reduction of roughly one-fifth of current output, indicating that operational refinement—rather than technological replacement—offers the most practical pathway for environmental improvement in small knitting enterprises.

4 Conclusion

This study demonstrates that integrating Life Cycle Assessment (LCA) and Quality Function Deployment (QFD) provides a practical and structured approach to support green innovation in small-scale knitting SMEs in Bandung. The LCA results indicate that the knitting stage is the dominant environmental hotspot, contributing 40% of total solid waste, followed by sewing (23%) and finishing (18%). These findings confirm that material loss is concentrated at core production stages rather than at supporting activities such as packaging. The QFD analysis translates these environmental hotspots into prioritized technical responses that align with customer requirements, particularly consistent product quality, reduced defects, and environmentally responsible production. The House of Quality results highlight machine setup optimization, pattern standardization, operator skill improvement, and waste segregation as the most influential technical priorities. The correlation analysis further shows that these technical actions reinforce each other, strengthening their potential impact on both environmental performance and customer satisfaction. By linking LCA-based waste identification with QFD-driven decision-making, this study identifies feasible green innovation opportunities that do not rely on high capital investment. Instead, the proposed improvements focus on process control, design efficiency, and operational discipline, making them suitable for community-based and resource-limited knitting SMEs. Overall, the integrated LCA–QFD framework offers a replicable decision-support tool for improving environmental efficiency while maintaining product competitiveness in small-scale textile industries. This study is limited to 3 SMEs and is grounded in expert-based evaluation rather than broad statistical sampling. The intention is to generate context-sensitive insights that support practical decision-making at the enterprise level. Future studies may expand the framework to a wider sample or incorporate digital production monitoring to enable more detailed environmental quantification.

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