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Development and Implementation of Smart Eco-STEAM Technology to Reduce Defects and Improve Efficiency in Ecoprint MSMEs

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ABSTRACT

Background: Micro, small, and medium-sized ecoprint enterprises (MSMEs) face persistent challenges, including high defect rates, lengthy steaming cycles, and energy-wasting manual production processes. These issues undermine product quality and restrain MSMEs' competitiveness in the sustainable textile sector.
Contribution: This study employed a participatory framework to develop and implement the Smart Eco-STEAM system to improve production accuracy and sustainability in ecoprint MSMEs. The model incorporates technological innovation, enhances artisan capacity, and encourages collaborative design to establish an adaptive, user-centered, and eco-efficient production system.
Methods: The research team used Participatory Action Research (PAR). Twelve artisans from Tembindigo ecoprint MSME in Yogyakarta helped co-design, prototype, and test Smart Eco-STEAM. The team collected data through observations, interviews, questionnaires, and production records. They analyzed the results using descriptive and comparative statistics, as well as Microsoft Excel 2021 and thematic analysis.
Results: Implementation of the Smart Eco-STEAM system resulted in a reduction of defective products from 35% to 12%, a decrease in steaming time by 45 minutes per cycle, and an improvement in energy efficiency by 37%. The system also doubled the daily production rate. Artisans reported increased working comfort, improved motif definition, and greater confidence in managing bulk orders. These results suggest that participatory innovation can

substantially improve both technical performance and operational consistency in small-scale ecoprint production.
Conclusions: The Smart Eco-STEAM technology integrates innovation and artisanal participation to deliver a sustainable and efficient MSME production model. This study provides a replicable framework for integrating eco-friendly technology into small-scale textile manufacturing.

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1. Introduction

Ecoprinting is an environmentally friendly fabric dyeing technique. It uses natural materials, such as leaves, flowers, and other biological resources, to create unique motifs on textiles. With increasing global awareness of sustainable fashion, ecoprint-based micro, small, and medium-sized enterprises (MSMEs) have great potential. They can strengthen the creative economy and participate in the eco-fashion market. However, ecoprint production in Indonesia remains largely manual and relies on the skill and experience of artisans. This results in inconsistent product quality and low production efficiency [1]–[3]. As a result, competitiveness remains limited, especially when the market demands sustainability, precision, and technological innovation.

MSMEs, such as Tembindigo ecoprint in Yogyakarta, still face key challenges. These include low production output, inconsistent colors, and defect rates up to 30–35% per cycle [4]–[7]. These problems often stem from poor temperature and steaming time control, impacting color and design clarity [8]–[10]. Research shows color quality relies on steady heat, humidity, and selected natural dyes [9]–[12]. While some studies have created automatic steaming machines [13], [14], most MSMEs use traditional equipment due to limited skills, high cost, and minimal collaboration with research bodies. Thus, a solution integrating new technology, skill training, and institutional support is needed to improve sustainability and competitiveness in the ecoprint sector [15], [16].

This study uniquely contributes by developing and implementing Smart Eco-STEAM technology through a Participatory Action Research (PAR) approach that involves artisans in problem identification, solution design, and testing. The research specifically targets reducing production defects, improving efficiency, and enhancing motif consistency by automatically controlling temperature and pressure. Notably, this work is among the first to apply a participatory technological framework to the efficiency of eco-innovation in Indonesian MSMEs. Key theoretical contributions include advancing sustainable production frameworks, while practical contributions empower artisans and strengthen their competitiveness in the eco-fashion sector [17], [18].

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2. Method

2.1. Study Approach

This study employed a Participatory Action Research (PAR) approach [19], which was considered appropriate for developing contextual solutions for ecoprint MSMEs. PAR emphasizes collaboration between researchers and practitioners, enabling the joint identification of problems and the design of participatory, adaptive, and sustainable solutions [20]. Its strength lies in combining action with reflection, fostering empowerment, and enhancing community capacity [21], [22]. The flexibility of PAR enables adaptation to evolving needs and enhances the acceptance of solutions through active stakeholder engagement. Previous studies highlight that technology adoption is more successful when users are involved in the design process [23]. Accordingly, the use of PAR in this study not only addressed technical challenges but also fostered long-term innovation capacity within ecoprint MSMEs.

2.2. Respondents

Twelve participants were purposively selected from Tembindigo ecoprint MSME in Yogyakarta. As seen in Table 1, most participants were women (11 individuals, 91.7%) aged 23 to 47 years, with work experience ranging from one to ten years. This composition highlights the significant role of women in ecology-based creative industries [24].

Table 1. Characteristics of Tembindigo ecoprint MSME respondents

Characteristic	Category	Number	Percentage (%)
Gender	Female	11	91.7
	Male	1	8.3
Age	< 30 years	2	16.7
	30–40 years	5	41.6
	> 40 years	5	41.6
Work Experience	< 3 years	4	33.3
	3–5 years	6	50.0
	> 5 years	2	16.7

Purposive sampling was employed to prioritize depth of understanding over broad representativeness [25]. The inclusion and exclusion criteria, detailed in Table 2, were established to ensure methodological rigor and data validity [26]. Participants were required to be directly involved in production with a minimum of one year of experience, while individuals in managerial or marketing roles were excluded.

2.3. Instruments

The study used several instruments aligned with PAR stages in Table 3. Observation sheets identified technical barriers, such as inconsistent steaming and high defect rates. Semi-structured interview guides explored participants' perceptions and areas for improvement.

Validation checklists ensured the feasibility and ergonomic suitability of the prototype. Questionnaires gathered quantitative and qualitative feedback on usability and efficiency. Production records documented outcomes. All instruments were validated through a Focus Group Discussion (FGD) with researchers and artisans to ensure clarity and contextual accuracy [27].

Table 2. Inclusion and exclusion criteria of research respondents

No	Inclusion Criteria	Exclusion Criteria
1	Ecoprint MSME actors at Tembindigo directly involved in ecoprint production	MSME actors engaged only in managerial or marketing roles
2	Minimum of one year of experience in ecoprint production	Respondents with less than one year of production experience
3	Willingness to participate in the entire research process from start to completion	Unwillingness to participate in the full research process
4	Willingness to provide information through observation, interviews, and questionnaires	Refusal to provide information or required data for the research

Table 3. Research instruments based on par stages

Research Stage	Instrument	Parameters
Needs Analysis	Observation sheets, semi-structured interview guide	Production barriers: inconsistent steaming temperature, high defect rate, excessive energy consumption [24].
Design & Testing	Validation checklist	Component feasibility, prototype functionality, ergonomic suitability of Smart Eco-STEAM [28].
Implementation	Questionnaire	User perceptions: ease of use, efficiency, improvement in product quality [29].
Monitoring	Production records	Processing time efficiency, energy savings, reduction in defective products, motif sharpness [30].

2.4. Procedures

The study, conducted from April to August 2025, used four participatory action research (PAR) cycles: (1) needs analysis, (2) design and development of the Smart Eco-STEAM technology, (3) implementation, and (4) monitoring and evaluation. During needs analysis, data were collected through observation and interviews to identify the main production challenges: unstable motif quality, high fuel use, and ergonomic concerns. The Smart Eco-STEAM prototype, developed in SolidWorks, was evaluated for temperature stability, steam distribution, and ergonomic performance. After validation, the prototype was integrated into

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daily production under the research team's supervision. Evaluation covered user experience, energy efficiency, and product quality. Respondents' direct quotations are omitted here and included in the Results section as recommended.

2.5. Data Analysis

Descriptive and comparative statistical techniques were applied using Microsoft Excel 2021 for quantitative data, while thematic analysis was applied to interview transcripts to explore recurring themes and participants' perspectives. Descriptive statistics, including percentages, means, and frequencies, were used to summarize demographic data and questionnaire responses. A comparative analysis evaluated performance differences before and after the implementation of Smart Eco-STEAM, focusing on steam time, fuel consumption, and defect rate reduction. Triangulation, which combined observation, questionnaires, and production data, was employed to enhance the reliability and validity of the findings [31]. This methodology ensured that quantitative results were corroborated by qualitative insights, resulting in a comprehensive understanding of production improvements.

3. Results

3.1. Needs Analysis

The initial stage of the study focused on identifying the main challenges faced by Tembindigo ecoprint MSME in using conventional steaming machines. Through observation, structured interviews, and survey instruments, four major themes emerged: unstable motif quality, long processing duration, excessive fuel consumption, and ergonomic issues affecting artisans' health and comfort. Figure 1 illustrates the observation process and the resulting ecoprint motifs.

Figure 1. Observation of the steaming process and ecoprint motif results

Interviews revealed fundamental production issues. Artisans reported that unstable temperatures and uneven steam distribution often produced blurred motifs, leading to inconsistency and defect rates as high as 35%. One artisan noted, *"Sometimes the results are good, sometimes they are blurred, even though I use the same method"* (R3). The steaming process also took two to three hours per cycle, significantly limiting daily output. As one respondent explained, *"One cycle can take up to three hours, so in a day, we cannot produce much"* (R5).

High fuel costs were another concern, as extended steaming duration increased LPG consumption. *"The gas runs out quickly, so operating costs become higher,"* said R7. Additionally, artisans highlighted ergonomic problems with conventional machines, which exposed them to excessive heat and discomfort. *"If I stay too long in front of the machine, I feel dizzy and exhausted"* (R9). These findings are summarized in Table 4 and underscore the need for technological innovations that ensure process stability, energy efficiency, and improved working conditions.

Table 4. Results of needs analysis in ecoprint production using conventional steaming machines

Main Aspect	Causal Factors	Indicators	Observation Findings
Imperfect motifs	Unstable steaming temperature, uneven steam distribution	Blurred motifs, dull colors, product defects up to 35%	Artisans often disappointed and experienced material loss
Lengthy process	Steaming duration 2–3 hours per production cycle	Limited daily production, averaging only 2–3 batches	Restricted production capacity of MSMEs
High fuel consumption	Excessive gas use due to extended steaming duration	Operational costs increased by ±25% per month	Higher expenditures than expected
Worker fatigue	Non-ergonomic equipment design, excessive heat exposure	Workers easily fatigued, complaints of dizziness, discomfort	Reduced productivity and motivation

3.2. Design and Testing of Smart Eco-STEAM Technology

At this stage, the research team designed the Smart Eco-STEAM technology using SolidWorks software to visualize the machine's dimensions, steam components, temperature control systems, and steam circulation pathways in Figure 2. The digital design enabled early simulation of heat stability, energy efficiency, and ergonomic considerations. Following validation, the prototype was manufactured with heat-resistant materials, automated temperature sensors, and a controlled steam release system. Each component was tested to ensure functionality.

The final design incorporated a central steaming chamber with a closed-loop circulation system, an automatic temperature sensor, ergonomic handles, and side ventilation to reduce

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heat exposure. The design not only improved production quality but also enhanced user safety and comfort. Component testing confirmed that Smart Eco-STEAM effectively addressed the primary limitations of conventional machines: unstable temperature, high fuel use, inconsistent motifs, and worker fatigue.

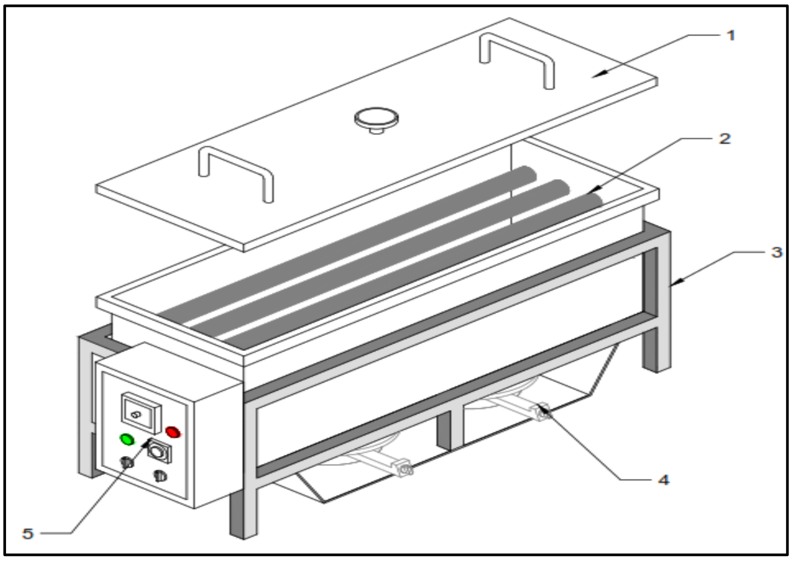

Figure 2. Component inspection and functional testing of smart eco-steam.
Description: Key components include: Steamer lid (1), Roll filter (2), Frame support for the tank and installation panel (3), LPG gas stove and base plate (4), and Automation control panel (5).

3.3. Implementation

The implementation phase evaluated the application of Smart Eco-STEAM in routine production by 12 artisans who previously relied on conventional machines. Researchers supervised the process to assess usability, energy efficiency, and product quality. Respondents' perceptions are presented in Table 5.

Table 5. Respondents' perceptions of smart eco-steam (n = 12)

Aspect	Indicator	Implementation Results
Ease and comfort of use	Ease of use	10 respondents (83%) stated "very easy"; 2 respondents (17%) stated "quite easy"
	Work comfort	12 respondents (100%) stated comfortable and ergonomic
Energy efficiency	LPG consumption per cycle	Decreased by 30% compared to conventional steaming machines
Production duration	Steaming time	Average of 1.5 hours (compared to 3 hours using conventional machines)
Product defects	Percentage of blurred/failed motifs	Decreased from ±20% to ±5%
Product quality	Motif sharpness	11 respondents (92%) rated motifs sharper
	Consistency of results	10 respondents (83%) expressed satisfaction with consistent results, without folding marks

Findings showed that 83% of respondents rated Smart Eco-STEAM as “very easy to use,” while all respondents (100%) found it comfortable and ergonomic. Steaming duration decreased from three hours to 1.5 hours per cycle, and LPG consumption dropped by 30%. Defect rates declined from 20% to 5%, while motif clarity and consistency improved significantly, with 92% of respondents rating motifs as sharper and more uniform. One artisan stated, *“Now it’s easier, no need to constantly check the temperature”* (P4), while another added, *“Production is faster, saves gas, and I can accept more orders”* (R2). These findings demonstrate that Smart Eco-STEAM not only enhanced technical efficiency but also increased artisans’ confidence in fulfilling larger orders.

3.5. Monitoring and Evaluation

Monitoring and evaluation were conducted over three months to assess long-term impacts on production efficiency, energy use, motif quality, and daily productivity. Comparative analysis in Table 6 showed substantial improvements: steaming time reduced by approximately 45 minutes per cycle, LPG consumption decreased by 37%, and defect rates dropped from 35% to 12%. Average daily production increased from 3–4 items to 6–7 items. Weekly production records in Table 7 confirmed consistent growth in fabric, shoe leather, and hat materials produced.

Table 6. Comparison of production performance before and after using smart eco-steam

Aspect	Before (Conventional)	After (Smart Eco-STEAM)	Change
Steaming duration	± 3 hours	± 2 hours 15 minutes	Saved ± 45 minutes per cycle
LPG consumption	1 cylinder for ± 5 cycles	1 cylinder for ± 8 cycles	Savings of ± 37%
Defective products	± 35% of total production	± 12% of total production	Decrease of ± 23%
Motif quality	Inconsistent, often blurred	Sharper, more consistent	Significant improvement
Finished products/day	3–4 items	6–7 items	Productivity doubled

Table 7. Productivity of semi-finished ecoprint products during four weeks of implementation

Week	Ecoprint Fabric (pieces)	Leather for Shoes (units)	Material for Hats (units)	Total Products (100%)
1	15 (55,7)	6 (23,1)	5 (19,2)	26
2	18 (57,2)	8 (25,0)	6 (18,8)	32
3	20 (55,6)	9 (25,0)	7 (19,4)	36
4	22 (55,0)	10 (25,0)	8 (20,0)	40

Artisans emphasized the improved stability of steaming processes, enhanced motif sharpness, and reduced failures. One respondent remarked, *“Now I am more confident taking*

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large orders because failures are rare" (R6), while another added, *"The results are more consistent, and the motifs are sharper"* (R11). Beyond technical gains, artisans reported increased confidence, reduced operating costs, and stronger business sustainability. These outcomes establish Smart Eco-STEAM as not only a technological solution but also a tool for empowering MSMEs and enhancing competitiveness in the eco-fashion market.

The findings show that Smart Eco-STEAM resolved three key barriers in ecoprint MSMEs: temperature instability, prolonged steaming, and high energy use. Defect rates dropped clearly as a result. These outcomes match previous research on process control and quality optimization in sustainable textile production [25], [26]. This supports the Technological Diffusion Theory [32].Technology adoption increases when innovations offer distinct advantages, fit current practices, and provide measurable benefits. Artisans in this study rapidly adopted Smart Eco-STEAM for its ease of use, energy savings, and higher output.

The study also strengthens the concept of Eco-Innovation by showing that businesses can achieve both environmental performance and economic competitiveness. Specifically, Smart Eco-STEAM enables businesses to automate temperature control during natural dye processes, resulting in three key benefits: reduced human error, lower energy consumption, and stabilized production quality. Similarly, Höffken & Limmer (2019) and Kutty (2020) found that automation in dye processes led to reduced energy use and improved product quality [27], [33]. Earlier studies also show that eco-innovation helps MSMEs shift from manual, resource-intensive production to more sustainable and efficient systems [34]. Overall, the Smart Eco-STEAM initiative clearly demonstrates that technology enhances both ecological performance and market readiness by delivering specific, measurable improvements.

The outcomes also align with Socio-Technical Transition Theory, which emphasizes the need for synergy between technology, human capacity, and institutional support to achieve sustainable innovation. In this context, designers of Smart Eco-STEAM involved artisans in a participatory process, fostering a sense of ownership, improving acceptance, and supporting long-term sustainability. Additionally, participatory technology approaches in community-based industries have promoted durable change [35], [36]. Thus, this study shows that participatory innovation accelerates the shift of traditional MSMEs towards sustainability-focused business models.

From a social perspective, the findings reaffirm that women drive innovation in MSMEs. Notably, most participants were female, which reflects the gendered nature of ecoprint production and its potential for empowerment. This aligns with the results of Aziz (2011) and Sanu (2020). Moreover, women's involvement in technology development increases productivity, confidence, and socio-economic empowerment [21], [37]. Thus, inclusive technological interventions not only enhance technical outcomes but also strengthen community resilience and foster sustained empowerment.

Theoretically, this study advances the integration of technological diffusion, eco-innovation, and socio-technical transition frameworks within creative and sustainable MSMEs. The findings indicate that effective diffusion of eco-technology relies on technical innovation, participatory co-design, and human empowerment. Key benefits include increased adaptability, more efficient resource use, and stronger stakeholder engagement. From a practical perspective, these results guide policymakers, educators, and MSME enablers in developing participatory technology-transfer models that incorporate training, digitalization, and sustainability principles, ultimately fostering greater innovation capacity and long-term competitiveness.

Several limitations should be acknowledged. The study's focus on a single MSME with a small participant group constrains the generalizability of the results, and reliance on descriptive and comparative statistics, while suitable for exploratory analysis, limits the ability to draw causal inferences. To address these issues, future research should use larger samples and examine a broader range of eco-friendly technologies. Researchers should also apply advanced analytical methods, such as structural equation modeling or mixed-methods approaches, to validate the relationships among technology adoption, efficiency, and empowerment. Nevertheless, this study establishes a robust foundation for understanding the role of participatory eco-technological innovation in accelerating sustainability transitions in MSMEs and enhancing community-based entrepreneurship.

4. Conclusion

This study confirms that the integration of Smart Eco-STEAM technology, developed through a Participatory Action Research (PAR) approach, effectively enhances efficiency, product quality, and sustainability in ecoprint MSMEs. Overall, the findings reveal that precise control of temperature and time, combined with structured training and collaborative innovation, significantly reduces production failures, shortens processing time, and increases output capacity. From a theoretical perspective, this study contributes to the literature by expanding the understanding of eco-textile innovation through a user-centered and participatory framework. It strengthens the conceptual link between technological efficiency and human capacity building, positioning PAR as a practical approach for fostering long-term sustainability in creative industries. Practically, the findings offer actionable insights for artisans, MSMEs, and stakeholders in the eco-fashion sector. The adoption of Smart Eco-STEAM not only improves production processes but also empowers artisans, enhances competitiveness, and promotes ecological responsibility. For policymakers and supporting institutions, this study provides evidence-based recommendations to design interventions that combine technology transfer, training, and multi-stakeholder collaboration.

Therefore, it is essential to integrate eco-friendly technological innovations into MSME development strategies. Practitioners and policymakers are encouraged to invest in digital steaming technologies, expand technical training programs, and strengthen partnerships with universities and research institutions to accelerate sustainable innovation. This study has limitations, including its small sample size, focus on a single MSME, and the application of a single specific technology. These factors restrict the generalizability of the findings. Future research should explore broader applications by involving diverse MSMEs across regions,

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testing variations of eco-friendly technologies, and conducting more comprehensive quantitative analyses of economic and environmental impacts. Such efforts will further advance the development of sustainable innovation ecosystems in the global eco-fashion industry.

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